

TABLE III

PHYSICAL CONSTANTS OF <i>n</i> -BUTYRAMIDES NR'R'' in <i>n</i> -C ₄ H ₉ CONR'R''	B.P.		<i>n</i> _D ²⁰	Ref.
	°C.	Mm.		
Dimethylamine	86.0	10	1.4418	^a
Diethylamine	73-74	5	1.4421	^b
Diisopropylamine	80-81	8	1.4438	^c
N-Methylamine	141-141.5	17	1.5215	^d
Piperidine	65-66	1	1.4777	^e
Pyrrolidine	95-96	5	1.4727	^f
Ethylenimine	48-50	8	1.4422	^g
Pyrrrole	83.8-84.0	10	1.4978	^h
N,N-Dimethylbenzamide	M.p. 42-43			ⁱ

^a J. R. Ruhoff and E. E. Reid, *J. Am. Chem. Soc.*, **54**, 401 (1934); *n*_D²⁰ 1.4391. ^b J. Brown and A. Heymons, *Ber.*, **62**, 411 (1928); *n*_D²⁰ 1.4403. ^c S. I. Gertler and A. Yerington, *C. A.*, **50**, 17297 (1956); *n*_D²⁰ 1.4344. ^d Ref. *c*: *n*_D²⁰ 1.5183. ^e J. D. Ianni and H. Adkins, *J. Am. Chem. Soc.*, **60**, 1675 (1938); *n*_D²⁰ 1.4750. ^f *Anal.* Calcd. for C₅H₁₀NO: C, 68.04; H, 10.71; N, 9.92. Found: C, 68.02; H, 10.28; N, 9.83. ^g See Experimental Part. ^h *Anal.* Calcd. for C₅H₁₀NO: C, 70.04; H, 8.08; N, 10.21. Found: C, 70.23; H, 8.35; N, 10.26. ⁱ H. Staudinger and N. Kon, *Ann.*, **384**, 114 (1911); m.p. 43°.

flask was placed 0.040 mole of N,N-dimethylbutyramide in 40 ml. of ether cooled by an ice-bath. To the stirred solution was added 10 ml. of a 1 M solution of lithium aluminum hydride over a period of 30 minutes. The reaction mixture was stirred for an additional 1 hour at 0° and then decomposed with a saturated aqueous solution of potassium sodium tartarate. The aqueous layer was washed with 20 ml. of ether. An aliquot of the ethereal solution was analyzed for the aldehyde with 2,4-dinitrophenylhydrazine.

Hydrogen evolved on decomposition was measured to determine the hydride consumption. The yield of the aldehyde was established by weighing the 2,4-dinitrophenylhydrazone after drying to constant weight. The hydrazone thus obtained was essentially pure, giving the same melting point as authentic pure specimen, m.p. 121-122° (lit.¹⁶ 122°).

Preparation of Aldehydes via 1-Acylaziridine. Cyclopropanecarboxaldehyde.—Cyclopropanecarbonyl chloride (42.2 g., 0.40 mole) was added over a period of 1 hour to a stirred solution of ethylenimine (17.5 g., 0.40 mole) and triethylamine (40.0 g., 0.40 mole) in 200 ml. of ethyl ether cooled by an ice-salt mixture. The reaction mixture was stirred for an additional 0.5 hour and precipitated triethylamine hydrochloride was filtered off and washed with 100 ml. of ether. The combined ether solution was cooled to 0° and 80 ml. of 1.25 M lithium aluminum hydride in ether was added to the stirred solution over 0.5 hour. After an additional hour, cold 5 N sulfuric acid was added, the ether layer was separated, and the aqueous layer extracted. The combined ether extracts were washed with water, sodium bicarbonate, water again, and dried over sodium sulfate. Analysis of an aliquot with 2,4-dinitrophenylhydrazine indicated a yield of 67%. Distillation yielded 16.8 g. of cyclopropanecarboxaldehyde, b.p. 97-100° at 740 mm., *n*_D²⁰ 1.4302, a yield of 60%.

Similarly, α-ethylbutyraldehyde, b.p. 116-119° at 740 mm., *n*_D²⁰ 1.4020 (lit.¹⁷ b.p. 117-118°, *n*_D¹⁵ 1.40398), was obtained in 69% yield, and pivalaldehyde, b.p. 73-75° at 740 mm., *n*_D²⁰ 1.3790 (lit.¹⁸ b.p. 71-74° at 730 mm., *n*_D²⁰ 1.3791), was obtained in 54% yield from the corresponding acid chlorides.

(16) R. L. Shriner and R. C. Fuson, "The Systematic Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1948, pp. 229-230.

(17) A. Behal and M. Sommelet, *Bull. soc. chim. France*, **31**, 300 (1904).

(18) K. N. Campbell, *J. Am. Chem. Soc.*, **59**, 1982 (1937).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF THE UNIVERSITY OF DELAWARE, DOVER, DEL.]

Studies on the Effect of Remote Substituents on Reactivity: The Rates of Addition of 2,4-Dinitrobenzenesulfonyl Chloride to Cyclohexenes and Norbornenes (I)^{1a}

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The second-order rate constants for the addition of 2,4-dinitrobenzenesulfonyl chloride to a number of transannularly substituted cyclohexenes and norbornenes have been determined in glacial acetic acid at 30.1°. The rates for the 4-substituted cyclohexenes could be correlated by means of Taft's equation, $\log k/k_0 = \sigma_{1\rho_1}$, thereby indicating that the substituents effects were almost entirely electronic in character. The *cis*-4,5-disubstituted cyclohexenes fit the correlation in only an approximate manner, presumably because of the inequivalence of the axial and the equatorial positions into which the substituents are forced in the modified chair conformation. The substituent effects appear to be similar for the transannularly substituted norbornenes, although *endo* and *exo* substituents affect the rate to a different degree. These results permit some discussion of the nature of transmission of inductive effects on the rates of reactions. The ρ_1 value measured for the monocyclic series is significantly greater than the ρ_B value reported for the Hammett series of *p*-substituted styrenes. These and other data are interpreted in the context of the discussion of how inductive effects are transmitted.

