[CONTRIBUTION FROM THE CHEMISTRY SECTION, JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY]

The Inductive Effect in Ethylene Oxide Ring Openings[1]

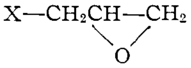
BY PETER L. NICHOLS, JR., AND JOHN D. INGHAM

RECEIVED JANUARY 24, 1955

The rate of addition of thiocyanate ion to the epihalohydrin, glycidol and propylene oxide in neutral solution has been measured at several temperatures. Additional data on uncatalyzed hydration of these oxides was also obtained. Analysis of these data and other data available in the literature was made in terms of the inductive effect. Quantitative charge-distribution calculations were conducted by the method of Smith and Eyring. Attempts to correlate the experimental data in terms of absolute rate theory are discussed. Use of the Scott-Swain free energy relationship for nucleophilic displacement reactions is also considered. As a result of the comparisons made it was decided that qualitative trends in the observed rates can clearly be attributed to the inductive effect. The use of charge-distribution calculations was moderately successful in quantitatively estimating relative rates in the series $X{-}CH_2\underbrace{CH{-}CH_2}_{O}$ where X = H, Cl, Br, I and OH. Linear correlation of the free energy of activation in terms of the charge on the carbon atom involved in the nucleophilic displacement reaction and simple electrostatic calculations of the change of heat of activation with charge were also reasonably satisfactory.

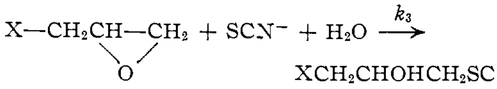
Introduction

For the purpose of explaining relative reactivities in ethylene oxide ring openings and the point of entry of an incoming nucleophilic species, the inductive effect has frequently been used to draw qualitative conclusions.[2] In a recent series of papers on the inductive effect and chemical reactivity, Eyring and collaborators[3-6] describe a proposed semiempirical method for the calculation of charge distributions, using primarily bond polarizabilities and electric dipole moments. Since no rate data were available in the literature which could be used to assess adequately the value of such calculations in correlating the relative rates of addition of nucleophilic reagents to the ethylene oxide ring, rate measurements were made on a series of oxides of the type



$$X{-}CH_2\underbrace{CH{-}CH_2}_{O}$$

where X = H, Cl, Br and I, and on several miscellaneous oxides available at the time of the investigation. The reaction studied was the addition of thiocyanate ion to the oxide ring in neutral aqueous solution at several temperatures, as



$$X{-}CH_2\underbrace{CH{-}CH_2}_{O} + SCN^- + H_2O \xrightarrow{k_3} XCH_2CHOHCH_2SCN + OH^-$$

Charge-distribution calculations were then made for each of the oxides. Using the basic equations of the absolute rate theory, attempts were made to determine the relative importance of the inductive effect on the rate of these reactions.

In addition to the study of charge distribution and its effect on rate, general considerations of the influence of correlating rates in both acid-catalyzed reactions and reactions in neutral solution are included. The linear free energy correlation of Swain[7] is discussed in reference to these considerations. Together with other experimental data available in the literature,[2,8,9] a small amount of rate data pertaining to hydration of oxides in neutral solution was obtained to explain certain points in the discussion.

Experimental

Materials.—Reagent-grade sodium thiocyanate was used in all k_3 measurements where k_3 refers to the rate of uncatalyzed addition reaction. Ethylene oxide, propylene oxide, epibromohydrin and 1,2-epoxy-3-isopropoxypropane were obtained from Eastman Kodak Company, and 1,2-epoxy-3-alloxypropane and epichlorohydrin, from Shell Chemical Company. The commercial Shell products were redistilled before being used. Epiiodohydrin was prepared from epichlorohydrin,[10] glycidol from 3-chloro-1,2-propanediol,[11] and 1,2-epoxy-3-nitratopropane from 1-chloro-3-nitrato-2-propanol.[9,12] All oxides were analyzed by epoxide determination,[13] and concentrations used in rate calculations were corrected accordingly.

