154. I. M. Kolesnikov, G. M. Panchenkov, and V. A. Tulupov, Zhur. Fiz. Khim., 39, 1869 (1965) [Russ. J. Phys. Chem., 994 (1965)].

Zelinskii Institute of Organic Chemistry, USSR Academy of Sciences, Moscow

U. D. C. 547.239.1 : 547.339.1

KINETICS AND MECHANISM OF THE REACTIONS OF ISOCYANATES WITH COMPOUNDS CONTAINING "ACTIVE" HYDROGEN

S. G. Entelis and O. V. Nesterov

CONTENTS

1. Introduction 917
2. Structure of isocyanates and some of their properties 917
3. Kinetics of the reaction of isocyanates with alcohols 918
4. Effect of the properties of the medium on the reaction of isocyanates with alcohols 919
5. Dependence of rate of reaction on structure of isocyanate 919
6. Kinetic features of the reaction of di-isocyanates with alcohols 920
7. Dependence of rate of interaction of isocyanates with alcohols on the structure of the alcohol 921
8. Catalysis in the reaction of isocyanates with alcohols 922

1. INTRODUCTION

Research workers and technologists have recently been showing great interest in the reactions of isocyanates with alcohols and other compounds containing "active" hydrogen. The reason is that these processes underlie the preparation of several present-day chemical products [1-3].

The reaction of the isocyanate NCO group with an alcoholic hydroxyl is an act of chain propagation in the synthesis of polyurethanes, and has therefore been studied rather more thoroughly than other reactions of isocyanates. In contrast to many known reactions involving nucleophilic addition, however, investigation of the reactions of isocyanates is only in its initial stages.

A few reviews have been published [1,4] on the reactions of isocyanates, but fresh results make it necessary to re-examine several accepted ideas. Furthermore, many aspects of the kinetics and mechanism of these reactions are not yet clear, and demand new quantitative investigations.

2. STRUCTURE OF ISOCYANATES AND SOME OF THEIR PROPERTIES

The nature of the reactions undergone by isocyanates and their mechanism are largely determined by the structure of the NCO group and the distribution of electron density in the isocyanate molecule.

The isocyanate group NCO has a linear structure [5-7]. The angle between the R–N and N–C bonds in isocyanates RNCO varies with the nature of the group R. [5-8] There is probably no appreciable conjugation between the R and NCO groups in alkyl isocyanates, as is indicated, for example, by the low energy barrier of 49 ± 3 cal mole^{-1} to rotation of the methyl group in methyl isocyanate [6]. Thermochemical calculations suggest that the conjugation energy in isocyanates is small. According to Pauling [9] it does not exceed 7 kcal mole^{-1} in methyl and ethyl isocyanates. New data on the heats of combustion of isocyanates [10] and on the mean bond energies [11] yield a conjugation energy close to zero for methyl, ethyl, and phenyl isocyanates. This is understandable when it is remembered that the N=C and C=O π-bonds in the –N=C=O group are formed by carbon by means of p_y- and p_z-electrons, and are located in perpendicular planes. Nevertheless, the N=C and C=O interatomic distances in methyl isocyanate and isocyanic acid, measured by an electron diffraction method [5], indicate that these bonds are stronger than ordinary double bonds.

Table 1 shows that isocyanates RCNO possess large dipole moments, to which a substantial contribution is made by the NCO group. The fact that the dipole moment decreases† on passing from alkyl isocyanates to HNCO, i.e. with increase in the $R(\delta^+)-N(\delta^-)$ dipole from μ_{CN} = = 0.61 D to μ_{HN} = 1.42 D, [15] indicates that the sign of the moment of the NCO group is opposite to that of the R⇌N bond. Hence the nitrogen atom in the NCO group can be assumed to be more negative than the oxygen atom. This view is supported also by the increase in dipole moment on passing from isocyanates to isothiocyanates, which can be interpreted as resulting from replacing the oxygen atom in NCO by the less electronegative sulphur (according to Pauling [9] the electronegativities of oxygen and sulphur are 1.4 and 0.4 eV respectively).

The chemical behaviour of isocyanates agrees most completely with a distribution of charge and electron density in the NCO group represented by conjugation of the valency structures (I)–(III) [6,9]

$$\underset{\text{(II)}}{R-\ddot{\bar{N}}-\bar{C}=\ddot{O}:} \longleftrightarrow \underset{\text{(I)}}{R-N=C=O} \longleftrightarrow \underset{\text{(III)}}{R-\ddot{N}=\overset{+}{C}-\ddot{\bar{O}}:}.$$

TABLE 1. Dipole moments μ of some isocyanates and isothiocyanates.

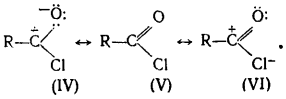
Compound	HNCO	CH_3NCO	C_2H_5NCO	C_6H_5NCO	HNCS	CH_3NCS	C_2H_5NCS	C_6H_5NCS
μ, D	1.59 [12]	2.81 [6]	2.81 [13]	2.3 [13]	1.72 [14]	3.18 [13]	3.31 [13]	3.0 [13]

† The decrease in the dipole moment of RNCO and RNCS when the alkyl radical is replaced by hydrogen is larger than would follow from vectorial addition of the dipoles [6].

TABLE 2. Rates of reaction of phenyl isocyanate with various compounds in toluene at 80° [17].

Compound	$10^4 k$, litre × mole^{-1} s^{-1}	Relative rate	Compound	$10^4 k$, litre × mole^{-1} s^{-1}	Relative rate
Butan-1-ol	30	1500	Butyric acid	2	100
Water	6	300	Butyranilide	0.3	15
Diphenylurea	2	100	Ethyl phenylcarbamate	0.02	1

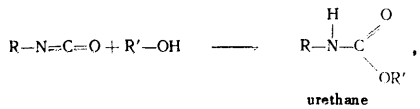
The carbon of the NCO group is a strong acceptor, resembling in several of its properties the carbon of an acid chloride — structures (IV)–(VI)



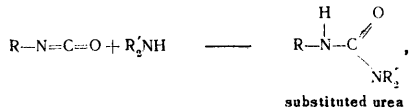
(IV) (V) (VI)

The nitrogen and the oxygen in the NCO group generally carry a negative charge, and possess electron-donor properties. This group is therefore subject to both nucleophilic and electrophilic attacks.

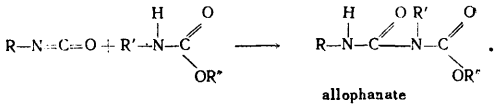
In most cases isocyanates behave as electrophilic reagents. Their most typical reactions are nucleophilic additions involving substances containing oxygen and nitrogen, e.g.



urethane



substituted urea



allophanate

Few thermodynamic data are available on additions to isocyanates. We can mention only the paper by Lovering and Laidler [16], who measured the heats of reaction of certain aryl isocyanates with butyl alcohols.

In the absence of catalysts, the reactivity of different nucleophilic compounds towards an isocyanate usually varies in the sequence

$$RNH_2 > ROH > H_2O > C_6H_5OH > RSH > RCOOH,$$

the sequence for amines being

$$R_2NH > RNH_2 > NH_3 > C_6H_5NH_2,$$

and that for nitrogen-containing compounds

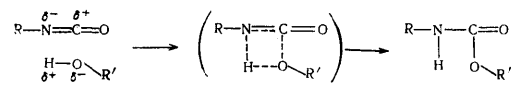
$$\underset{\text{amine}}{RNHR'} > \underset{\text{urea}}{RNHCONHR'} > \underset{\text{amide}}{RNHCOR'} > \underset{\text{urethane}}{RNHCOOR'}.$$

Numerical values of the relative rates are given in Table 2.

3. KINETICS OF THE REACTION OF ISOCYANATES WITH ALCOHOLS

The interaction of isocyanates with alcohols has been more thoroughly studied than other reactions, but even in this case the mechanism is still far from clear. Several possible reaction schemes are now being discussed in the literature, a common feature being the assumed nucleophilic attack by the alcohol or other reagent on the NCO group of the isocyanate. Non-catalytic nucleophilic addition of an alcohol to an isocyanate can be imagined as occurring in several ways. Analogous schemes may be suggested for the reactions of thiols as well as of isothiocyanates.

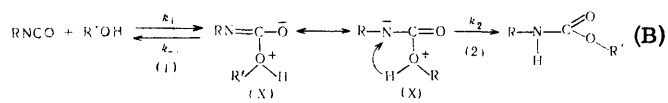
(A) Direct addition of R'OH to RNCO with the formation of a four-membered activated complex [18–20]:



(A)

Preliminary coordination corresponding to the relative arrangement of molecules in the activated complex is inherent in the formation of solvates. This mechanism is supported by the large negative entropies of activation in the non-catalytic reactions of isocyanates with alcohols [16]: in the reaction of *p*-chlorophenyl isocyanate with methanol in heptane [21], for example, $\Delta S^{\neq} = -44.5$ e.u. with $E = 8.2$ kcal mole^{-1}.

(B) Preliminary reversible addition with formation of an intermediate complex (X) of ionic structure by the scheme accepted for the reactions of other carbonyl compounds [22,23], and its subsequent unimolecular conversion into the urethane by prototropic rearrangement:



(B)

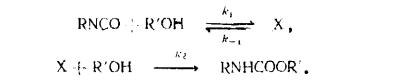
This scheme resembles that proposed by Zahradník [24] for the reactions of isothiocyanates with the hydroxide ion in aqueous–dioxan and aqueous–alcoholic solutions. The large positive values of the parameter ρ in the Hammett equation (see Section 5) observed in the reactions of isocyanates and isothiocyanates support mechanism (B) provided that (*a*) the rate of the process is limited by the nucleophilic attack (1), or (*b*) reaction (1) is rapid and reversible, the equilibrium constant increasing with increase in the electrophilic character of the substituent in group R (e.g. in phenyl).

Schemes (A) and (B) are indistinguishable by formal kinetic criteria. In both cases the reaction velocity is described by the second-order equation

$$-dC_{RNCO}/dt = kC_{RNCO}C_{R'OH}. \qquad (3)$$

For scheme (A) we have $k = k_{true}$. For scheme (B) with (*a*) $k_1 C_{R'OH} \ll k_{-1}$, k_2, we have $k = k_1 k_2/(k_{-1} + k_2)$, or in the limit, when $k_2 \gg k_1$, we find that $k = k_1$; or with (*b*) $k_1 C_{R'OH} \gg k_2$ (equilibrium), we obtain $k = Kk_2$, where K is the equilibrium constant for stage (1).