Introduction

Electronic effects of polar groups have often been assumed to be transmitted *via* a chain of connecting atoms; for such cases Roberts and Moreland,² in 1953, reserved the term "inductive effect." The term "field effect" was applied by these authors to those electronic influences which are transmitted across intraannular space. These authors as well as Grob and his co-workers³ have

extensively explored the interactions between non-adjacent atoms and functional groups in cyclic and bicyclic structures that regulated the positions of acid-base equilibria.

Transannular interactions involving the formation of a partial bond or a field effect influencing cyclic structures have been ascertained by Leonard and co-workers.⁴ Transannular reactions implying the formation of a full bond or the shift of a bond across intraannular space have been shown by several groups of workers to be capable of con-

(1) (a) Taken in part from the dissertation of Leroy J. Miller, submitted in partial fulfillment of the requirements of the Ph.D. degree at the University of Delaware, June, 1959. (b) Support of this work by the National Science Foundation under Grant NSF-G6037 is gratefully acknowledged.

(2) J. D. Roberts and W. T. Moreland, *J. Am. Chem. Soc.*, **75**, 2167 (1953).

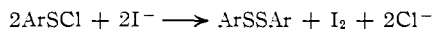
(3) (a) C. A. Grob, E. Renk and A. Kaiser, *Chem. & Ind. (London)*, 1222 (1955); (b) 598 (1957).

(4) See N. J. Leonard, *Record Chem. Progr.*, **17**, 243 (1956), for discussion and references pertaining to this work.

trolling the stereochemical course of many reactions of medium sized rings.⁵ The decisive role that transannular substituents can play in determining the steric course of reactions in cyclohexenes and related bicycloheptene derivatives has been pointed out in the results of Henbest and co-workers.⁶

Observations of the influence of remote substituents on the rates of reactions and, in general, on the reactivity of functional sites are quite isolated and uncorrelated. Thus, *trans*-4,5-dihydrocyclohexene and its dibenzoate were found to be resistant to bromination in carbon tetrachloride, in contrast to the 3,4-diol, which is brominated readily.⁷ Bromination of 4,5-dibromocyclohexene was found to require rather vigorous conditions,⁸ and epoxidation of the same olefin was unusually slow.^{7b} Epoxidation of 1,4-dihydronaphthalene proceeded at a rate one fifth of that determined for cyclohexene.⁹ 4-Hydroxycyclohexene was epoxidized at a rate 0.042 times that of cyclohexene and less than two thirds of the rates for 3-methoxy- and 3-ethoxycyclohexene,^{5a} the comparison being made possible by the fact that hydroxyl and alkoxy groups possess almost the same electron-withdrawing power.¹⁰

In these laboratories we have sought to gain a quantitative estimate of the origin, nature and magnitude of the influence of remote substituents on reaction rates. In subsequent publications we will discuss these effects in a variety of reactions at polar sites on carbocyclic structures. In the present work the addition of 2,4-dinitrobenzenesulfonyl chloride to the cyclic olefins was chosen as the reaction by which we might analyze the substituent effect. Kharasch and co-workers have presented ample evidence for the polar, electrophilic nature of the reaction.¹¹ They also followed the addition of this reagent to cyclohexene,¹² *p*-substituted styrenes,^{11c,d} vinyl acetate^{12b} and *cis*- and *trans*-stilbene¹³ by following the disappearance of the sulfonyl chloride. The remaining sulfonyl chloride was measured by titrating with a standard thiosulfate solution the iodine released by reaction with iodide ion.¹⁴ The precision of



the method was reported^{11c} to be approximately 1%. The sulfonyl chloride additions were second order,

(5) See particularly the papers on this subject by A. C. Cope and co-workers in the *J. Am. Chem. Soc.*, 1930-1937, and by V. Prelog and co-workers in the *Helv. Chim. Acta*, 1952-1957.

(6) (a) H. B. Henbest and B. Nicholls, *J. Chem. Soc.*, 221 (1959); (b) H. B. Henbest and B. Nicholls, *Proc. Chem. Soc.*, 61 (1957); 225 (1958); (c) *J. Chem. Soc.*, 4608 (1957); 227 (1959); (d) H. B. Henbest and R. A. L. Wilson, *ibid.*, 1958 (1957); (e) H. B. Henbest and R. S. McElhinney, *ibid.*, 1834 (1959).

(7) (a) C. E. McCasland and E. C. Horswill, *J. Am. Chem. Soc.*, **76**, 1654 (1954); (b) E. E. van Tamelen, *ibid.*, **77**, 1704 (1955).

(8) J. P. Wibaut and F. A. Haak, *Rec. trav. chim.*, **67**, 85 (1948).

(9) D. Swern, *Chem. Revs.*, **45**, 1 (1949).

(10) R. W. Taft and I. C. Lewis, *J. Am. Chem. Soc.*, **80**, 2436 (1958).

(11) (a) N. Kharasch and C. M. Buess, *ibid.*, **71**, 2724 (1949); (b) N. Kharasch and S. J. Assony, *ibid.*, **75**, 1081 (1953); (c) W. L. Orr and N. Kharasch, *ibid.*, **75**, 6030 (1953); (d) **78**, 1201 (1956).

(12) (a) D. R. Hogg and N. Kharasch, *ibid.*, **78**, 2728 (1956); (b) N. Kharasch and H. H. von Duesel, *J. Org. Chem.*, **24**, 1806 (1959).

(13) N. R. Slobodkin and N. Kharasch, *J. Am. Chem. Soc.*, **82**, 5837 (1960).