Uncatalyzed Addition of Thiocyanate Ion to Oxides.—Rates were obtained by a slight modification of Brönsted's method for values of k_3.[8] A Beckman Model H-2 *p*H meter was used to keep the *p*H of solutions within the necessary limits for all uncatalyzed additions. Rate data for ethylene oxide were obtained using a magnetically agitated closed system. Concentrations of reactants were adjusted so that salt effects were negligible, producing variations in values of k_3 of less than 0.5%, as shown by sample calculations.

The accuracy of the rate measurements by the Brönsted method is influenced slightly by the volume change resulting from the addition of perchloric acid; however, the magnitude of this effect was calculated to increase the reported rate constant by at most 1%. A microburet was used in the titration which read to ±0.002 ml., and the total amount of solution added in each titration for each reaction was 1 to 2 ml. The bath temperature variation of ±0.1° also allows a variation of about ±1% in the rate constant. Therefore, it is reasonable to assume that the over-all accuracy of the measured rate constants was within 5%.

Uncatalyzed Addition of Water to Oxides.—Hydrolysis rates were measured by the method of Brönsted,[8] each measurement requiring a waiting period of weeks, during which time the temperature was controlled with ±0.005°. Hydrolysis rates were measured in duplicate to eliminate the possibility of large errors.

Charge-Distribution Calculations

Direct application of the method described fully in two papers by Smith and Eyring[3,4] was made in the calculations

---

[1] This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. DA-04-495-Ord 18, sponsored by the Department of the Army, Ordnance Corps.

[2] (a) W. C. Ross, *J. Chem. Soc.*, 2257 (1950); (b) D. Swern, G. N. Billen and H. B. Knight, THIS JOURNAL, **71**, 1152 (1949).

[3] R. P. Smith, T. Ree, J. L. Magee and H. Eyring, *ibid.*, **73**, 2263 (1951).

[4] R. P. Smith and H. Eyring, *ibid.*, **74**, 229 (1952).

[5] H. Eyring and R. P. Smith, *J. Phys. Chem.*, **56**, 972 (1952).

[6] R. P. Smith and H. Eyring, THIS JOURNAL, **75**, 5183 (1953).

[7] C. G. Swain and C. B. Scott, *ibid.*, **75**, 141 (1953).

[8] J. N. Brönsted, Martin Kilpatrick and Marjorie Kilpatrick, *ibid.*, **51**, 428 (1929).

[9] W. L. Petty and P. L. Nichols, Jr., *ibid.*, **76**, 4385 (1954).

[10] E. Wedekind and E. Bruch, *Ann.*, **471**, 73 (1929).

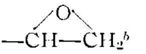
[11] T. H. Rider and A. J. Hill, THIS JOURNAL, **52**, 1521 (1930).

[12] P. L. Nichols, Jr., A. B. Magnusson and J. D. Ingham, *ibid.*, **75**, 4255 (1953).

[13] S. Siggia, "Quantitative Organic Analysis *via* Functional Groups," John Wiley and Sons, Inc., New York, N. Y., 1949, pp. 108-109.

TABLE I

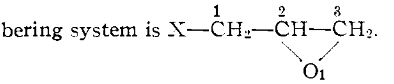
CALCULATED CHARGE DISTRIBUTIONS[a] FOR A SERIES OF EPOXIDES



$X{-}CH_2{-}CH{-}CH_2$[b]

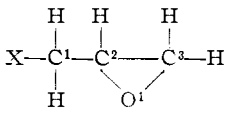
X	ϵ_X	ϵ_{H1}	ϵ_{H2}	ϵ_{H3}	ϵ_{C1}	ϵ_{C2}	ϵ_{C3}	ϵ_{O1}	$\Sigma_i \epsilon_i$
O[c]	−2.646	0.113	0.123	0.121	0.908	0.987	0.964	−2.373	0.007
H	0.0347	0.0347	.101	.113	.278	.808	.900	−2.416	.001
I	− .570	.116	.113	.0775	.620	.905	.935	−2.392	.000
Br	− .773	.118	.117	.0920	.736	.938	.947	−2.384	.001
Cl	− .914	.119	.120	.102	.816	.961	.955	−2.379	.001
F	−1.194	.121	.125	.122	.973	1.003	.971	−2.368	− .004