(C) Formation of the addition product X in the first stage, as in scheme (B), and its conversion into the urethane by a bimolecular reaction with a second R'OH molecule:



(C)

Scheme (C) was suggested by Baker and his coworkers [25,26] to explain the increase, observed under certain conditions, in the second-order rate constant with the alcohol content of the mixture. In fact, with $k_1 C_{R'OH} \ll k_{-1}$, k_2, when the

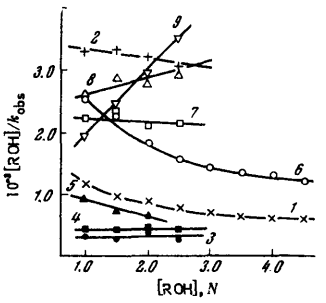


Fig. 1. Reactions of phenyl isocyanate with alcohols and glycols:
1) ethanol; 2) 2-ethoxyethanol; 3) trimethylene glycol; 4) tetramethylene glycol; 5) hexamethylene glycol; 6) ethylene glycol; 7) diethylene glycol; 8) triethylene glycol; 9) tetraethylene glycol [27].

method of quasi-stationarity with respect to the intermediate product is applicable, we have for the rate of the process, in conformity with scheme (C), the equation

$$-dC_{RNCO}/dt = \\ = k_2 C_{RNCO} C^2_{R'OH}/(k_{-1} + k_2 C_{R'OH}). \quad (4)$$

Consequently, if we start from Eqn. (3) in analysing the rate of the process, the "second-order constant" observed here will be the apparent parameter

$$k_{obs} = k_2 C_{R'OH}/(k_{-1} + k_2 C_{R'OH}). \quad (5)$$

Many facts have now been accumulated to indicate that in most cases the second-order relation is strictly satisfied up to considerable extents of conversion in reactions of both monomeric and polymeric compounds [21,27]. There are also data which in several instances do not support Baker's mechanism. Thus Robertson [28], in a kinetic study of the reaction of phenyl isocyanate with a series of alcohols and glycols, has obtained results which in most cases are not described by Eqn. (5): i.e. a linear relationship between C_{ROH}/k and C_{ROH} having a positive slope is not observed (Fig. 1).

4. EFFECT OF THE PROPERTIES OF THE MEDIUM ON THE REACTION OF ISOCYANATES WITH ALCOHOLS

The dependence of the second-order rate constant on the concentration of alcohol in certain solvents, which has been observed by several authors, is probably associated not so much with "catalysis" by the alcohol as with the change in polar and other properties of the medium. Together with Tiger [29,30] we have established, for example, that the rate constant for the reaction of phenyl isocyanate with methanol is increased by increasing the concentration of the alcohol in dioxan solution. However, a similar increase in the rate constant is observed if the concentration of the polar dichloroethane is increased while the alcohol concentration is kept constant. Since a linear relation between the logarithm of the rate constant and Kirkwood's function $(\epsilon - 1)/(2\epsilon + 1)$ (where ϵ is the dielectric constant of the medium) is maintained in both cases, it may be concluded that it is the increase in polarity of the medium produced by adding the alcohol and the dichloroethane which is responsible for the increase in the reaction rate constant. The fact that reaction velocity increases with increase in the dielectric constant of the medium is indicated also by kinetic data on the reaction of hexamethylene di-isocyanate with alcohols in the sequence of solvents [31] toluene < *o*-chlorobenzene < nitrobenzene.

Thus the conclusion reached by Ephraim et al.[32], that increase in polarity of the medium results in suppression of the reaction, is incorrect. It is probable that, apart from polarity, specific interaction between solvent molecules and the alcohol and isocyanate molecules plays an important part in the action of the solvent on the reaction velocity. Such interaction usually results in deactivation of the reactant molecules. For example, a weakly polar solvent, which undergoes no specific interaction with the reactants, is able to accelerate the reaction. Thus, according to data obtained together with Tiger [29,30], the reaction of phenyl isocyanate with methanol becomes more rapid with increasing proportion of heptane in a mixed heptane–dioxan solvent, although the dielectric constant of the system is unchanged.

5. DEPENDENCE OF RATE OF REACTION ON STRUCTURE OF ISOCYANATE

The activity of the isocyanate group is fundamentally affected by the structure of the radical R in the RNCO molecule. In conformity with the electronic structure of NCO discussed above, electron-attracting radicals will increase the fractional positive charge on the carbon, and electron-donating radicals will diminish it.

Aromatic isocyanates are usually more active than aliphatic and aralkyl isocyanates [33]. However, results obtained by different workers yield quantitative comparisons of their reactivities which show significant differences. In the case of reaction with n-butanol in the presence of triethylamine in toluene at 37°, for example, the rate constants k' and k'' (for the first and second isocyanate groups respectively in a di-isocyanate) are [34] 330×10^{-4} and 28×10^{-4} litre mole^{-1} s^{-1} for 4-methyl-1,3-phenylene di-isocyanate, while the corresponding rate constants for hexamethylene di-isocyanate are 0.83×10^{-4} and 0.42×10^{-4} litre mole^{-1} s^{-1}. In the case of reaction with a polyethylene glycol adipate at 100° we have [35] $k = 36 \times 10^{-4}$ litre mole^{-1} s^{-1} and $E = 11$ kcal mole^{-1} for the above methylphenylene di-isocyanate, compared with values of 8.3×10^{-4} litre mole^{-1} s^{-1} and 11 kcal mole^{-1} for hexamethylene di-isocyanate.

The work of Sato [27] and of Greenshields et al.[31] shows that, at high degrees of conversion, the kinetics of the reaction of alkyl or alkylene isocyanates with alcohols diverges appreciably from a bimolecular law, owing to the greater sensitivity of the rate of the process to the catalytic effect of the urethane. In the view of the latter workers [31], the kinetics of the interation of hexamethylene di-isocyanate with butan-2-ol and with polyethylene glycol in toluene are described by the equation

$$dx/dt = \alpha(a-x)(b-x)^2 + \beta(a-x)(b-x)x, \quad (6)$$

where x is the instantaneous concentration of the urethane, a and b are the initial concentrations of the isocyanate and the alcohol respectively, and α and β are constants.

In the case of aryl isocyanates the introduction of substituents into the benzene ring changes the activity of the

TABLE 3. Hammett σ-constants for NCO and other substituents.

Substituent	σ from Ref. 39	σ from Ref. 38	Substituent	σ from Ref. 39	σ from Ref. 38
p-NO_2	1.27 *	—	*p*-NHCOOR **	—	0.038
m-NCO	0.43	0.30	*p*-$(CH_2C_6H_4NHCOOC_2H_5)$	0.01	—
p-NCO	0.35	0.24	*p*-$NHCOOC_6H_9$-n	−0.05	—
p-Cl	0.23 *	—	*p*-$(CH_2C_6H_4NHCOOC_4H_9$-n)	−0.05	—
p-$(CH_2—C_6H_4—NCO)$	0.04	—	*m*-CH_3	−0.07 *	—
m-$NHCOOC_4H_9$-n	0.01—0.06	—	*p*-CH_3	−0.17 *	—
m-NHCOOR **	—	0.025			

* From Hammett's results [37].

** R = 2-ethylhexyl.

NCO group. On substitution of phenyl isocyanate the reaction velocity varies in conformity with the Hammett equation [37]

$$\log(k_{subst}/k_0) = \rho\sigma, \quad (7)$$

where k_0 and k_{subst} are the rate constants for the unsubstituted and the substituted phenyl isocyanate, σ is a parameter characteristic of the substituent, and ρ is a parameter characteristic of the type of reaction and its sensitivity to the action of the substituent. The results of different authors [38,39] indicate that ρ = 1.69–1.98. It is interesting that ρ = 1.7 for substituted isothiocyanates [40]. A positive value of ρ indicates that the reaction is accelerated by the introduction of electron-attracting substituents.

Values of σ for NCO and urethane groups, like those of ρ, have not yet been determined sufficiently accurately for calculation of the reaction velocity of individual NCO groups in substituted and multifunctional isocyanates. Table 3 gives the values of σ obtained from a comparison of the reaction velocities of isocyanates with alcohols. It includes for comparison values of σ for other substituents from Hammett's data.

No results have been published on the effect of *ortho*-substituents on the activity of aryl isocyanates. This effect can be estimated by means of the Taft equation [37]. Furthermore, values of ρ usually change with variation in the temperature and in the solvent, and without a knowledge of these it is impossible to calculate the rate constants for substituted isocyanates. Results obtained by us together with Tiger [29,30], for example, indicate that the parameter ρ = 3.3 for the uncatalysed reaction of substituted phenyl isocyanates with methanol in heptane, this value falling on addition of dioxan to the heptane, and reaching 2.6 in pure dioxan.

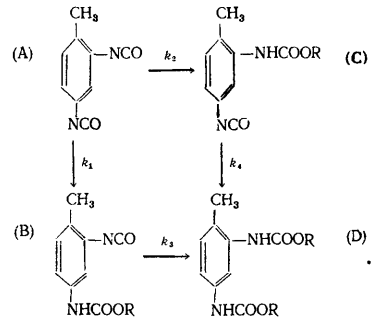
6. KINETIC FEATURES OF THE REACTION OF DI-ISOCYANATES WITH ALCOHOLS

The possibility of calculating in advance the rate constant, for interaction with an alcohol, of each of the NCO groups in a di-isocyanate is not only of theoretical but also of great practical importance. The unequal reactivities of the two NCO groups has a fundamental effect on the kinetics of the formation of the polyurethane, its average molecular weight, and the character of the molecular-weight distribution [41]. This appears especially clearly in one of the most widely used technical products — a mixture of 2- and 4-methyl-1,3-phenylene di-isocyanates.

The difference in reactivity between the NCO groups should be especially marked in 4-methyl-1,3-phenylene di-isocyanate, since the group in position 1 is not "blocked" by the methyl substituent, it is activated by the isocyanate group in position 3, and the second NCO group reacts mainly only when substitution by the urethane group has already occurred in position 1. Consequently the numerous published values for k' and k'' in di-isocyanates actually represent in the former case (k') mainly the reactivity of the first, most active NCO group in the di-isocyanate, and k'' (indirectly) the reactivity of an isocyanate group which is now present in an alkoxycarbonylaminophenyl isocyanate, not in a di-isocyanate. After reaction of the more active NCO group in position 1 in 4-methyl-1,3-phenylene di-isocyanate, for example, the NCO group in position 3 is now accompanied by a new *meta*-substituent — the urethane group — and the parameter σ changed from ~ 0.43 to close to zero. With ρ = 2, this corresponds, as follows from the Hammett equation, to an almost tenfold increase in the rate constant, which can by no means be neglected, as is done by Ferstandig and Scherrer [33].