(14) N. Kharasch and M. M. Wald, *Anal. Chem.*, **27**, 996 (1955).

first order in each of the reactants, and the rate constants for the *p*-substituted styrenes could be correlated by means of the Hammett equation. The procedure of Kharasch and co-workers was employed in this work with a few minor modifications.

Experimental

Compound used	Reference to properties, method of purification and/or source
2,4-Dinitrobenzenesulfonyl chloride	15, 3x recrystd.
Cyclohexene	12, distln.
4-Methylcyclohexene	Eastman white label, distln.
4- <i>t</i> -Butylcyclohexene	16a, 98% by v.p.c.
4-Methoxycyclohexene	16b, distln.
4-Bromocyclohexene	16c, distln.
4-Cyanocyclohexene	17, distln.
4-Carboxycyclohexene	17a
4-Carbomethoxycyclohexane	17a, estfin. and distln.
<i>cis</i> -4,5-Dicarboxycyclohexene anhydride	18, recrystd. CCl ₄ and heptane; m.p. 98-99°
<i>cis</i> -4,5-Dicarboxycyclohexene	18, 4x recrystd. H ₂ O; m.p. 166.5-167°
<i>cis</i> -4,5-Dicarbomethoxycyclohexene	Eastman white label, distln.
Norbornene	B.p. 95.0-95.5°
<i>cis-endo</i> -5,6-Dicarboxynorbornene anhydride	National Aniline Co., 2 batches: 165.5-166.5° (subl. above 145°); 163.5-165° (subl. above 140°); same kinetic properties
<i>cis-endo</i> -5,6-Dicarboxynorbornene	18a, 19, 3 samples with different m.p.'s gave same kinetic results
<i>cis-exo</i> -5,6-Dicarboxynorbornene hydride	19b
<i>cis-exo</i> -5,6-Dicarboxynorbornene	19, 20, 157-159° dec.
<i>exo</i> -5,6-Trimethylenenorbornene	29b, 95% by v.p.c.

Preparation of Reagents Previously Unknown

cis-4,5-Dimethylcyclohexene.—The *cis*-4,5-dicarboxycyclohexene anhydride was reduced with lithium aluminum hydride to the diol, which was then converted to the di-*p*-toluenesulfonate ester; this was further reduced with lithium aluminum hydride to the dimethylcyclohexene. After two distillations a material was obtained, b.p. 123.0-124.2°, *n*_D²⁰ 1.4459.

Anal. Calcd. for C₈H₁₄: C, 87.19; H, 12.81. Found: C, 86.68; H, 12.66.

endo-5-Methylnorbornene was prepared from *endo*-5-carbomethoxynorbornene by Mr. Harold Feller. Lithium aluminum hydride was used first to reduce the ester to the alcohol and then to reduce the corresponding *p*-toluenesulfonate ester to the hydrocarbon. Gas chromatography indicated a probable purity of 99.7%; b.p. 115-116.5°, *n*_D²⁰ 1.4598.

(15) "Organic Syntheses," Coll. Vol. I, 2nd Ed., John Wiley and Sons, Inc., New York, N. Y., 1941, p. 220.

(16) (a) S. Winstein and N. J. Holness, *J. Am. Chem. Soc.*, **77**, 5562 (1955); (b) C. J. Gogek, R. V. Moir and C. B. Purves, *Can. J. Chem.*, **29**, 946 (1951); (c) W. Sobocki, *Ber.*, **43**, 1038 (1910).

(17) (a) F. D. Bergmann and D. F. Herman, *J. Appl. Chem.*, **3**, 42 (1953); (b) E. D. Bergmann, U. S. Patent 2,563,206, Aug. 7, 1951; *Chem. Abstr.*, **46**, 3074 (1952).

(18) (a) O. Diels and K. Alder, *Ann.*, **460**, 98 (1928); (b) E. H. Farmer and L. Warren, *J. Chem. Soc.*, 897 (1929).

(19) (a) K. Alder and G. Stein, *Ann.*, **504**, 247 (1933); (b) D. Craig, *J. Am. Chem. Soc.*, **73**, 4889 (1951).

(20) P. D. Bartlett and A. Schneider, *ibid.*, **68**, 6 (1946).

Anal. Calcd. for C₈H₁₂: C, 88.82; H, 11.18. Found: C, 88.69; H, 11.16.

exo-5-Methylnorbornene was prepared by Mr. Harold Feller from *exo*-5-carbomethoxynorbornene by the method employed for the *endo* isomer; b.p. 116.0–116.7°, *n*_D²⁰ 1.4601. The infrared spectra as well as the boiling points and the refractive indices of the *endo* and *exo* isomers were very similar; however, differences in the structure and intensity of the absorption bands were evidence of a subtle difference in structure.

Rate Measurements.—The rates of addition were determined by two techniques which were similar to that of Kharasch and co-workers.^{11a,4,12–13}

Procedure 1.—This procedure was utilized for all of the olefins except norbornene and the alkylnorbornenes. The solutions of the reactants were warmed to the bath temperature (30.1°) in a two-bulbed flask in which they could conveniently be mixed to start the reaction. At appropriate intervals 10.0 ml. samples were pipetted into a flask containing 0.5 g. of dry reagent grade sodium iodide. The flask was swirled 5 times and allowed to stand for exactly 3 min., the flask being swirled 3 more times in the last 10 sec. At the close of the 3 min., 50 ml. of water was added and the iodine was titrated with standard sodium thiosulfate solution to the end-point with a starch indicator. The volume of thiosulfate solution was corrected for a blank titration using 10 ml. of acetic acid at the same temperature.

The above procedure differed from that of Orr and Kharasch^{11a} in that solid sodium iodide rather than an acetic acid solution of the iodide served as the quenching agent. It was found that iodide in acetic acid was oxidized quite rapidly by air, and the procedure was changed as a consequence.