[a] All values are to be multiplied by 10^{-10} and expressed in e.s.u. [b] The numbering system is



$X{-}\overset{1}{C}H_2{-}\overset{2}{C}H{-}\overset{3}{C}H_2$, O_1. [c] O is given as X for glycidol. The charge on the hydrogen atom attached to the oxygen atom ϵ_{HO} is 1.576×10^{-10} e.s.u.

of charge distributions for the epihalohydrins and glycidol. For the purpose of convenient reference the atoms of the epihalohydrin molecules were numbered as



The Greek letter ϵ is used to refer to the net charge on an atom, and subscripts to this letter identify the given atom; *e.g.*, ϵ_{C2} signifies the net charge on the carbon atom labeled 2, and ϵ_{H3} is the net charge on the hydrogen atom connected to the carbon atom labeled 3. The oxygen atom is labeled 1 since in this manner the same numbering system can be employed with glycidol by labeling the hydroxyl oxygen as 2.

The basic computational technique involves the simultaneous solution of equations for each bond of the type

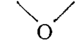
$$Q^b{}_a = \alpha_{ab} + \beta^a{}_b\, \epsilon_b - \beta^b{}_a\, \epsilon_a$$

where $Q^b{}_a$ is the net charge on atom a due to the polarization of the electron pair of the bond a–b; ϵ_a and ϵ_b are the total net charges on atoms a and b, respectively; α_{ab} is a parameter determined by electric dipole moment measurements; and the values of β are computed directly from screening constants, longitudinal polarizabilities and covalent bond radii. The simultaneous solution of the equations for all bonds in the molecule, together with a charge balance, yields ϵ values for each atom. Charge distributions for the epihalohydrins and glycidol are given in Table I.

In order to calculate charge distributions for the oxides, values of α_{OC}, α_{HO}, $\beta^H{}_O$[14] and $\beta^O{}_H$[14] were required. In deriving these quantities it was necessary to use the dipole moment data available on ethers and alcohols. Data in the literature appear to be in conflict with respect to the bond moment for the C–O bond. Pauling[15] gives an experimental value of 0.8 *D* and compares this value with that of 1.0 *D* which is obtained from the difference in electronegativity between the oxygen and carbon atoms. Gent[16] gives a value of 1.7 *D* for the dipole moment of the C–O bond in ethers. In view of this discrepancy it was necessary to find the effect of the assumed moment of the C–O bond on the calculated charge differences in oxide molecules since these differences, according to Smith and Eyring,[3] are presumably of importance in determining relative rates. The results are shown in Table II.

TABLE II

EFFECT OF ASSUMED C–O DIPOLE MOMENT IN DIFFERENCES IN CHARGES CAUSED BY A SUBSTITUENT X IN



$X{-}CH_2{-}CH{-}CH_2$, O

μ_{CO}, *D* assumed	$\gamma'_{OC} \times 10^{10}$, e.s.u.	$\alpha_{OC} \times 10^{10}$, e.s.u.	$\epsilon^H{}_{C3} \times 10^{10}$, e.s.u.	$\epsilon^F{}_{C3} \times 10^{10}$, e.s.u.	$(\epsilon^F{}_{C3} - \epsilon^H{}_{C3}) \times 10^{10}$, e.s.u.
1.7	−2.72	−2.64	0.897	0.970	0.073
1.2	−1.921	−1.867	.627	.700	.073
0.8	−1.281	−1.245	.423	.495	.072

It is apparent that widely different assumed values for the C–O bond moment yield essentially the same charge differences. This situation is comparable to that with the C–H bond where the convenient assumption of a zero bond moment does not appreciably affect calculated charge differences in molecules.[3]