The use above of the terms "mainly" and "indirectly" is not accidental. The point is that calculation of the rate constants from two linear sections in the anamorphoses of the kinetic curves, as is done by the authors of almost all existing papers, is sometimes not altogether correct, and frequently altogether incorrect. Let us consider this in greater detail.

If we carry out the reaction of 4-methyl-1,3-phenylene di-isocyanate with excess of an alcohol ROH, we must distinguish four pseudounimolecular reactions:



The variation in the total concentration of isocyanate groups [NCO] = 2[A] + [B] + [C] can be represented by the equation

$$[NCO] = [A]_0\left\{2e^{-(k_1+k_2)t} + \frac{k_1}{k_3-k_1-k_2}\left[e^{-(k_1+k_2)t} - e^{-k_3t}\right] + \right.$$
$$\left. + \frac{k_2}{k_4-k_1-k_2}\left[e^{-(k_1+k_2)t} - e^{-k_4t}\right]\right\}. \quad (8)$$

Brock [39] used the Hammett equation to estimate the ratios between k_1–k_4, and adopted the values $k_2 = 0.34k_1$, $k_3 = 0.0745k_1$, and $k_4 = 0.219k_1$. Putting $k_1 = 0.01$, he plotted by means of the above equation the time variation in the concentrations of the compounds A, B, and C and in the total concentration of isocyanate groups. When log [NCO] is plotted against t, an anamorphosis is actually obtained consisting of two linear sections, from which the apparent rate constants k' and k'', which do not correspond to the true values k_1 and k_2, can be found. In fact values of k' = = 0.0053 and k'' = 0.001 were obtained, instead of the values $k_1 = 0.01$ and $k_2 = 0.034$ originally introduced into the calculation.

Values of the constants and their ratios, obtained by different authors under closely similar conditions, often differ substantially from one another. Table 4 gives rate constants for reaction of the two NCO groups in 4-methyl-1,3-phenylene di-isocyanate with alcohols. The data of

TABLE 4. Rate constants for the reaction of 4-methyl-1,3-phenylene di-isocyanate with alcohols according to various workers.

Temp., °C	Solvent	Reactant	$10^4 k'$, litre mole^{-1} s^{-1}	$10^4 k''$, litre mole^{-1} s^{-1}	k'/k''	E', kcal mole^{-1}	E'', kcal mole^{-1}	Ref.
30	chlorobenzene	diethylene glycol adipate	0.45	0.057	7.9	9.3	12.6	42
25	xylene	n-butanol	0.62	0.25	10.5	8.5	10.5	42
35	xylene	n-butanol	4.22	0.44	9.6	—	—	42
25	toluene	n-butanol	13.0	0.42	31.0	1.0	—	42
21.4	toluene	n-butanol	25.5	20.5	12.4	3.1	3.6	34
40	toluene	ethanol	27.6	1.3	21.3	11.0	—	33

TABLE 5. Rate constants ($10^4 k$, litre g-equiv.$^{-1}$ s^{-1}) for the reaction of phenyl isocyanate with alcohols in toluene at 30° (catalyst concentration 10^{-4} M; [NCO] : [OH] = 1) [46].

Catalyst	$k \cdot 10^4$ л/экв·сек											
	1-C_4H_9OH	2-C_4H_9OH	$\frac{k_{prim}}{k_{sec}}$	POEG*	POPG*		methoxypropanols			k_A/k_B	k_A/k_C	k_B/k_C
					k_{prim}	k_{sec}	A = 3,1	B = 2,1	C = 1,2			
No catalyst	0.9	0.3	3.0	—	—	—	0.5	0.4	0.2	1.2	2.5	2.0
Dibutyltin(IV) dilaurate	290.0	24.2	12.0	151 **	17.5	6.6	262.0	75.7	15.2	3.5	12.2	4.9
Tin(II) octanoate	12.0	3.4	3.5	—	—	—	60.3	—	48.5	—	1.2	—
Tin(II) oleate	6.9	2.0	3.5	—	—	—	40.4	—	41.4	—	1.0	—
Lead(II) naphthanate	6.3	0.9	7.0	—	—	—	32.0	106.5	68.0	0.3	0.5	1.6

* From Ref. 47; POEG = polyoxyethylene glycol; POPG = polyoxypropylene glycol.

** Catalyst concentration 0.5×10^{-4} M.

Morton and Deisz [42] differ markedly from those obtained by Tazuma under similar conditions. The constants k' and k'', calculated by Burkus and Eckert [34] from a simple two-stage scheme using Frost's improved method [43] in the case of the unsymmetrical 4-methyl-1,3-phenylene di-isocyanate, are composite quantities, which do not reflect the reactivities of the two NCO groups.

With rise in temperature the difference in reactivity of the NCO groups in a di-isocyanate and the urethane–isocyanate is usually smoothed out, and the break in the anamorphosis of the kinetic curve disappears. This occurs earlier the less marked the inductive or steric interaction between the two reaction centres in the di-isocyanate. Even with 4-methyl-1,3-phenylene di-isocyanate the anamorphosis of the kinetic curve has no breaks at 100°. In the case of diphenylmethane *pp'*-di-isocyanate the anamorphosis has no break up to 70% conversion even at 30°. [1]

It is quite clear that constants for the individual stages in such multistage consecutive and parallel reactions as those of unsymmetrical di- and tri-isocyanates can be obtained only by means of electronic computers. An example is provided by the work of Ferstandig and Scherrer [33], who give a series of reliable values of the constants for several symmetrical aryl and aralkyl di-isocyanates.

7. DEPENDENCE OF RATE OF INTERACTION OF ISOCYANATES WITH ALCOHOLS ON THE STRUCTURE OF THE ALCOHOL

The activity of an alcohol depends both on the position of the hydroxyl and on the presence of substituents in the molecule. Available data are unsystematic and frequently contradictory. However, it has been firmly established that primary hydroxy-groups are more active than secondary hydroxyls. According to Lovering and Laidler [16], for example, the observed rate constants for the reactions of phenyl isocyanate with n-C_4H_9OH, iso-C_4H_9OH, and s-C_4H_9OH in alcohol at 25° are respectively 4.6×10^{-4}, 3.0×10^{-4}, and 1.44×10^{-4} litre mole^{-1} s^{-1}. Dyer et al.[44] obtained values of 4.4×10^{-4} and 1.4×10^{-4} litre mole^{-1} s^{-1} for the reaction rate constants of phenyl isocyanate with n-C_4H_9OH and s-C_4H_9OH in xylene at 25°.

The rate constants for the reaction of methylphenylene di-isocyanate with glycols at 40° are 0.4×10^{-4} and 0.78×10^{-4} litre mole^{-1} s^{-1} for polyoxypropylene glycol and polyoxyethylene glycol [45].

t-Butyl alcohol reacts still more slowly. Thus according to Baker [25,26] the rate constants for the reaction of phenyl isocyanate in dibutyl ether at 20° with the series of alcohols CH_3OH, C_2H_5OH, $CH_3CH(OH)CH_3$, and t-C_4H_9OH are $(0.28, 0.48, 0.23, \text{and } 0.008) \times 10^{-4}$ litre mole^{-1} s^{-1}.

However, the difference in rates is especially large for the catalysed reactions. According to Wissman et al.[45], for example, the rate constants for the reactions of methylphenylene di-isocyanate with glycols at 40° in the presence of 0.005% of dibutyltin dilaurate are 0.87×10^{-4} and 27.1×10^{-4} litre mole^{-1} s^{-1} for polyoxypropylene glycol and polyoxyethylene glycol.

Both the absolute rates of reaction of primary and secondary alcohols with isocyanates and their ratio depend on the nature and concentration of the catalyst. Data for a series of alcohols with phenyl isocyanate in toluene solution show (Table 5) that dibutyltin dilaurate has a particularly strong effect in increasing the difference in reaction velocity between primary and secondary hydroxy-groups. It is interesting that with polyoxypropylene glycol two stages can be observed, with constants k_{prim} and k_{sec}, characterising interaction of phenyl isocyanate with the primary and the secondary hydroxyls of the diol respectively [47]. However, it is difficult to assume that the investigators were able to separate quantitatively these two stages of the reaction. Both constants are evidently effective values.

The reactivity of a molecule is diminished by the introduction of electron-attracting substituents, owing both to a decrease in the basic character of the oxygen of the hydroxy-group and to the appearance of steric hindrance. Thus the following rate constants have been determined for the reaction of 3,3-dinitropentamethylene di-isocyanate with alcohols in dimethylformamide at 30° [48]

	k, litre mole^{-1} s^{-1}
Propane-1,3-diol	3×10^{-4}
3,3-Dinitropentane-1,5-diol	0.29×10^{-4}
2,2-Dinitropropane-1,3-diol	0.064×10^{-4}

Detailed investigations of the reactions of nitro-alcohols with phenyl isocyanate have recently been made by Solodova [49] (Table 6). The change in reactivity on passing from primary to tertiary alcohols is found [49] to be less marked with nitro-alcohols (Table 7), which is attributed to steric causes. Since the nitro-alcohols already contain "bulky" nitro-groups, which cause strong steric blocking of the hydroxyls, the introduction of alkyl groups (in the case of secondary and tertiary alcohols) has less effect on the activity of the alcohol.

Introduction of a methoxy-group into an alcohol molecule enhances its activity in comparison with a methyl or an ethyl group. For the reaction of 4-methyl-1,3-phenylene di-isocyanate in ethyl acetate at 78°, for example, the rate constants with 2-methyl-2-nitropropane-1,3-diol and with 2-hydroxymethyl[methoxymethyl(?)]-2-nitropropane-1,3-diol are respectively 14.6×10^{-4} and 40.0×10^{-4} litre × × mole^{-1} s^{-1}.

The chain lengths of polymeric diols have an extremely important effect on the reactivity of their terminal groups. Although very little information has been published on this topic, the available data suggest that the degree of polymerisation has a slight effect on the rate constant [28,36,45,50] (Table 8). At low degrees of polymerisation, when the length of the glycol chain is 3–6 monomer units, some variation in the rate constant with the number of units is observed. However, the fact that the type of variation depends on the concentration of the diol (Table 9) suggests rather that the ratio between terminal groups and groups in the chain influences the properties of the medium, and hence the reaction velocity.

The degree of multifunctionality of polyols has little effect on the rate constant per equivalent (Table 10).

TABLE 6. Rate constants for the reaction of phenyl isocyanate with some nitro-alcohols in ethyl acetate at 50° ([NCO] = [OH] = 0.6) [49].