As was noted by Orr and Kharasch,^{11a} the end-point was not sharp, and there was a tendency to release additional iodine after the first end-point was observed. The additional iodine was also titrated and the small amount of thiosulfate required in this second titration was added to that required in the first. Several types of behavior were noted. With some olefins (*e.g.*, cyclohexene) the amount required for the second titration decreased with succeeding samples; for these the best explanation is a reversible equilibrium between the iodine and the olefin and the iodine-olefin adduct. Removal of the iodine by titration would allow the adduct to revert to iodine and olefin; and, as the remaining olefin decreased, the formation of adduct and therefore the release of additional iodine decreased. With other olefins (*e.g.*, *cis*-4,5-dicarboxycyclohexene anhydride) the opposite was true, and samples from the latter part of the run required a greater volume for the second titration than did those removed at the start of the run. For these one can only offer the explanation of Orr and Kharasch^{11a} that some of the iodine adheres to the solid organic material which is precipitated by the addition of water, and invoke the further condition that iodine is absorbed more strongly by the products than by the reactants. Indeed, the color of the iodine-starch complex did in all cases arise on the surface of the precipitate, but the time required for the release of iodine (from 5 to 45 min.) was sometimes too long to make this explanation plausible. The appearance of additional iodine was not noticeably accelerated by vigorous shaking of the solution (as suggested by the report of Orr and Kharasch^{11a}). An alternate rationalization would be that one of the products of the reaction reacted with iodide, or with air and iodide, to produce iodine. Whatever the explanation, a limited quantity of iodine was formed, for allowing the samples to stand for a prolonged period of time after the second titration—even when open to the air—either produced negligible quantities of iodine or generated iodine at a greatly reduced rate. To complete the picture, in some runs (*e.g.*, bornylene) no additional iodine was observed after the first end-point was reached and the end-point was relatively sharp, while with other runs (*e.g.*, norbornene, followed by procedure 2) the amount of iodine released appeared to have no limit. With runs of the latter type only the first titration was recorded, since the additional iodine did not seem to be linked to any small quantity of material in solution.

Two attempts were made to follow the norbornene addition by procedure 1. In the first it was found that the reaction was entirely too fast for the usual method. In the second the samples were treated as usual, but the iodine was not titrated until the completion of the run. The result

was that all samples required approximately the same small quantity of thiosulfate to titrate the iodine present. Obviously the iodine was consumed after the reaction was quenched.


Procedure 2.—These runs were made by determining one point at a time. The reaction flask was suspended by a cord with the bottom of the flask immersed in the bath. This afforded the opportunity to mix the contents of the flask rapidly and to remove the flask from the bath quickly after quenching the reaction. The solutions of the reactants were pipetted into the reaction flask with a pipet which delivered its contents in about 2 sec. The time for the start of the reaction was taken as the time at which half of the second solution was out the pipet. The addition of the second solution was accompanied by simultaneous shaking of the flask to mix the contents. After a suitable time interval the reaction was arrested by dumping in 3 g. of dry sodium iodide. The contents were thoroughly mixed with about 10 swirls, 60 ml. of water was added at once (about 10 sec. after the sodium iodide quenching), and the iodine was titrated as quickly as possible. It was assumed that the value of a blank would be negligible.

TABLE I

THE ADDITION OF 2,4-DINITROBENZENESULFENYL CHLORIDE TO SUBSTITUTED CYCLOHEXENES ^a					
X	X'	$k \times 10^3$, l./mole sec.	Relative rates	5 + log k	σ^b
H	H	11.6	100	3.064	0.00
C(CH ₃) ₃	H	10.4	89.7	3.017	-.07
CH ₃	H	9.42	81.2	2.974	-.05
OCH ₃	H	2.21	19.1	2.344	+.25
COOCH ₃	H	1.30	11.2	2.114	+.30
COOH	H	1.13	9.74	2.053	+.30
Br	H	0.536	4.62	1.729	+.45
CN	H	0.123	1.06	1.090	+.58
CH ₃	CH ₃	4.52	39.0	2.655	-.10
COOCH ₃	COOCH ₃	0.303	2.61	1.481	+.60
COOH	COOH	.189	1.63	1.276	+.60
	CO-O-CO	.0358	0.309	0.554
Norbornene		150	1290	4.176

^a Carried out in glacial acetic acid at 30.1°. ^b Taken from ref. 10.

TABLE II

THE ADDITION OF 2,4-DINITROBENZENESULFENYL CHLORIDE TO SUBSTITUTED NORBORNENES ^a				
X	X'	$k \times 10^3$, l./mole sec.	Relative rates	6 + log k
<i>exo</i> -CH ₂ CH ₂ CH ₂ (<i>cis</i>)		208	139	5.318
H	H	150	100	5.176
<i>exo</i> -CH ₃	H	131	98.3	5.117
<i>endo</i> -CH ₃	H	99.7	66.5	4.999
<i>exo</i> -COOH	COOH (<i>cis</i>)	0.955	0.637	2.980
<i>endo</i> -COOH	COOH (<i>cis</i>)	2.25	1.50	3.332
<i>exo</i> -CO-O-CO (<i>cis</i>)		0.0752	0.0501	1.876
<i>endo</i> -CO-O-CO (<i>cis</i>)		0.00134	0.000893	0.127
Cyclohexene		11.6	7.73	4.004

^a Carried out in glacial acetic acid at 30.1°.