An incoming nucleophilic species attacks carbon atom 3 almost exclusively in neutral aqueous solution.[17,18] Consequently, it is at this site that a charge shift might be expected to have the largest effect. Therefore an equation which relates ϵ_{C3} to those parameters which control the effect of changing the substituent X was derived as

$$\epsilon_{C3} = \left(\frac{0.255 - 1.79\phi}{5.59\phi - 1.146}\right) \gamma'_{OC} - \left(\frac{0.570}{5.59\phi - 1.146}\right) \gamma_{XC} \quad (1)$$

where

$$\gamma'_{OC} = \frac{2\alpha_{OC}}{1 + 2\beta^C{}_O}$$

and

$$\phi = \beta_{XC} + 1.968$$

In making comparisons of relative rates, propylene oxide is chosen as the reference compound, and net charges on the atoms of these molecules are identified by an appropriate superscript, *e.g.*, the net charge on carbon atom 3 of epichlorohydrin is designated $\epsilon^{Cl}{}_{C3}$. The following approximate relation was then obtained

$$\epsilon^X{}_{C3} - \epsilon^H{}_{C3} \cong -0.102 \frac{\gamma_{XC}}{\phi} \quad (2)$$

This relation immediately demonstrates the unimportance of the parameter γ'_{OC} (which depends on α_{OC}) in determining charge differences. An exception to the rule applies in the case of glycidol where α_{OC} is of definite importance in determining relative charge, as is discussed more fully in the following section.

Discussion of Results

In order to make a quantitative correlation of the relative rates of addition of thiocyanate ion to the epihalohydrins and glycidol, the usual application of absolute rate theory[19] was made using the two basic equations for reaction rates

$$k' = \frac{\mathbf{k}T}{h}\, e^{-\Delta F^{\ddagger}/RT} \quad (3)$$

(where k' is the rate constant; **k** is the Boltzmann constant; h is Planck's constant; $\Delta F^{\ddagger}$ is the standard free energy of activation; R and T are the gas

---

(14) K. G. Denbigh, *Trans. Faraday Soc.*, **36**, 936 (1940). For the evaluation of these quantities the longitudinal bond polarizability was estimated by using Denbigh's empirical formula, $b_e \times 10^{25} = 3.5r^6 + 1.9$, where b_e is the longitudinal polarizability and r is the bond distance.

(15) L. Pauling, "The Nature of the Chemical Bond," 2nd ed., Cornell University Press, Ithaca, N. Y., 1948.

(16) W. L. G. Gent, *Trans. Faraday Soc.*, **45**, 1021 (1949).

(17) Discussion by S. Winstein, R. B. Henderson and R. C. Elderfield, "Heterocyclic Compounds," Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1950.

(18) J. D. Ingham and P. L. Nichols, Jr., THIS JOURNAL, **76**, 4477 (1954).

(19) S. Glasstone, K. J. Laidler and H. Eyring, "The Theory of Rate Processes," McGraw-Hill Book Co., Inc., New York, N. Y., 1941.

TABLE III

VALUES CALCULATED FROM EXPERIMENTAL ACTIVATION ENERGIES (E_p) FOR REACTION OF SCN^- WITH EPOXIDES

Epoxide	E_p, kcal./mole	$\Delta H^\ddagger_{298^\circ}$, kcal./mole	$\Delta S^\ddagger_{298^\circ}$, e.u.	$\delta\Delta S^\ddagger_{298^\circ}$, e.u.	$\Delta F^\ddagger_{298^\circ}$, kcal./mole	$\delta\Delta F^\ddagger_{298^\circ}$, kcal./mole
Propylene oxide	14.90 (±0.33)	14.32 (±0.33)	−19.40 (±1.11)	0.00	20.10	0.0
Epiiodohydrin	13.61 (±0.74)	13.01 (±0.74)	−21.65 (±2.48)	2.25 (±3.59)	19.47	.628
Epibromohydrin	13.47 (±1.26)	12.88 (±1.26)	−22.41 (±4.23)	3.01 (±5.34)	19.34	.764
Epichlorohydrin	12.99 (±0.19)	12.40 (+0.19)	−23.00 (±0.64)	−3.60 (±1.75)	19.25	.854

constant and absolute temperature, respectively; and the transmission coefficient is assumed to be unity) and

$$\ln \frac{k^X}{k^H} = -\frac{g^\ddagger}{RT}(\epsilon^X_{C3} - \epsilon^H_{C3}) \qquad (4)$$

where

$$g^\ddagger = \left(\frac{\delta \Delta F}{\delta \epsilon_{C3}}\right)_T$$

From the experimental data the experimental activation energy E_p was computed for each reaction. The changes in entropy of activation were then computed, using eq. 3, the relation $E_p = \Delta H^\ddagger + RT$, and values of $\Delta F^\ddagger$. All results are given in Table III.