Alcohol	$10^4 k$, litre mole^{-1} s^{-1}	$k_{alc}/k_{nitroalc}$
Ethanol	34.6	17.9
Nitroethanol	1.93	—
Propan-2-ol	10.5	7.37
1-Nitropropan-2-ol	1.42	—
t-Butyl alcohol	3.9	7.2
1-Nitro-2-methylpropan-2-ol	0.54	—

TABLE 7. Relative activities of alcohols and nitro-alcohols [49].

Alcohols	Tertiary	Secondary	Primary
Simple alcohols	1	2.7	8.9
Nitro-alcohols	1	2.6	3.6

TABLE 8. Effect of chain length of polyoxypropylene glycol on its reactivity with methylphenylene di-isocyanate at 50° [45].

Equiv. wt. of polyol	Concn. of OH groups, N	$10^4 k$, litre × × g-equiv.$^{-1}$ s^{-1}
980	0.8	1.0
525	1.49	1.3
388	1.88	1.3
680	0.8	1.0
525 + toluene*	0.89	0.7
388 + toluene*	0.89	0.8

* Toluene added in these experiments to maintain the OH concentration constant with change in the molecular weight of the polyol.

TABLE 9. Dependence of rate constant ($10^4 k$, litre g-equiv.$^{-1}$ min^{-1}) on structure and concentration of diols in dioxan as solvent at 30° ([C_6H_5NCO] = 0.2 M) [28].

Glycol	[ROH], N		
	0.2	1.0	2.0
C_2H_5OH	—	7.74	20.5
$HOCH_2CH_2OH$	1.02	3.78	10.5
$HO(CH_2CH_2O)_2H$	1.56	4.32	9.18
$HO(CH_2CH_2O)_3H$	1.92	3.66	6.84
$HO(CH_2CH_2O)_4H$	2.84	4.86	6.24
$HO(CH_2)_3OH$	—	22.1	39.6
$HO(CH_2)_4OH$	—	19.2	37.9
$HO(CH_2)_5OH$	—	9.8	26.3

TABLE 10. Reaction of methylphenylene di-isocyanate with polyoxypropylene glycol (of mean equivalent weight 1000) at 60° [45].

Alcohol*	$10^4 k$, litre × ×g-equiv.$^{-1}$ s^{-1}	Alcohol*	$10^4 k$, litre × × g-equiv.$^{-1}$ s^{-1}
Tetraol (pentaerythritol)	1.68	Diol (propylene glycol)	1.73
Triol (2,2-dimethylbutane-1,1',1''-triol)	1.86	Triol (glycerol)	1.59

* The alcohol used to initiate polymerisation of propylene oxide is indicated in parentheses.

8. CATALYSIS IN THE REACTION OF ISOCYANATES WITH ALCOHOLS

The question of the mechanism of catalysis in reactions of isocyanates with alcohols is closely interlinked with the problem of the mechanism of catalysis in reactions of other carbonyl compounds [22] on the one hand, and with the activation of alcohols and other hydroxyl compounds [51] on the other. However, apart from the extremely interesting and little studied theoretical aspects of catalysis in the former reactions, the problem is also of great practical importance.

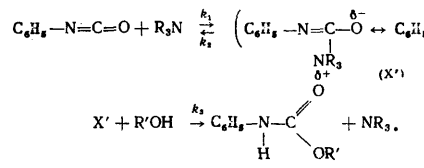
In the choice of industrial catalysts for the manufacture of polyester–urethane rubbers, the requirements which they have to meet depend on the character of the process and its technology. In the moulding of articles directly from the polymer mass, for example, it is necessary that it should retain its plasticity and mobility for a certain time after the reactants have been mixed, and then be converted quite rapidly into the completely vulcanised polyurethane rubber [1]. The requirements are the same in the application of polyurethane films and lacquers: the mixture must remain "lively" from the instant of mixing of the polyol and the di-isocyanate until it is applied to the surface, and then set rapidly to a stable film [52]. In the production of polyurethane foams the catalyst must be selective towards the di-isocyanate–polyether-diol and the di-isocyanate–water reactions. In all the above cases the catalysts should not promote ageing of the polyurethane rubbers obtained with their aid, either by accelerating oxidative degradation or photodegradation of the goods or by catalysing the formation of additional, allophanate bonds by interaction with traces of unchanged isocyanate.

From the above, far from complete list of the varied requirements to be met by the catalysts it is evident that a rational choice thereof can be made only on the basis of systematic combined investigations of the kinetics, the mechanism, and the chemistry of their action. Only a few quantitative studies have been published on the nature and action of catalysts for the reactions of isocyanates.

Although a large number of catalysts have been described, the problem of the mechanism of catalysis, i.e. of why a catalyst enhances the activity of a reactant molecule, remains unsolved. Its solution is complicated by the fact that compounds belonging to different classes, and frequently having directly opposite properties, catalyse the reactions of isocyanates with alcohols. The catalysis of the reactions of isocyanates has several features in common with that of reactions of certain carbonyl compounds, e.g. acid chlorides, anhydrides, esters, etc. In the present case, however, peculiarities are present associated both with the structure of the NCO group and with the fact that in all the above cases nucleophilic substitution is involved, whereas nucleophilic addition occurs in the reactions of isocyanates. Like the hydrolysis and the alcoholysis of certain carbonyl compounds, the reactions of isocyanates are accelerated by bases [53,54]. They are typically catalysed by organic compounds of metals [4], which is less characteristic of carbonyl compounds, but nevertheless has been described in the literature [55]. Acid catalysis, which is very widespread with esters and amides, is not very effective with isocyanates, which makes them akin to acid chlorides. This is apparently associated in both cases with the weak basic character of the compounds. As in the case of acylation with acid chlorides and anhydrides, the addition of alcohols to isocyanates is accelerated by tertiary amines [4,56,57].

Many authors explain the action of a catalyst by the occurrence of complex formation, but it is not sufficient to assume that a catalyst forms a complex with one of the reactants. It is not even sufficient to establish that a complex is in fact formed: many cases are known in which the complexes observed do not take part in the reaction. It is necessary to show that the reaction velocity is proportional to the concentration of a complex formed by the catalyst with one of the reactants. To understand the action of a catalyst, it is very important to ascertain why formation of a particular complex results in enhanced reactivity of a reactant molecule. Catalysts of amine type have been studied the most thoroughly. However, the mechanism by which they catalyse the reaction of isocyanates with alcohols is still not clear.

The possibility that the amine activated both the isocyanate molecule [25,26,58,59] and the molecule of the hydroxyl compound [60–62] has been discussed since the first quantitative work on catalysis [25,26]. In the first case a scheme (D) was proposed [25,26] in conformity with existing views on the catalysis by amines of nucleophilic substitution reactions at a carbonyl group [22]



(D)

As in the case of the catalysis of acylation by acid chlorides [57], it may be supposed that the appearance of the extremely strong electron-attracting substituent $^{+}NR_3$‡ substantially increases the deficiency of electron density on the carbon, while a new electron-donor centre appears. Both factors favour subsequent addition of an alcohol molecule to the complex X″.

The scheme (D) led to the rate equation

$$-dC_{RNCO}/dt = \frac{k_1 k_3 C_{R'OH} C_{RNCO} C_{NR_3}}{k_2 + k_3 C_{R'OH}}, \qquad (9)$$

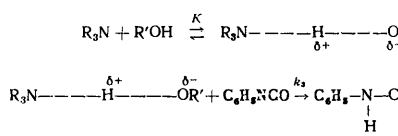
based on the hypothesis of a steady state with respect to the intermediate complex, consumption of the complex being more rapid than its formation. Some authors consider [25,26,58] that the correctness of scheme (D) is confirmed by the fact that the kinetic data give linear plots of $1/k_{cat}$ against $C_{R'OH}$ in conformity with Eqn. (9), where $k_{cat} = k_1 k_3/(k_2 + k_3 C_{R'OH})$ is the catalytic rate constant in the equation for the observed rate constant

$$k_{obs} = k_0 + k_{cat} C_{NR_3}, \qquad (10)$$

k_0 being the rate constant for the uncatalysed reaction. An equation similar to (9) can be obtained also on the hypothesis that equilibrium in the formation of the complex is established rapidly, whereas consumption of the complex is slow

$$-dC_{RNCO}/dt = \frac{K k_3 C_{R'OH} C_{RNCO} C_{NR_3}}{1 + K C_{R'OH}}. \qquad (9')$$

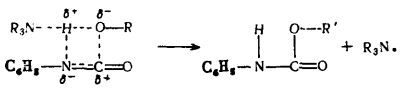
On the basis of scheme (D), however, the slope of the above linear plot should be independent of the nature of the alcohol in both cases, which is not in fact so [25,26]. The sole piece of work [63] in which a complex resembling the postulated intermediate product X′ was supposed to have been detected by infrared spectroscopy proved to be erroneous [47,62]. A fresh discussion has now appeared in the literature of a mechanism of catalysis by amines involving formation of an amine–alcohol complex [62], which then reacts slowly with the isocyanate (scheme E)



(E)

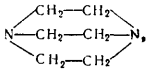
‡ For example, the value of σ^* for $^{+}N(CH_3)_3$ is +5.3, compared with +3.9 and +3.1 for NO_2 and F [37].

The latter reaction may involve formation of a four-membered activated complex[62], e.g.



The kinetic equation for mechanism (E) is identical with Eqn. (9). On the basis of formal kinetic data, therefore, no choice can be made between the two mechanisms. Mechanism (E) is supported by the fact that various amines can form hydrogen bonds with compounds containing OH and SH groups[51,62,64,65]. Formation of such complexes substantially polarises the OH and SH bonds, which is shown in an increase in the dipole moments, the polarisation increasing monotonically with the basic strength of the amine[51]. The formation of hydrogen bonds quite often increases the reactivity of compounds containing hydroxy-groups[66].

Until recently the absence of a direct correlation between the basic strength of an amine and its catalytic activity told against scheme (E). Although increasing basic strength of the amine is usually accompanied by enhancement of catalytic activity, several cases are known in which a feebly basic amine is highly active, and conversely. A linear relationship has been found[59] between the rate constant for the reaction of phenyl isocyanate with 2-ethylhexanol in benzene and the pK_a values of a series of amines. With pentamethylguanidine and 1,4-diazabicyclo[2,2,2]octane (triethylenediamine), however, the rates are respectively an order of magnitude smaller than, and five times as great as, would be expected from their basic strengths. The high catalytic activity of triethylenediamine is connected with its structure



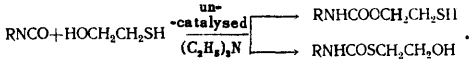
which makes both nitrogen atoms accessible to attack by the isocyanate.