Results.—The data follow the integrated second order rate equation

$$kt = \frac{2.303}{a-b} \log \frac{b(a-x)}{a(b-x)}$$

Plots of $\log(b(a-x)/a(b-x))$, versus time were linear for all but one of the cyclohexenes to at least 72% completion. The exception, *cis*-4,5-dicarboxycyclohexene anhydride, was linear to 62% completion. The plots for the norbornenes were linear to at

least 68% of completion with the exception of *cis*-*endo*-5,6-dicarboxynorbornene anhydride. The addition to the anhydride was extremely slow (the reaction was followed for 3 months), and the rate increased slightly with time. It is quite likely that the anhydride slowly reacted with the solvent, acetic acid, to form the more reactive *endo*-acid. This view was supported by the observation that when a 47-day old solution was used the initial reaction was faster than it was for a fresh solution. The recorded value of k is the estimated initial rate constant.

The rate constants and the relative rates are summarized in Tables I and II. The σ_I constants given for the *cis* disubstituted cyclohexenes in Table I are twice the σ_I values for a single substituent.

Figure 1 is a plot of the logs of the rate constants against the ρ_I constants for the 4-monosubstituted cyclohexenes. The line which is drawn on the graph is the least squares plot minimizing the squares of the differences along the y-axis. The slope, σ_I , is -2.88 , the standard deviation of ρ_I is 0.20 , and the correlation coefficient is 0.985 . The points provided by the *cis* 4,5-disubstituted *cis*-cyclohexenes are also shown, but they were not used in placing the line.

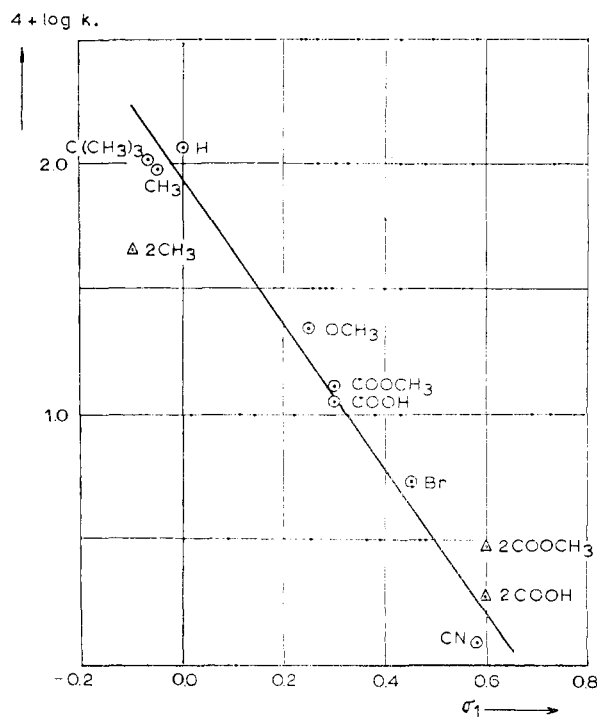


Fig. 1.—A plot of $\log k$ vs. σ_I for 4-monosubstituted and *cis*-4,5-disubstituted cyclohexenes: \circ , monosubstituted; Δ , disubstituted cyclohexenes.

A plot of $\log k$ for the substituted cyclohexenes against $\log k$ for the analogously substituted norbornenes is given in Fig. 2.

Discussion.—A most suitable means of evaluating substituent effects by correlation of reaction rates of a series of analogous compounds is provided by the Taft equation.²¹

$$\log k/k_0 = \Sigma \text{ general inductive}^{22} + \text{steric} + \text{resonance effects} \quad (1)$$

In the above equation k_0 and k are the rate constants for a standard compound in the series and a substituted analog, respectively. When resonance interaction between the substituent and the reaction site is impossible, the resonance effects can be omitted. When steric effects are constant

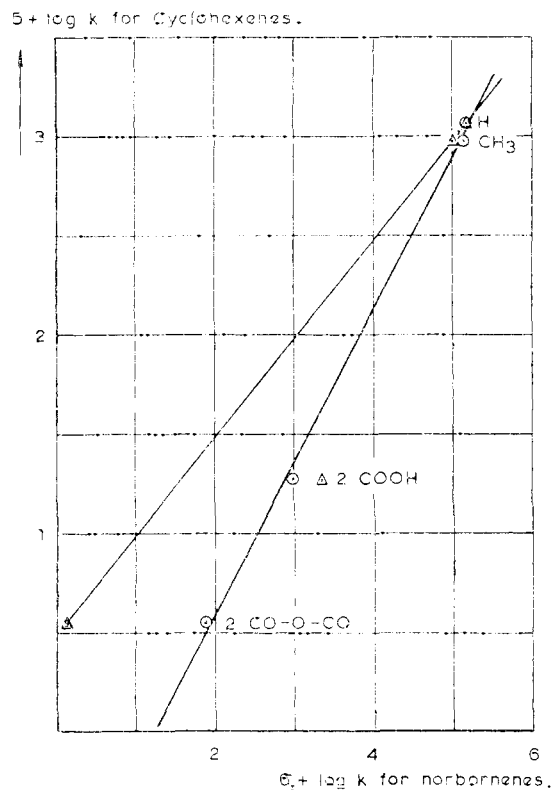


Fig. 2.—A plot of the rate constants for the cyclohexenes vs. the rate constants for norbornenes: \circ , *exo*; Δ , *endo*.

throughout the series, they also can be omitted and only the inductive effects need be considered for the correlation. The inductive effect can be described as the product of two parameters, as

$$\log k/k_0 = \sigma_I \rho_I \quad (2)$$

where σ_I is the inductive substituent constant and ρ_I is the inductive reaction constant.^{10,23} The same equation was deduced earlier for a specific case by Roberts and Moreland.² Adherence to eq. 2 is a criterion for the negligibility of all effects of other than electronic origin.

The experimental results obtained here permit one definite conclusion: the effect of the substituents of the 4-monosubstituted cyclohexenes on the rate of addition of 2,4-dinitrobenzenesulfonyl chloride is predominantly electronic in nature, and the rate constants can be correlated with fair precision by eq. 2.