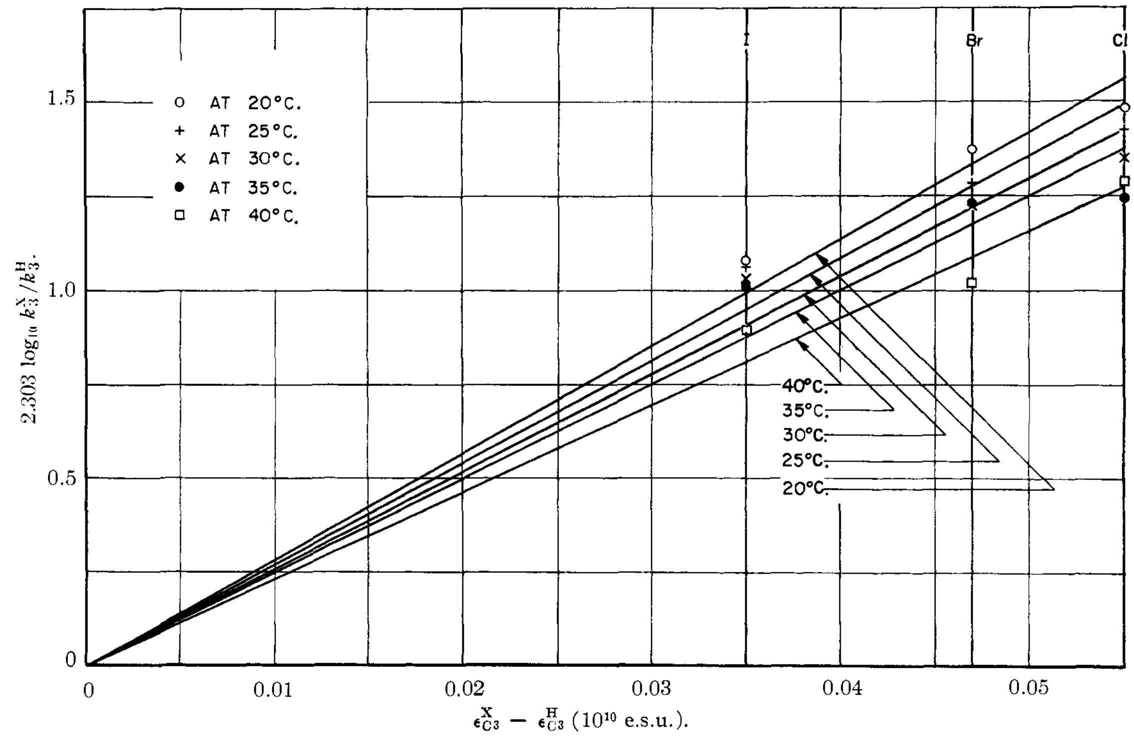


Fig. 1.—A plot of 2.303 $\log_{10} k^X_3/k^H_3$ *vs.* $\epsilon^X_{C3} - \epsilon^H_{C3}$ at varying temperatures for addition of SCN^- to $\mathrm{X{-}CH_2{-}\underset{\diagdown\, O\, \diagup}{CH{-}CH_2}}$.

Where the quantity $g^\ddagger$ is constant and not a function of ϵ_{C3}, a plot of $\ln k^X/k^H$ *vs.* $\epsilon^X_{C3} - \epsilon^H_{C3}$ should be linear. Figure 1 corroborates the linearity and demonstrates that this quantity depends on temperature, as is to be expected.[20] The constancy of $g^\ddagger$ implies that under isothermal conditions $\Delta F^\ddagger$ is a linear function of ϵ_{C3}, a fact which is also verified by Fig. 1. If steric effects were unimportant, $\Delta H^\ddagger$ should be linear with ϵ_{C3}. The inability to obtain sufficiently accurate values of E_p makes this point difficult to prove.