On the other hand, diethylaniline, which has similar basic strength, possesses practically no activity, because the nitrogen atom is strongly screened by the ethyl groups. A similar discrepancy between the basic strength of an amine and its catalytic activity is observed in the catalysis of acylations with acid chlorides[57]. Special experiments have shown that an important part is played in these cases by steric hindrance to the approach of the amine catalyst to the acid chloride. It has been shown[59], however, that the activity of amines with respect to the polymerisation of phenyl isocyanate varies strictly in the sequence of their basic strengths (Table 11), which suggests that steric hindrance to the approach of an amine to the isocyanate is absent. If an amine–isocyanate complex is actually the active complex formed in the first stage of the catalytic reaction (scheme D), steric hindrance should arise only when the alcohol attacks the complex molecule.

According to Flynn and Nenortas[59] mechanism (E) is not consistent with the increase in the isotope effect, with increasing basic strength of the amine, observed in the reaction of phenyl isocyanate with 2-ethylhexanol. These workers consider that, if such a mechanism were operative, increase in basic strength of the amine should be accompanied by an increase in the "detachment" of hydrogen from the alcohol, which should diminish the role of the isotope effect, in contradiction to the results obtained§.

All comparisons between the activity of an amine catalyst and its basic character have been based on the value of pK_a in aqueous solution as a measure of basic strength, although the reaction is carried out in non-aqueous media. Transfer from one solvent to another may change not only the absolute basic strength but also the sequence of amines with respect to this property[68]. In fact, from a comparison of the rate of the catalysed reaction between phenyl isocyanate and 2-ethylhexanol in ethyl acetate, Farkas and Strohm[62] found a correlation between the rate constant k_{cat} and the parameter $E_{\frac{1}{2}}$¶, characterising the basic strength of an amine in this non-aqueous solvent (Table 12). Therefore these workers[62], in agreement with the results of other investigations[60,61], give their preference to scheme (E) in catalysis by amines. It is evident from Table 12 that there is no correlation between k_{cat} and pK_a.

It is interesting that, when an isocyanate reacts with 2-mercaptoethanol, the uncatalysed reaction yields only the *O*-urethane, the *S*-urethane being formed when an amine catalyst is introduced into the reaction medium:



The explanation given[60] for this fact is that the amine interacts preferentially with the more acidic SH group to form intermediate compounds of the type $R_3N\ldots H{-}SCH_2CH_2OH$, with subsequent ionisation of the mercaptoalkanol. Since

TABLE 11. Relative activity of a series of amines in the polymerisation of phenyl isocyanate and in the formation of a urethane in the reaction of phenyl isocyanate with 2-ethylhexanol and the isotope effect in the latter reaction compared with the basic strength of the amine[59].

Amine	pK_a	Catalytic activity in: polymerisation	Catalytic activity in: urethane formation	k^H_{cat}/k^D_{cat}
1,4-Diazabicyclo[2,2,2]octane	8.7	4	2	1.48
1,1,3,3-Tetramethyl-2-*N*-phenylcarbamoylguanidine	10.4	3	3	1.79
Pentamethylguanidine	15.6	2	4	1.96
Heptamethylisobiguanidine	17.1	1	1	2.5

TABLE 12. Comparison of catalytic activity, pK_a value, and basicity in ethyl acetate ($E_{\frac{1}{2}}$) for a series of amines in the reaction of phenyl isocyanate with 2-ethylhexanol[62].

Amine	$k_{cat,2}$, g mole^{-1} s^{-1}	Relative activity	pK_a	$E_{\frac{1}{2}}$
Triethylenediamine	5600	1	8.60	124
2-Methyl-1,4-diazabicyclo[2,2,2]octane	5130	0.92	8.86	168
Triethylamine	500	0.19	10.64	186
N-Ethylmorpholine	315	0.05	7.15	291

§ The arguments of Flynn and Nenortas are by no means self-evident. In the reaction of tritiated and light water with triphenylsilane catalysed by bases, for example, the increase in basic strength on passing from pyridine to aqueous–alcoholic alkali results in an increase in k^H_{cat}/k^D_{cat} by a factor of 2.3[67].

¶ According to Hall[69] the basic strength of an amine in a non-aqueous medium is measured by the position of the point of inflection on the curve for potentiometric titration with perchloric acid (72% $HClO_4$ in dioxan), expressed in millivolts — $E_{\frac{1}{2}}$.

$HOCH_2CH_2S^-$ is more basic than $HSCH_2CH_2OH$, reaction in the presence of a catalyst yields the *S*-urethane.

It must be noted that the concept of catalysis as a result of activation of an OH or SH bond by hydrogen bonding leaves it obscure why only amines and a few oxygen compounds which do not possess a high donor ability — tetrahydrofuran, dioxan, and ethers — should exhibit catalytic properties. In the relationship between the basicity constants of substances and their capacity for hydrogen bonding there is usually no qualitative difference between nitrogen and oxygen compounds[70], which simply arrange themselves one after the other in the sequence of their basic strengths. Nevertheless, transfer from hydrocarbon solvents to ethers, dioxan, and tetrahydrofuran[28] is accompanied by a sharp drop in reaction velocity, which is clearly caused by the formation of hydrogen bonds.

Organometallic compounds and metal salts have recently begun to be widely used as catalysts for the reactions of isocyanates. They include, for example, alkyl carboxylates and alkyl halides of Sn^{IV} (dibutyltin diacetate, dibutyltin dichloride, etc.); octanoates, stearates, and naphthenates of Cr^{III}, Ni^{II}, Zn^{II}, Bi^{III}, Fe^{III}, Sn^{II}, etc.; and acetylacetonates of Fe^{III}, Pb^{II}, Cu^{II}, Mn^{III}, Co^{II}, etc. A quite full analysis of published data will be found in papers by Farkas and Mills[4] and by Robins[71]. Table 13 gives for comparison the relative catalytic activities of two typical catalysts of different classes.

Organometallic compounds are more active by factors of 10^2–10^4 than amine catalysts of average activity. Although a large number of organometallic catalysts have been described[72–74], there is as yet no generally accepted view of the nature of their catalytic action. Again, the possibility has been discussed that a complex may be formed with the isocyanate[75], with the alcohol[76], and with both components[71,72,77]. Results have been published on the changes undergone by the spectral characteristics of isocyanates and alcohols when metal-containing catalysts are added to the system. For example, cobalt stearate[77] and cobalt octanoate[75] form with phenyl isocyanate complexes which are apparent in the infrared and ultraviolet spectra. Moreover, the catalytic activity of cobalt octanoate increases when it is kept mixed with phenyl isocyanate in toluene for 20 min or longer[75], which suggests the slow formation of an active product.

Recent results indicate[78] that tin compounds containing the Sn–O bond, e.g. R_3SnOR', readily add on to isocyanates and isothiocyanates to form carbamates containing tin:

$$(C_4H_9)_3SnOCH_3 + C_6H_5{-}N{=}C{=}O \rightarrow (C_4H_9)_3Sn{-}N(C_6H_5){-}COOCH_3.$$

Bloodworth and Davies suggest a mechanism of catalysis by organotin compounds of the reaction between isocyanates and alcohols, based on the fact that the above compounds readily react with alcohols to form urethanes. In the first stage any tin(IV) compound gives with an alcohol R'OH or phenol present in the system a tin alkoxide R_3SnOR'. This is followed by the reactions

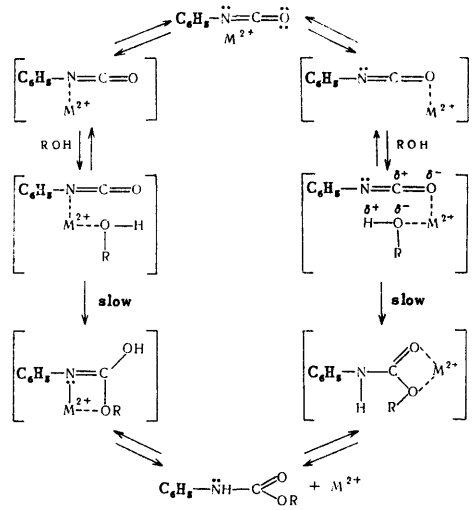
$$R_3SnOR' + C_6H_5{-}N{=}C{=}O \rightarrow R_3SnN(C_6H_5)COOR',$$
$$R_3SnN(C_6H_5)COOR' + R'OH \rightarrow R_3SnOR' + C_6H_5NHCOOR'.$$

However, the absence of quantitative data, on the basis of which the rates of known catalytic reactions could have been compared with those of the reactions suggested by these workers[78], makes it impossible either to accept or to reject this mechanism.

Observations have been made also on the activating effect of a metal-containing catalyst on the alcoholic component of the reaction mixture. For example, Blagonravova et al.[76] found that preliminary treatment of 2-hydroxyethyl adipate with zinc oxide or an acetate of this or several other metals activates the diol by forming an alkoxide. The sequence of activities is as shown in Table 14.

Complex formation between an organometallic catalyst and an alcohol is indicated also by an examination of the proton magnetic resonance spectra. According to Frisch et al.[47] 0.05–0.855 M dibutyltin dilaurate produces a substantial chemical shift (δ from 2.56 to 3.99 p.p.m.) of the hydroxyl proton in 1-methoxypropan-2-ol dissolved (0.54 M) in carbon tetrachloride, the value of δ being proportional to the concentration of tin(IV). Zabrodin and ourselves[79] have obtained similar results from an investigation of the proton resonance spectra of solutions of methanol in carbon tetrachloride in the presence of di-n-butyltin diacetate and dilaurate.

Several authors have concluded[71,72,77] that the active species is a ternary equilibrium complex containing the catalyst, the isocyanate, and the alcohol. Robins[71] puts forward two schemes for the formation of an active ternary complex of this type, of which scheme (F) applies to simple alcohols:



(F)

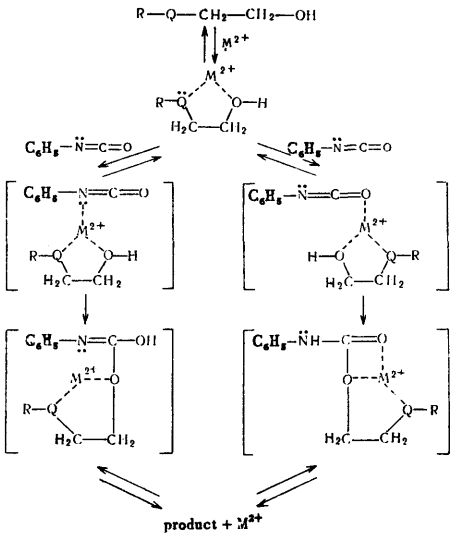
TABLE 13. Comparison of activities of triethylamine and di-n-butyltin diacetate as catalysts in the reaction of phenyl isocyanate with methanol in dioxan as solvent (Ref. 4, p. 421).