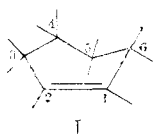
(21) R. W. Taft, in "Steric Effects in Organic Chemistry," edited by M. S. Newman, John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 13.

(22) We employ this term in the same manner as C. A. Grob and co-workers in ref. 3b.

(23) R. W. Taft, *J. Am. Chem. Soc.*, **79**, 1045 (1957).

The values of ρ_I are usually approximately equal to the values for ρ_H in the Hammett equation.^{2,10} This enables us to compare ρ_I for the present series of compounds with the value of ρ_H obtained by Orr and Kharasch^{11d} for the addition to the *p*-substituted styrenes. An increase in the absolute value of ρ would be expected from moving the double bond closer to the substituents. An increase from -2.35 to -2.88 has been observed.

According to Taft's theory, eq. 2 will fail when steric effects are not constant throughout the series. A steric effect would be considered unlikely for the preferred conformation of cyclohexene, the modified chair conformation²¹. In this conformation a substituent at position 4 will have the choice of an axial or an equatorial orientation, and, as is true of cyclohexane substituents, will prefer the equatorial one.^{21a} By reference to structure I it can be seen that an equatorial substituent on carbon 4



would be well out of the way of the attacking sulfonyl chloride. The work of Henbest^{5a} appears to indicate that the steric influence may be sufficient to direct the course of addition in the epoxidation of 4-substituted cyclohexenes. While both *cis*- and *trans*-epoxides were obtained when the substituent was small, only the *trans* could be isolated when the substituent was bulky. Nevertheless, the conformity of the rate data for the monosubstituted cyclohexenes (Fig. 1) to the Taft eq. 2 bears out the fact that in the ArSCl addition reaction steric effects have virtually no part in determining reactivity. Our interpretation, however, must allow for the occurrence of certain fortuitous circumstances.

Thus, to a certain extent, the cyclohexenes will exist in less acceptable conformations. In several of these (*e.g.*, the modified chair conformation with the substituent in the axial position) the substituent might easily exert a steric influence on the rate and mode of addition. This influence might be expected to prevent strict adherence to eq. 2. However, steric effects may be self-limiting. While a bulky substituent in an unpreferred conformation decreases the rate of reaction in that conformation, it also serves to decrease the population of that conformation by making it sterically undesirable.

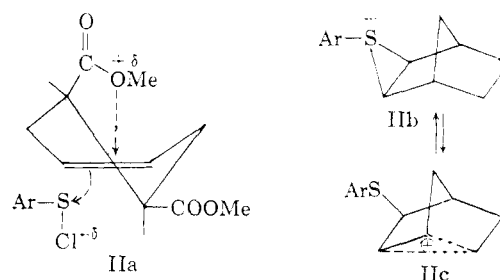
The *cis*-1,5-disubstituted cyclohexenes follow eq. 2 in approximate fashion. Since carbon atoms 4 and 5 are equivalent in their position relative to the double bond, and since polar substituent effects are additive,²⁵ assigning a value for σ_I equal to twice the σ_I value for a single substituent seems reasonable. However, one can see from the representation of the modified chair form (I) that one substituent will have to assume the axial

position. The second substituent, therefore, is not equivalent to the first. The chain length separating the substituents from the double bond is the same, but the distance across space is different. Having observed the rate retarding effect of a single methyl substituent, it is not unexpected, on the basis of the reduced distance from the addition reaction centers, to find that the second *cis* substituent (assuming the position in the modified chair conformation) decreases the reaction rate even more than does the first. It is not entirely unlikely, however, that some ponderal influences may have resulted from this change to an axial orientation, thus accounting for the increased rate retardation.

The rate for *cis*-4,5-dicarbomethoxycyclohexene is somewhat greater than predicted by eq. 2 and its point stands above the line in Fig. 1. This result can be plausibly ascribed to the anchimeric assistance of the axial carbomethoxyl group. It is well known that γ,σ -unsaturated esters and acids can form lactones when treated with electrophilic reagents, including 2,4-dinitrobenzenesulfonyl chloride.²⁶ The axial carbomethoxyl group is well situated to participate in such a reaction since the bond between C₄ and an axial substituent is partly directed toward the center of the ring.²⁷

Normally, however, anchimeric assistance produces much greater rate exaltations²⁸ than we observe here for the axial carbomethoxyl. This net effect is consequently the result of a balance between an enhanced rate-retarding field effect of an axial carbomethoxyl and an even greater rate increase due to the anchimeric assistance that is geometrically facilitated by the axial orientation of the substituent.

The agreement of the rate constant for *cis*-4,5-dicarboxycyclohexene with the value predicted by the plot in Fig. 1 is clearly the result of a fortuitous balance of these opposing effects. The anchimeric assistance to be realized from neighboring group participation²⁸ of the carboxylic acid group in the addition reaction transition state, analogous to IIA, is just cancelled by the smaller (than the carbomethoxyl) inductive retardation.



The greater rate of reaction of ArSCl with norbornene than with cyclohexene reflects the correspondingly greater stability of the arylsulfonium norbornyl cation, IIb,c. The rate factor of less than 13 would seem to indicate that the highly

(24) (a) W. Klyne, "Progress in Stereochemistry," Vol. 1, Butterworths Scientific Publications, London, 1954, pp. 81-83; (b) C. W. Beckett, N. K. Freeman and K. S. Pitzer, *J. Am. Chem. Soc.*, **70**, 4227 (1948).

(25) Reference 21, pp. 590-592, 623-625.

(26) M. de M. Campos, *J. Am. Chem. Soc.*, **76**, 4480 (1954).