If it is to be assumed that the linear relations which are presented in Fig. 1 support the theory of applying charge–distribution calculations to the estimation of relative rates of oxide ring openings, some justification in terms of the accuracy of the experimentally determined quantities is required. Moreover, an independent calculation of $g^\ddagger$ on the basis of the charge difference would be valuable. This evidence, however, would probably be inconclusive until it was shown that an alternate treatment in terms of a field effect was not possible. Obviously unequivocal proof that this treatment is unique cannot be acquired at present because of undetermined facts in regard to field effects, nevertheless it is possible to supplement the discussion with respect to the points mentioned. For example, a direct attempt was made to correlate the changes in rate of reaction with changes in free energy associated with charge displacements resulting from field effects of different substituent groups. Calculations were made using the Westheimer–Kirkwood

---

[20] The method of least squares was applied to establish the linear plots shown in Fig. 1. Although the data show considerable scatter, they are essentially within experimental error, and the general features of the inductive effect are reasonably demonstrated.

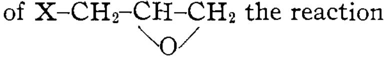
TABLE IV

RATE CONSTANTS[a] FOR UNCATALYZED ADDITION OF SCN⁻ TO EPOXIDES (VALUES OF k_3)

Epoxide	k_3 at 0°	20°	25°	30°	35°	40°
Ethylene oxide	.....	......	0.0113	....	0.0238	0.0389
Glycidol	.....	0.00781[b]	.0116	....	.0284	.0392
1,2-Epoxy-3-isopropoxypropane	.....	......	.0127	....	.0275	.0407
1,2-Epoxy-3-alloxypropane	.....	......	.0111	....	.0230	.0409
1,2-Epoxy-3-nitratopropane	.....	......	.0389	....	.0953	.131
Propylene oxide	.....	.00848	.0128	0.0200	.0296	.0430
Epiiodohydrin	0.00447	.0247	.0368	.0558	.0811	.105
Epibromohydrin	.00545	.0332	.0464	.0676	.101	.122
Epichlorohydrin	.....	.0370[b]	.0537	.0768	.109	.155

[a] All rate constants are expressed in cc./mole min. [b] Data from J. N. Brönsted, *et al.*, THIS JOURNAL, **51**, 428 (1929).

method.[21] Neither the observed trend in rate or magnitude of the rate changes resulted from these calculations.

The maximum change in the measured rate of thiocyanate ion addition was obtained using epichlorohydrin. This amounts to an almost fourfold change which in turn corresponds to a change in $\Delta F^{\ddagger}$ of about two kcal./mole, a figure that initially seems to be small since an accuracy of ±25% in the rate constant corresponds to about ±0.1 kcal./mole; however, it is believed that the relative changes observed possess significance. For each activation energy of  $X{-}CH_2{-}\underset{\diagdown O \diagup}{CH{-}CH_2}$ the reaction rate was measured at five different temperatures. By the method of least squares it was shown that the precision of measuring the activation energy was that which is given in Table III.

The principles involved in calculating the change in free energy of activation have been thoroughly discussed elsewhere.[19] According to absolute rate theory the changes in rate produced by different substituents are related to the change in the electric intensity at some appropriate site in the molecule, namely, the atom to which the incoming substituent is joined. Therefore $\epsilon^X{}_{C3}$ is the appropriate parameter for the present correlation. The theory also states that the change in rate produced by a substituent is also a function of $\partial\Delta F^{\ddagger}/\partial\epsilon^X{}_{C3}$. In calculating this quantity all ϵ's must be considered. To apply absolute rate theory all ϵ's, however, must change in direct proportion to $\epsilon^X{}_{C3}$. For example, the data of Table I show the proportionality of $\epsilon^X{}_{C3}$ to $\epsilon^X{}_{C2}$ as X varies; that is, the ratio lies between 0.97 and 1.10, which is sufficiently constant for the application of absolute rate theory. The calculated value of $g^{\ddagger}$ for epichlorohydrin was found to be −79,800 cal./mole/e.u. This is in favorable agreement with the experimental value of −73,900 cal./mole/e.u. Therefore, from a knowledge of the reaction rate of propylene oxide, the rates of the epihalohydrins may be predicted accurately by means of charge-distribution calculations and the absolute rate theory.