Catalyst	Concn., mole %	$10^4 k$, litre mole^{-1} s^{-1}
No catalyst	—	0.51
Triethylamine	1	6.7
Di-n-butyltin diacetate	0.009	118.0

TABLE 14. Comparison of catalytic activities of acetates of various metals[76].

Acetate	Activity	Acetate	Activity
K	3.45	Cu	0.90
Na	2.49	Ca	0.64
Co	1.20	Mg	0.53
Zn	1.00		

When the alcohol contains an "active" donor group Q in the α-, β-, or γ-position with respect to the hydroxy-group, the scheme of the reaction appears as follows:



(G)

In effect, neither mechanism is based on any strict evidence, but merely on general considerations relating to the structure of the reactants and on qualitative data on the activities of a series of catalysts, containing metal atoms or ions, towards isocyanates and alcohols of various structures.

In conformity with the above schemes, Robins formulates the following requirements to be satisfied by an organometallic catalyst: (*a*) it must possess some minimum capacity for complex formation in order that an adequate concentration of the ternary complex shall be maintained; (*b*) it should not suppress the nucleophilic character of the alcoholic oxygen, at any rate not sufficiently to make the reaction improbable; and (*c*) it should not yield with the reaction products a stable complex, which would make departure of the metal ion from the reaction zone improbable.

To obtain quantitative data on the alcohol–isocyanate reaction catalysed by tin(IV) compounds, we have recently made a detailed kinetic study of the reaction between methanol and *p*-chlorophenyl isocyanate in heptane in the presence of a series of tin compounds (di-n-butyltin diacetate, dilaurate, and dichloride)[79-82]. The rate of the catalytic reaction was shown (Fig. 2) to be proportional to the concentration of the alcohol–catalyst complex, which was determined independently by a spectroscopic method. Experiments on the thermodynamics of complex formation showed it to be an equimolecular complex. The equilibrium constant, heat of reaction, and entropy of complex formation were determined.

The equation for the reaction, deduced on the assumption that the equilibrium

$$Sn^{IV} + ROH \overset{K}{\rightleftharpoons} ROH \cdot Sn^{IV} \qquad (11)$$

was established, with a slow bimolecular interaction between the complex and the isocyanate

$$ROH \cdot Sn^{IV} + R'NCO \xrightarrow{k} R'NHCOOR + Sn^{IV}, \qquad (12)$$

satisfactorily reproduces the kinetic data obtained over wide ranges of temperature and concentration:

$$w_{cat} = k_{cat} C_{R'NCO} C_{Sn^{IV}}, \qquad (13)$$

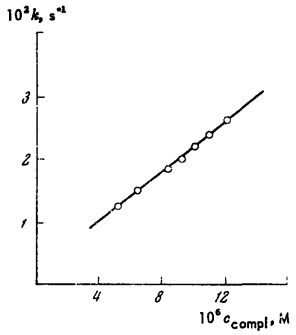


Fig. 2. Dependence of rate constant for the reaction of *p*-chlorophenyl isocyanate with methanol in heptane in the presence of di-n-butyltin dilaurate at 25° on the concentration of the alcohol–catalyst complex.

where w_{cat} is the rate of the catalytic reaction, and

$$k_{cat} = C_{ROH} kK/(1 + KC_{ROH}). \qquad (14)$$

It is seen from Eqn. (14) that both k and K can be evaluated from a plot of $1/k_{cat}$ against $1/C_{ROH}$. The complex formation constants K found from the kinetic data agree, within the limits of experimental error, with those measured directly. Values of k and K are listed in Table 15.

From the temperature dependence of k and K, values were obtained of $E = 6.7 \pm 0.5$ kcal mole^{-1} and $\Delta S^{\neq} = -23.7$ cal mole^{-1} deg^{-1}, and also the heat and the entropy of complex formation $\Delta H_{compl} = -1.3 \pm 0.5$ kcal mole^{-1} and $\Delta S_{compl} = -3.2 \pm 1.0$ cal mole^{-1} deg^{-1}. Within the limits of experimental error, the latter two values are close to the corresponding values, -0.9 ± 0.5 kcal mole^{-1} and -1.2 ± 1.0 cal mole^{-1} deg^{-1}, found directly from spectrophotometric data on complex formation between dibutyltin dilaurate and methanol.

The results obtained show that introduction of a catalyst increases the rate constant for the step involving interaction between isocyanate and alcohol, by a factor of about 10^6 in comparison with the uncatalysed reaction. Comparison of the kinetic parameters for the uncatalysed and the catalysed reactions of *p*-chlorophenyl isocyanate with methanol shows that decrease in the activation energy from $E_{uncat} = 8.2$ kcal mole^{-1} to $E_{cat} = 6.7$ kcal mole^{-1} results in an increase in rate by a factor of about 10, the main acceleration of the process (by a factor of 10^5) being a result of a sharp decrease in the negative entropy of activation from $\Delta S^{\neq}_{uncat} = -44.5$ cal mole^{-1} deg^{-1} to $\Delta S^{\neq} = -23.7$ cal $\times$ $\times$ mole^{-1} deg^{-1}: i.e. the structural requirements when the reactants approach one another in the reaction step become less rigorous. Since in our experiments the reaction medium was n-heptane, solvation phenomena played little part in the variation in $\Delta S^{\neq}$, everything being determined by the structure of the activated complex. In the uncatalysed reaction, in which a four-membered activated complex is formed in a single step, rigid limitations are imposed on the mutual disposal of isocyanate and alcohol molecules, which is reflected in the large negative entropy of activation.

Table 15 shows that the constant K, determined from kinetic data, did not change on passing from *p*-chlorophenyl to phenyl and *m*-chlorophenyl isocyanates. This provides further confirmation that only the alcohol is involved in the complex formation which is active in catalysis.

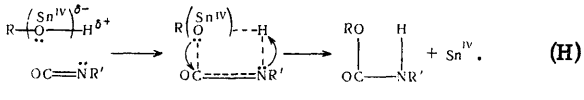
TABLE 15. Temperature dependence of k and K for various phenyl isocyanates.

T, °K	$10^3 k$, litre mole^{-1} × ×s^{-1} *p*-chlorophenyl	K, litre mole^{-1} *p*-chlorophenyl	K, litre mole^{-1} phenyl	K, litre mole^{-1} *m*-chlorophenyl
25	1.26	5.9	5.9	5 6
35	1.76	5.5	—	—
45	2.56	5.1	—	—

Since a specific feature of quadrivalent tin compounds is their ability to form donor–acceptor complexes, it may be supposed that the active intermediate product in the catalytic reaction between isocyanate and alcohol is formed by vacant 5*d*-orbitals of the tin and the lone pair of electrons on the basic oxygen of the alcohol. Apparently the main result of interaction between alcohol and organotin catalyst which accelerates the reaction is a change in properties of the hydroxy-group: firstly, the dipole moment of the bond is increased by the redistribution of electron density accompanying complex formation, and such redistribution can be a consequence not only of the formation of an O–Sn bond but also of the presence of conjugation between vacant 5*d*-shells of the tin and a free pair of 2*s*-electrons of the alcoholic oxygen not involved in formation of the O–Sn bond; secondly, the OH bond is lengthened by the diminution in the density of the cloud of valency electrons.

It is still too early to specify the mechanism of the reaction between the alcohol–catalyst complex and the isocyanate, but two probable routes can be imagined for the interaction.

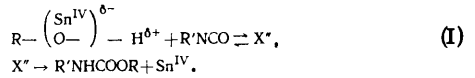
1. Reaction takes place in a single step with simultaneous transfer of a lone pair of electrons from the isocyanate nitrogen atom to the alcoholic proton and from the alcoholic oxygen to the isocyanate carbon[18-20]:



(H)

With this reaction mechanism, lengthening the OH bond and bringing it close to the C=N bond length in the isocyanate group (1.18 Å) should substantially facilitate formation of the four-membered activated complex and lower the absolute value of the negative entropy of activation.

2. Reaction takes place in stages. In the first stage the isocyanate is attacked by the alcoholic proton in the complex with formation of an intermediate product X″, which is ionic or polar in nature. The bond thus formed results in substantial activation of the carbonyl carbon in the product X″ by the appearance on it of a deficiency of electron density, and hence a fractional positive charge. The alcoholic oxygen is still firmly bound to the tin of the catalyst. In the second stage, as a result of detachment of the alcoholic oxygen from the tin and its transfer to the carbon of the isocyanate, which has already added on a proton, the intermediate product X″ is converted into a urethane with liberation of the catalyst molecule:



(I)

With such a two-stage mechanism, involving the intermediate formation of linear activated complexes, the entropy of activation should be considerably less negative than in the case of the uncatalysed reaction.

It is as yet difficult to tell which of these schemes operates during the reaction. However, examination of either of them leads to the extremely interesting conclusion that the reaction rate constant depends on the equilibrium constant of the intermediate complex. In the above cases the reactivity of the alcoholic hydrogen should increase with the stability of the complex. On the other hand, increase in its stability will diminish the nucleophilic character of the oxygen, and thereby diminish its reactivity towards the isocyanate carbon. If these views on the reaction mechanism are correct, both a considerable increase in stability of the complex and a considerable decrease should lower the rate constant of the catalytic reaction. The most active catalysts should be those which form complexes of optimum stability, characterised by definite values of the equilibrium constant.

The presence of a maximum in the activities of the series of catalysts investigated (Fig. 3) provides still further support for our hypothesis on the nature of the catalytic effect of organotin compounds in reactions between isocyanates and alcohols.

Complex formation between an organotin compound and an alcohol results in increased mobility of the hydroxyl hydrogen and an enhancement of its electrophilic activity towards the NCO group.

In the case of a catalytic reaction of this type, a change in the mechanism of addition is apparently to be expected, from nucleophilic to electrophilic. Such a change should be accompanied by a decrease in the absolute magnitude of the parameter $\rho > 0$ in the Hammett equation on passing from the non-catalytic to the catalytic reaction. Fig. 4 shows the dependence of $\log(k/k_0)$ on σ for a series of substituted phenyl isocyanates. It is seen that actually the value of $\rho = 0.9$ for the reaction catalysed by di-n-butyltin dilaurate, which is significantly less than the value of 3.3 for the uncatalysed reaction. The sign of ρ may be expected to change on passing to stronger acceptors.