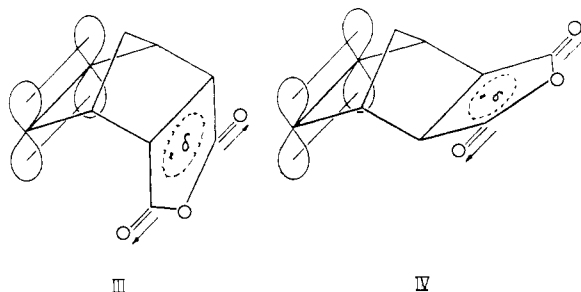
(27) E. J. Corey and R. A. Sneen, *ibid.*, **77**, 2505 (1955).

(28) S. Winstein, C. R. Lindgren, H. Marshall and L. L. Ingraham, *ibid.*, **75**, 147 (1953).

stabilized bridged ion structure IIc has not been formed in the transition state, for which event a rate enhancement of greater than 100 could have been anticipated.²⁹ Confirmation, however, of the importance of the bridged ion in stabilization of the intermediate can be perceived in a comparison of the relative rates of similarly substituted cyclohexenes and norbornenes (Tables I and II). A given electron-attracting (remote) substituent clearly causes a much greater decrease in rate of addition to the bicyclic than the monocyclic olefin. Obviously, also, the valences of the transannular carbon atom to which the substituent is attached are deeply involved in the stability of the cationic arylsulfonium-norbornene adduct. The attachment of a strong, electron-attracting 5,6-anhydride group, for example, is (depending on orientation) *ca.* 7 to 350 times more rate retarding than in the corresponding *cis* monocyclic case. However, the variation in this effect with orientation of the substituent on the bicyclic structure also indicates that part of these rate differences are attributable to transannular inductive effects of the same nature as identified for the monocyclic cases (*vide infra*).

The unimportance of substituent size in determining the rates observed for transannularly substituted norbornenes may be deduced from previous work³⁰ on the stereochemical course of addition of 2,4-dinitrobenzenesulfonyl chloride. The usual rule of *exo* attack on the double bond was found to explain the products of this addition as well as the addition of other sulfonyl chlorides.³¹ If *exo* attack occurs, size effects are highly unlikely to assert themselves for either *exo* or *endo* substituents. A reagent attacking at the *exo* side, even a bulky reagent, could not be sterically hindered by transannular substituents.

The magnitude of difference between an *endo* and *exo* electron-withdrawing substituent is seen to be greatest (a factor of *ca.* 50) in the case of the anhydrides. Presumably the anhydride in either orientation is equally destructive of the intermediate cation stabilization discussed for the unsubstituted bicyclic olefin. However, even though inductive effects of the same nature are manifest, the transmission of these effects to the reaction site is more efficient in the case of the *endo*-anhydride. The *endo*- and the *exo*-anhydride groups are separated from the double bond by the same carbon chain length, but the electronic effects of these substituents apparently are not controlled by the length of the carbon chain alone. The transmission of electronic effects across intraannular space, *i.e.*, a field effect,³² is most strongly implicated by these results. This is perhaps more clearly seen in the structural diagrams III and IV, where the anhydride groups are characterized



by a center of heavy charge deficiency somewhere midway between the carboxyl carbons and where the moments of the carboxyl are directed away from this center in a plane almost parallel to the orbitals of the transannular double bond. The positively charged center, being closer to the π -lobes of the double bond, evidently controls the inductive effect of the anhydride group. Thus, two factors are of governing importance; the *exo* substituent is farther from the double bond than the *endo*, and the methylene bridge intervening between the *exo* substituent and the double bond alters the dielectric constant of the intervening cavity from that which prevails on the *endo* side of the structure. Other authors^{32b,33} have discussed such "horseshoe effects" in trying to assess the influence on the acidity of carboxylic acids produced by variation in the orientation of substituent group moments attached to rigid neighboring center.

The absolute magnitude of rate retardation produced by the anhydride group, a factor of more than 10^5 , merits closer scrutiny. Part of this rate factor is attributable to the loss of the bridged ion stabilization of the cationic intermediate in the bicyclic reaction, as discussed previously, which can account for a factor of *ca.* 13 when compared to the alicyclic rate. Considering the corresponding rate reduction produced by anhydride in the alicyclic case (*ca.* 330), we can then attribute a factor of about 25 in the rate to the reduced intraannular distance across which the effect of the *endo*-anhydride is transmitted. Grob and co-workers³⁴ have confirmed the Bjerrum relation³⁴ in which the $\log K$, an equilibrium constant, is linearly related to the reciprocal of the distance, separating the substituent and seat of ionization. We can thus calculate that the corresponding (equatorial) substituent in the alicyclic case is approximately 1.4 times further removed from the seat of reaction than the bicyclic *endo* substituent, assuming the same dielectric for the cavity intervening between the substituent and reaction centers and the same substituent vector. The assumption is also made that rate and equilibrium constants are controlled by the same factors. The relative distances from the reaction center of the *endo* and *exo* transannular bicycle substituents cannot be compared on the same basis because of difference of dielectric medium induced by the presence of the intervening methylene bridge in only one of these orientations.

(29) (a) For illustration see S. Winstein and D. S. Trifan, *J. Am. Chem. Soc.*, **74**, 1147, 1154 (1952); (b) For a more complete discussion of the factors controlling the addition reactions of norbornene see L. Kaplan, H. Kwart and P. von R. Schleyer, *ibid.*, **82**, 2341 (1960).

(30) H. Kwart and R. K. Miller, *ibid.*, **78**, 5678 (1956).

(31) S. J. Cristol, R. P. Arganbright, G. D. Brindell and R. M. Heitz, *ibid.*, **79**, 6035 (1957); H. Kwart, R. K. Miller and J. L. Nye, *ibid.*, **80**, 887 (1958).

(32) (a) See ref. 2 and 3 as well as C. K. Ingold, *Chem. Revs.*, **15**, 225 (1934); (b) J. D. Roberts and R. A. Carboni, *J. Am. Chem. Soc.*, **77**, 5554 (1955).