Whether or not the troublesome hydroxyl group could be equally well treated was of interest and accordingly rate measurements were made using the thiocyanate ion and glycidol. In the process of making this calculation, it became necessary to ascertain the proper bond moment for the C–O bond since the value of this moment would be important in determining the charge difference. The charge distribution for glycidol based on a C–O moment of 1.7 *D* is given in Table I. If the moment is assumed to be 0.8 *D*, then $\epsilon^{OH}{}_{C3}$ is 0.218, and $\epsilon^{OH}{}_{C3} - \epsilon^{H}{}_{C3}$ is −0.206. Since the corresponding charge difference from Table II is 0.064, and since the value obtained from Fig. 1 and from experimental rate data is approximately −0.0032, it is apparent that either the C–O bond moment is intermediate between 0.8 and 1.7 *D*, or the behavior of glycidol is anomalous. In the absence of a more accurate value for the C–O moment, no definite answer can be given at present. In Table IV miscellaneous rate data on the addition of thiocyanate to 1,2-epoxy-3-isopropoxypropane, to 1,2-epoxy-3-alloxypropane, to 1,2-epoxy-3-nitratopropane, and to ethylene oxide appear to be in agreement with the expected charge distributions, although detailed quantitative calculations were not made.

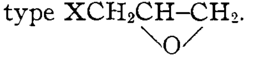
As a further test of the utility of charge-distribution calculations, the correlation introduced by Swain and Scott for nucleophilic displacement reactions was examined. The relation is

$$\log\frac{k}{k_0} = ns$$

where k is the rate constant for uncatalyzed addition of nucleophilic reactant, k^0 is the rate constant for uncatalyzed addition of water, n is a constant characteristic of the reactant, and s is a constant characteristic of the substrate which, in this instance, is an oxide. A previous publication[9] demonstrates that the Swain–Scott relation applies very well to the oxide addition reactions.

In order to demonstrate the connection between the inductive effect and the Scott–Swain equation, it will again be convenient to apply absolute rate theory. Equation 4 is put in the form

$$\log\frac{k^X}{k^H} - \log\frac{k^X{}_0}{k^X{}_0} - \log\frac{k^H{}_0}{k^H{}_0} = -\frac{g^{\ddagger}}{2.303RT}(\epsilon^X{}_{C3} - \epsilon^H{}_{C3}) \qquad (7)$$

where $k^H{}_0$ is the rate constant for the uncatalyzed addition of water to propylene oxide, and $k^X{}_0$ is the corresponding rate constant for compounds of the type  $XCH_2\underset{\diagdown O \diagup}{CH{-}CH_2}$. Rearrangement of eq. 7 and use of the equations

$$\log\frac{k^H}{k^H{}_0} = ns_H \qquad (8)$$

---

(21) F. H. Westheimer and J. G. Kirkwood, *J. Chem. Phys.*, **6**, 513 (1938).

(where s_H is the substrate constant for propylene oxide) and

$$\log \frac{k^X{}_0}{k^H{}_0} = -\frac{g^{\ddagger}{}_0}{2.303RT}(\epsilon^X{}_{C3} - \epsilon^H{}_{C3}) \quad (9)$$

lead to the relation

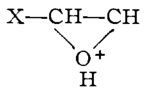
$$\log \frac{k^X}{k^X{}_0} = ns_H + \frac{g^{\ddagger}{}_0 - g^{\ddagger}}{2.303RT}(\epsilon^X{}_{C3} - \epsilon^H{}_{C3}) \quad (10)$$