An important but very little studied problem in the reactions of isocyanates is that of acid–base catalysis. Almost

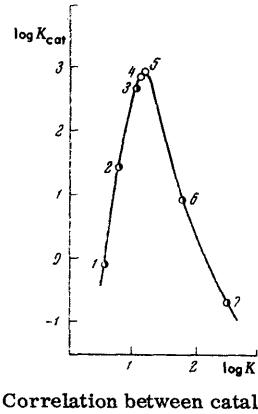


Fig. 3. Correlation between catalytic activity of catalysts and stability of their complexes formed with methanol:
1) $(C_2H_5)_4Sn$; 2) $(C_2H_5)_3SnCl$; 3) $(C_2H_5)_2SnCl_2$; 4) $(CH_3COO)_2Sn(C_4H_9)_2$; 5) $C_{11}H_{23}COO)_2Sn(C_4H_9)_2$; 6) $C_2H_5SnCl_3$; 7) $SnCl_4$.

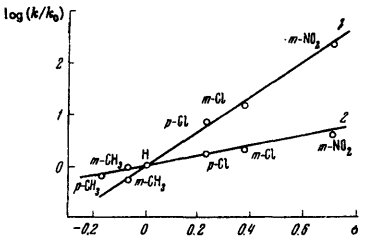


Fig. 4. Dependence of $\log (k/k_0)$ on Hammett σ-parameter for reactions of derivatives of phenyl isocyanate with methanol in heptane at 25°:
1) uncatalysed reaction; 2) in the presence of di-n-butyltin dilaurate.

all known papers on the influence of acids and bases on the reactions of isocyanates are cited in the review by Farkas and Mills[4]. The lack of quantitative data makes it difficult to give soundly based judgments on the mechanism. The most complete qualitative picture of the effect of acids and bases on the reactions of isocyanates has been described by Heiss et al.[53] These workers showed that the reaction is accelerated by the addition of basic reagents, including sodium and potassium hydroxides, sodium phenoxides, trisodium phosphate, benzyltrimethylammonium hydroxide, etc. The retarding action of small additions of acids to previously "purified" polyetherdiols is apparently merely the result of neutralisation of remaining traces of bases. The correctness of this view was demonstrated by the fact that, with reagents which had been completely freed from alkali, e.g. ethylene glycol and cyclohexanol, addition of acid produced no observable retarding effect. With higher concentrations ($> \mu$-equiv. g^{-1} oligomer) a slight accelerating effect is observed.

The boron trifluoride–ether complex also slightly accelerates the reaction of butanol with phenyl isocyanate. Sharp intensification of the catalytic action of boron trifluoride[48] and of zinc chloride[49] occurs on passing to nitro-alcohols, and this can be understood on the basis of the mechanism (H)–(I) suggested above: the strong acceptor boron trifluoride yields with butanol such a stable complex that it is difficult to transfer the combined oxygen to the isocyanate by reaction (12). The substantial decrease in basic strength on passing to nitro-alcohols produces an alcohol–catalyst complex of diminished stability and "moves" the reaction system into a region of higher catalytic activity (cf. Fig. 3). The same applies also to zinc chloride.

The catalytic action of alkalis on the reaction of an alcohol with an isocyanate can again consist either in activation of the OH bond of the alcohol by inducing a hydrogen bond

$$ROH + OH^- \rightleftarrows \overset{\delta-}{RO}\text{–}H \ldots \overset{\delta-}{OH},$$

or even in formation of an alkoxide ion

$$ROH + OH^- \rightleftarrows RO^- + H_2O.$$

Activation of the isocyanate group is also possible, with formation of an intermediate ion Y^- analogous to the ion suggested by Zahradník[24] for isothiocyanates:

$$RNCO + OH^- \rightleftarrows R\bar{N}\text{–}C(=O)\text{–}OH \leftrightarrow RN{=}C(O^-)\text{–}OH \quad (Y^-),$$

followed by an addition–substitution reaction occurring either in one stage

$$Y^- + ROH \rightarrow R\text{–}\bar{N}\text{–}C(=O)\text{–}OR \rightarrow R\text{–}N(H)\text{–}C(OR)=O + OH^-.$$

or in two stages with formation of an intermediate ion Z^-

$$Y^- + ROH \rightarrow RNH\text{–}C(OR)(O^-)\text{–}OH \rightarrow RNH\text{–}C(OR)=O + OH^-.$$

The study of catalysis by strong acids is complicated by the occurrence of secondary addition reactions. Sulphuric acid, for example, forms derivatives of sulphamic acids with isocyanates[83], carbon dioxide being evolved. It can definitely be stated, however, that an alcohol is so much more basic than an isocyanate that, at low acid concentrations, only the protonated form of the alcohol ROH_2^+ will be present even in non-aqueous solvents. Protonation of RNCO will be practically completely absent. It may therefore be supposed that, under the conditions described in the literature[4,53], alkyloxonium ions will constitute the active form.

In the range of acidities in which RNCO begins to be protonated, practically the whole of the alcohol will be in the ionic form. It is still possible, however, that the formation of small amounts of extremely active intermediate protonated forms of the isocyanate U^+ will result in acceleration of the reaction:

$$H^+ + R\text{–}NCO \rightleftarrows \begin{cases} RNH\text{–}\overset{+}{C}{=}O \\ RN{=}\overset{+}{C}\text{–}OH \end{cases} \quad (U^+),$$

$$U^+ + R'OH \longrightarrow RNHCOOR' + H^+.$$

Since only unprotonated alcohol molecules should take part in the latter reaction, and their concentration will fall with increase in acidity, an extremal dependence of the reaction velocity on the acidity of the medium should be observed, and should be found at higher acid concentrations the less basic the alcohol. In the case of acid-catalysed reactions, protonation of the isocyanate will be favoured by a substituent of nucleophilic character adjacent to the NCO group and in the ring of the phenyl isocyanate.

1. J. H. Saunders and K. C. Frisch, "Polyurethanes – Chemistry and Technology", Part 1, "Chemistry", Interscience, New York, 1962.
2. N. I. Mel'nikov, Yu. A. Baskakov, and K. S. Bokarev, "Khimiya Gerbitsidov i Stimulyatorov Rosta Rastenii" (The Chemistry of Herbicides and Plant Growth Stimulators), Goskhimizdat, Moscow, 1954.
3. M. Zlírovský, J. Myska, and J. Zemánek, "Herbicidy", Prague, 1960.
4. A. Farkas and G. A. Mills, Adv. Catalysis, 13, 393 (1962).
5. E. H. Eyster, R. H. Gillette, and L. O. Brockway, J. Amer. Chem. Soc., 62, 3236 (1940).
6. R. F. Curl, Jnr., V. M. Rao, K. V. L. N. Sastry, and J. A. Hodgeson, J. Chem. Phys., 39, 3335 (1963).
7. J. W. Linnet, Nature, 199, 168 (1963).
8. L. H. Jones, J. N. Shoolery, R. G. Shulman, and D. M. Yost, J. Chem. Phys., 18, 9902 (1950).
9. L. Pauling, "The Nature of the Chemical Bond and the