Assuming that the quantity $(g^{\ddagger}{}_0 - g^{\ddagger})(\epsilon^X{}_{C3} - \epsilon^H{}_{C3})/2.303RT$ is proportional to n gives

$$\log \frac{k^X}{k^X{}_0} = n(s_H + \sigma) \quad (11)$$

where σ is the proportionality constant and equals $(g^{\ddagger}{}_0 - g^{\ddagger})(\epsilon^X{}_{C3} - \epsilon^H{}_{C3})/2.303RT$n. In applying eq. 6 to various nucleophilic displacement reactions, Swain and Scott[7] chose methyl bromide as a standard and assigned the value unity to its substrate constant. With this assignment the substrate constant for propylene oxide is near unity. It is found experimentally that σ is a small quantity, and this fact is consistent with the result which might be expected from the definitions of $g_0^{\ddagger}$ and $g^{\ddagger}$. The dependence of σ on $\epsilon^X{}_{C3} - \epsilon^H{}_{C3}$ demonstrates the connection between the inductive effect and the Swain equation.

It was shown by Brönsted, *et al.*,[8] that $k_4/k_2 \simeq k_3/k_1$ where k_4/k_2 is the ratio of rates of acid-catalyzed nucleophilic addition to acid-catalyzed hydration, and where k_3/k_1 is the corresponding ratio for the uncatalyzed reaction. It follows that Swain's correlation should also apply fairly well to acid-catalyzed reactions. The inductive effect, however, must be applied with caution. Although the substitution of Cl for H increases the rate in uncatalyzed reactions, it decreases the rate in catalyzed reactions. Ross[2a] has offered a plausible explanation for this behavior. He assumes that the complex



is made less stable by the decrease in charge on the ring oxygen when X exerts an inductive effect and accordingly the rate is decreased. The calculated charge differences for the ring oxygen in Table I seem to be sufficiently large to produce differences in rate of the magnitude observed. This can be checked quantitatively by applying the relation

$$RT \ln \frac{K^X}{K^H} = \left(\frac{\delta \Delta F}{\delta \epsilon_{O1}}\right)_T (\epsilon^X{}_{O1} - \epsilon^H{}_{O1}) \quad (12)$$

where K^X and K^H = equilibrium constant for formation of complex with epihalohydrin and propylene oxide, respectively, and ΔF = free energy of complex. The assumption is also made that the concentration of complex is proportional to K. Qualitative agreement of data with these ideas may be demonstrated by reference to Tables I and V.

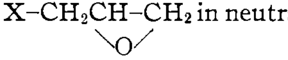
TABLE V

HYDROLYSIS RATE CONSTANTS AND APPROXIMATE ACTIVATION ENERGIES[a]

Epoxide	$k_1 \times 10^5$ at 20°	$k_1 \times 10^5$ at 22°	$k_1 \times 10^5$ at 25°	$k_1 \times 10^5$ at 37°	E_p, kcal./mole	k_2 at 20°
Ethylene oxide	2.17[b]	..	..	...	...	0.320[b]
Glycidol	1.68[b]	..	..	11.5[d]	18.72	0.147[b]
Propylene oxide	2.24[c]	2.81	4.15	13.3[d]	18.77	.....
Epichlorohydrin	5.84[b]	..	..	30.9[d]	17.73	0.0244[b]

[a] Values of k_1 are rate constants for the uncatalyzed addition of water to epoxides. Values of E_p are the corresponding approximate activation energies. Values of k_2 are rate constants for the acid-catalyzed addition of water to epoxides. All rate constants are expressed in reciprocal minutes. [b] Data from J. N. Brönsted, *et al.*, THIS JOURNAL, **51**, 428 (1929). [c] Extrapolated from data at higher temperatures. [d] Data from W. C. Ross, *J. Chem. Soc.*, 2257 (1950).

Conclusion

Quantitative calculations of the inductive effect by means of the semi-empirical treatment proposed by Smith and Eyring[3] combined with absolute rate theory makes possible a reasonably close prediction of the relative rates of addition of thiocyanate ion to oxides of the type  $X{-}CH_2CH{-}CH_2$ in neutral aqueous solution. Although an alternate treatment in terms of the field effect cannot be ruled out easily, the interpretation in terms of an inductive effect would seem to be adequate for most purposes in the discussion of reaction mechanisms and relative rates. The ideas can be extended moderately well to explain relative rates in acid-catalyzed additions to the oxide ring. Additional insight into the Swain–Scott correlation for nucleophilic displacement reactions is also provided.

PASADENA, CALIF.