Structure of Molecules and Crystals" (Translated into Russian), Goskhimizdat, Moscow, 1947, p.142.
10. Yu.A.Strepikheev, Yu.I.Baranov, and O.A.Burmistrova, Izv.Vys.Ucheb.Zaved., Khim.i Khim.Tekhnol., 5, 387 (1962).
11. T.L.Cottrell, "The Strengths of Chemical Bonds", Butterworths, London, 1958, p.270.
12. J.N.Shoolery and A.H.Sharbaugh, Phys.Rev., 82, 95 (1951).
13. O.A.Osipov and V.I.Mishkin, "Spravochnik po Dipol'nym Momentam" (Handbook of Dipole Moments), Izd.Vysshaya Shkola, Moscow, 1965.
14. C.I.Beard and B.P.Dailey, J.Chem.Phys., 18, 1437 (1950).
15. Ya.K.Syrkin and M.E.Dyatkina, "Khimicheskaya Svyaz' i Stroenie Molekul" (The Chemical Bond and Molecular Structure), Goskhimizdat, Moscow–Leningrad, 1946, p.250.
16. E.G.Lovering and K.J.Laidler, Canad.J.Chem., 40, 26, 31 (1962).
17. See Ref. 1, p.208
18. R.E.Dessy, G.F.Reynolds, and Jin-Young Kim, J.Amer. Chem.Soc., 81, 2683 (1959).
19. L.H.Toporcer, R.E.Dessy, and S.I.E.Green, J.Amer. Chem.Soc., 87, 1236 (1965).
20. L.M.Stock and A.R.Spector, J.Org.Chem., 28, 3272 (1963).
21. O.V.Nesterov and S.G.Entelis, Kinetika i Kataliz, 6, 178 (1965),
22. M.L.Bender, "Mechanisms of the Catalysis of Nucleophilic Reactions of Carboxylic Acid Derivatives" [Translated into Russian from (?) Chem.Rev., 60, 53 (1960)], Izd.Mir, Moscow, 1964, p.30.
23. J.F.Bunnett, Collected Papers, "Theoretical Organic Chemistry" (Translated into Russian), Inostr.Lit., Moscow, 1963, p.181.
24. R.Zahradník, Coll.Czech.Chem.Comm., 24, 3678 (1959).
25. J.W.Baker and J.B.Holdsworth, J.Chem.Soc., 713 (1947).
26. J.W.Baker and J.Gaunt, J.Chem.Soc., 9, 19, 27 (1949).
27. M.Sato, J.Amer.Chem.Soc., 82, 3893 (1960).
28. G.P.Robertson and J.E.Stutchbury, J.Chem.Soc., 4000 (1964).
29. R.P.Tiger and S.G.Entelis, Kinetika i Kataliz, 6, 544 (1965).
30. R.P.Tiger, Candidate's Thesis, Institute of Chemical Physics, USSR Academy of Sciences, Moscow, 1966.
31. S.J.N.Greenshields, R.H.Peters, and R.F.T.Stepo, J.Chem.Soc., 5101 (1964).
32. S.Ephraim, A.E.Woodward, and R.B.Mesrobian, J.Amer. Chem.Soc., 80, 1326 (1958).
33. L.L.Ferstandig and R.A.Scherrer, J.Amer.Chem.Soc., 81, 4838 (1959).
34. J.Burkus and C.F.Eckert, J.Amer.Chem.Soc., 80, 5948 (1958).
35. W.Cooper, R.W.Pearson, and S.Darke, Ind.Chemist, 36, 121 (1960).
36. K.J.Rauterkus and W.Kern, Chimia (Switz.), 16, 114 (1962).
37. V.A.Pal'm, Uspekhi Khim., 30, 1069 (1961) [Russ.Chem. Rev., 471 (1961)].
38. M.Kaplan, J.Chem.and Eng.Data, 6, 272 (1961).
39. F.H.Brock, J.Org.Chem., 24, 1802 (1959); J.Phys.Chem., 65, 1638 (1961).
40. C.N.R.Rao and R.Venkataraghavan, Tetrahedron, 18, 531 (1962).
41. L.C.Case, J.Polymer Sci., 29, 455 (1958); "Trudy Mezhdunarodnogo Sympoziuma po Makromolekulyarnoi Khimii" (Proceedings of an International Symposium on Macromolecular Chemistry), Moscow, 1960, Vol. 2, p.513.
42. See Ref. 1, pp.154–156.
43. A.A.Frost and W.C.Schwemer, J.Amer.Chem.Soc., 74, 1268 (1952).
44. E.Dyer, H.A.Taylor, S.J.Mason, and J.Samson, J.Amer. Chem.Soc., 71, 4106 (1949).
45. H.G.Wissman, L.Rand, and K.C.Frisch, J.Appl.Polymer Sci., 8, 2971 (1964).
46. L.Rand, B.Thir, S.L.Reegen, and K.C.Frisch, J.Appl. Polymer Sci., 9, 1787 (1965).
47. K.C.Frisch, S.L.Reegen, and B.Thir, International Symposium on Macromolecular Chemistry, Prague, 1965, preprint 263.
48. J.R.Fischer, Tetrahedron, 19, Suppl.1, 97 (1963).
49. N.Solodova, Candidate's Thesis, Kirov Kazan Institute of Chemical Technology, 1965.
50. Y.Iwakura and H.Okada, Makromol.Chem., 66, 91 (1963).
51. A.I.Shatenshtein, "Izotopnyi Obmen i Zameshchenie Vodoroda v Organicheskikh Soedineniyakh" (Isotopic Exchange and Substitution of Hydrogen in Organic Compounds), Izd.Akad. Nauk SSSR, Moscow, 1960, pp.52, 268.
52. H.A.Hampton, Färg och Lack, 11, 5 (1965).
53. H.L.Heiss, F.P.Combs, P.G.Gemeinhardt, J.H.Saunders, and E.E.Hardy, Ind.Eng.Chem., 51, 929 (1959).
54. See Ref. 22, p.119.
55. See Ref. 22, pp.65, 48.
56. See Ref. 22, p.81.
57. L.M.Litvinenko and A.I.Kirichenko, Ukrain.Khim.Zhur., 31, 67 (1965).
58. J.Burkus, J.Amer.Chem.Soc., 26, 779 (1961).
59. K.G.Flynn and D.R.Nenortas, J.Org.Chem., 28, 3527 (1963).
60. J.F.Smith and E.C.Friedrich, J.Amer.Chem.Soc., 81, 161 (1959).
61. Y.Iwakura and H.Okada, Canad.J.Chem., 38, 2418 (1960).
62. A.Farkas and P.F.Strohm, Ind.and Eng.Chem.(Fundamentals), 4, 32 (1965).
63. M.Pestemer and D.Lauerer, Angew.Chem., 72, 612 (1960).
64. S.Nagakura and M.Goeterman, J.Chem.Phys., 26, 881 (1957).
65. M.D.Joesten and R.S.Drago, J.Amer.Chem.Soc., 84, 3817 (1962).
66. D.G.Knorre and N.M.Emanuel', Collected Papers, "Voprosy Kataliza, Khimicheskoi Kinetiki i Reaktsionnoi Sposobnosti" (Problems of Catalysis, Chemical Kinetics, and Reactivity), Izd.Akad.Nauk SSSR, Moscow, 1955, p.106; Uspekhi Khim., 24, 275 (1955).
67. L.Kaplan and K.E.Wilzbach, J.Amer.Chem.Soc., 74, 6152 (1952); 77, 1297 (1955).
68. N.A.Izmailov, "Elektrokhimiya Rastvorov" (The Electrochemistry of Solutions), Izd.Khar'kovsk.Gos.Univ., Kharkov, 1959.
69. H.K.Hall, J.Phys.Chem., 60, 63 (1956).
70. See Ref. 51, pp.279, 283.
71. J.Robins, J.Appl.Polymer Sci., 9, 821 (1965).
72. J.W.Britain and P.G.Gemeinhardt, J.Appl.Polymer Sci., 4, 207 (1960).
73. F.Hostettler and E.F.Cox, Ind.Eng.Chem., 52, 609 (1960).
74. L.B.Weisfeld, J.Appl.Polymer Sci., 5, 424 (1961).
75. I.A.Pronina, Yu.L.Spirin, A.A.Blagonravova, S.M.Aref'eva, A.R.Gantmakher, and S.S.Medvedev, Dokl. Akad.Nauk SSSR, 161, 362 (1965).
76. A.A.Blagonravova, G.A.Levkovich, and I.A.Pronina, "Trudy Mezhdunarodnogo Sympoziuma po Makromolekulyarnoi Khimii" (Proceedings of an International Symposium of Macromolecular Chemistry), Moscow, 1960, Vol. 1, p.255.
77. H.A.Smith, J.Appl.Polymer Sci., 7, 85 (1963).
78. A.J.Bloodworth and A.G.Davies, J.Chem.Soc., 5238 (1965).
79. S.G.Entelis, O.V.Nesterov, and V.B.Zabrodin, Kinetika i Kataliz, 7, 627 (1966).
80. S.G.Entelis and O.V.Nesterov, Kinetika i Kataliz, 7, 464 (1966).
81. O.V.Nesterov, V.B.Zabrodin, Yu.N.Chirkov, and S.G.Entelis, Kinetika i Kataliz, 7, 805 (1966).

82. O.V.Nesterov, Candidate's Thesis, Institute of Chemical Physics, USSR Academy of Sciences, Moscow, 1966.
83. D.I.Bieber, J.Amer.Chem.Soc., 75, 1405 (1953).

Institute of Chemical Physics,
USSR Academy of Sciences,
Moscow

U.D.C. 546.16:547.022

FLUORIDES OF HIGH OXIDISING POWER AND THEIR APPLICATION TO THE PREPARATION OF ORGANIC FLUORINE COMPOUNDS

N.I.Gubkina, S.V.Sokolov, and E.I.Krylov

CONTENTS

I. Introduction 930
II. Higher fluorides of transition metals 931
1. Higher fluorides of lanthanides 931
2. Higher fluorides of uranium, neptunium, and plutonium 931
3. Higher fluorides of the vanadium subgroup 932
4. Fluorides of chromium, molybdenum, and tungsten 932
5. Fluorides of manganese and rhenium 932
6. Simple and complex fluorides of the iron subgroup 933
7. Higher fluorides of the platinium metals 934
8. Higher fluorides of copper, silver, gold, and mercury 935
III. Higher fluorides of elements in the main subgroups of the Periodic System 936
1. Higher fluorides of thallium, lead, antimony, and bismuth 936
2. Fluorides of the oxygen subgroup 936
3. Simple and complex halogen fluorides 937
4. Fluorine compounds of the inert gases 938

I. INTRODUCTION

The extraordinarily high reactivity of elementary fluorine, together with the chemical properties of organic fluorine compounds, make methods for synthesising the latter fundamentally different from those for obtaining other halogen derivatives. All methods of preparing organic fluorine compounds can be divided into four broad groups.

The first group comprises reactions of organic compounds with elementary fluorine or with fluorides of high oxidising power. These reactions are essentially oxidations, taking place by a radical mechanism, and involving either replacement of hydrogen (or halogen) by fluorine or addition of fluorine to a multiple bond.

The second group is formed by reactions involving the exchange of other halogens for fluorine by means of hydrogen fluoride or a metal fluoride possessing no oxidising power (potassium fluoride, antimony trifluoride).

In the third group of reactions functional groupings containing oxygen, sulphur, or nitrogen are exchanged for fluorine by interaction with sulphur tetrafluoride, by the Schiemann reaction, and by other methods.

The fourth group can be regarded as including the numerous reactions in which groupings containing fluorine are introduced into organic compounds containing no fluorine, by the scheme

$$R_H - X + R_F Z \rightarrow R_H - R_F + XZ,$$
$$R_{H(\text{or } F)} - CH = CH_2 + R_F - X \rightarrow R_H - \underset{X}{CH} - CH_2 - R_F.$$

The present review will cover only reagents which effect reactions of the first group, i.e. fluorides which oxidise organic compounds to organofluorine compounds. Attention will be paid primarily, not to summarising the extensive literature on the most important fluorinating agents (AgF_2, CoF_3), but to elucidating the theoretical possibility of using fluorides for this purpose as a function of the chemical properties of the element concerned and its position in the Periodic System. Higher fluorides of the transition metals and of certain elements in the main subgroups of the Periodic System are of great practical importance (in the atomic industry, as oxidants in rocket technology). Information on the fluorides of interest to us will be reported in the sequence in which the elements are arranged among groups of the Periodic System (the elements capable of forming fluorides having high oxidising power are V, Cr, Mn, Tc, Re, Ru, Os, Ni, Pd, Pt, Cu, Ag, Au, Hg, Tl, Pb, Sb, Bi, O, Po, Cl, Br, I, At, Kr, Xe, Rn, Ce, Pr, Nd, Tb, Dy, U, and Pu).

The oxidising power of these fluorides is extremely varied, and cannot yet be estimated quantitatively in any way. Considerable interest should attach, in connection with the assessment of the oxidising power of ElF_x, to the energy of formation of the El–F bonds, but unfortunately knowledge of these bond energies and of their orders is very far from what could be desired. Yet even in such a simple molecule as F_2 the order of the F–F bond is less than unity, which entails an abnormally low bond energy. The reason for such anomaly in this case has been analysed in detail by the molecular orbital method[1]. Some elements are not at all readily available, and therefore have been insufficiently investigated; while others, although readily available, have higher fluorides which cannot be purified, so that their study is difficult. The highly corrosive nature of some fluorides, which attack even polytetrafluoroethylene and platinum, make it impossible to study them by the usual methods. In this paper the assignment of some fluorides to the category of oxidising agents is made on the basis of their chemical properties, often studied quite superficially, and in some cases only on the basis of general considerations regarding their reactivity. Nevertheless, we feel that future quantitative results will hardly seriously contradict our purely qualitative considerations.

Fluorides of high oxidising power show increased stability and lower oxidising power on complex formation, which makes it possible to obtain fluorides in which the metals exhibit an abnormally high valency (Ni^{4+}, Cu^{4+}).