(33) Compare the interpretation in ref. 32b with that given by M. S. Newman and S. H. Merrill, *ibid.*, **77**, 5552 (1955).

(34) N. Bjerrum, *Z. physik. Chem.*, **106**, 219 (1923).

It must be reiterated, therefore, that three of the most important considerations determining substituent effects on reaction rates are: (i) the magnitude, orientation and distance of separation of the substituent dipole with respect to the seat of reaction; (ii) the dielectric constant of the transmitting medium; (iii) the electronic demand of the reaction. The last named, clearly the most complex variable, is often characterized by the ρ -value. As has previously been pointed out,³⁵ however, the magnitude of ρ partly reflects both the nature of the reaction³⁶ as well as the degree of interaction possible with a substituent center at a fixed distance from the reaction center. Thus, we can compare the ρ_I value we have measured for the corresponding alicyclic reaction with the ρ_H for the side chain addition of arenesulfonyl chloride in substituted styrene.^{4d} We realize thereby that the closer distance and lower cavity dielectric has produced somewhat greater interaction than is possible for substituents on the aromatic ring, which conceivably can exercise their influence on the side chain reaction center by a combination of both resonance and inductive interactions.

This comparison of the magnitude of effects in alicyclic and aromatic cases emphasizes once again that the substituent effect in the former could not have been induced through the hydrocarbon chain alone. Comparable rate effects in γ - or δ -substituted aliphatic functions simply cannot be realized (even though the substituent isn't any further removed from the reaction site than in the aromatic case), except those which originate from neighboring group participation²⁶, as was pointed out earlier in this discussion. Another instance of this can be perceived in the fact that the rate for the *endo*-dicarboxylic acid is greater than that for the *exo*, a relationship which is opposite to that of the dicarboxylic anhydrides. This reversal is in all likelihood due to the occurrence of anchimeric assistance or bridged stabilization resulting in the formation of a lactone from the *endo*-dicarboxylic acid. The corresponding *exo* isomers show no tendency toward lactone formation.³⁷

The inductive retardation afforded by an *endo*-carboxylic group is probably much greater than the *exo* and the greater reaction rate observed for the *endo* may indicate the extent of rate compensation *via* neighboring group participation.

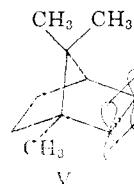
The consistent rate-retarding effect of the methyl substituent is perhaps puzzling, although the methyl derivatives (except for the dimethylcyclohexene) do not deviate from the inductive free energy correlation (Fig. 1) in an unusual manner. The 4-*t*-butylcyclohexene, while reacting more slowly than cyclohexene, reacted more

rapidly than 4-methylcyclohexene as predicted by the inductive substituent constants. If there were any steric inhibition by the alkyl substituents, the greatest interference would have been probably anticipated from the substitution of a methyl radical for one of the hydrogen atoms in an alkyl substituent, as in the change from methyl to tertiary butyl.

The effect of transannular methyl groups is reminiscent of the results of Brown, *et al.*,³⁸ for the unimolecular solvolysis of the 2-, 3- and 4-methyl derivatives of 1-methylcyclohexyl chloride. The inductive effect of the second methyl substituent should have served to accelerate the reaction, and the inductive effect should have increased as the substituent was brought closer to the leaving group. Indeed, the solvolysis rate did increase as the methyl group was moved from the 4- to the 3- to the 2-position, but the 3- and 4-methyl derivatives slightly decreased the rate relative to the unsubstituted 1-methylcyclohexyl chloride.

In the norbornene series, where a single methyl substituent is rate retarding, the *exo*-trimethylene accelerates the reaction. In this instance a decrease in the rate might have been expected, since the *exo*-trimethylene substituent decreases the anchimeric assistance afforded through σ -bond delocalization at C₄ in the solvolysis of *exo*-trimethylene-2-*exo*-norbornyl compounds.^{29b} If there is any inhibition of anchimeric assistance in the sulfonylation, it seems to be more than overcome by the favorable inductive effect of the methylene groups restrained in the substituent cyclopentane ring.

Admittedly these rate effects are quite small, but the usual electronic effects of alkyl substituents are found to be small because of the small σ_I -values. When alkyl is exercising its influence sterically the effects observed are dramatically greater. We have demonstrated this point by means of a rough determination of the rate of addition to bornylene V (where the sample on hand was slightly impure). The initial rate constant was estimated to be 2.5×10^{-5} l./mole sec., only 0.00017 times the norbornene rate constant. The very much slower reaction was unquestionably due in part to the steric hindrance of the *syn*-methyl group on the bridge, but the cumulative inductive influence of three methyl groups located close to the π -lobes in V cannot be ruled out as a rate governing factor (see discussion below).



The consequences of moving the alkyl substituent a little closer to the double bond were briefly investigated with an eye to demonstrating how close we were to the "steric precipice" we had exceeded in the case of bornylene. For this purpose we

(35) C. G. Swain and W. P. Langsdorf, *J. Am. Chem. Soc.*, **73**, 2813 (1951), give an extensive discussion of this matter.

(36) Henbest and Nicholls⁹ have reported second-order rate constants for the peroxidation of *endo*-5-substituted norbornenes. We have attempted to apply eq. 2 to their data where anchimeric assistance did not clearly occur. A satisfactory correlation could be obtained for only four of the five points, giving an approximate value of -1.3 for ρ_I .

(37) See, for example, C. D. Ver Nooy and C. S. Rondstedt, *J. Am. Chem. Soc.*, **77**, 3583, 4878 (1955), where this difference in behavior is constituted as an excellent method of isomer separation.

(38) H. C. Brown, R. S. Fletcher and R. B. Jollanesen, *ibid.*, **73**, 212 (1951).

loaded the dice by examining the case of the sterically sensitive *t*-butyl group. The rate constant for the sulfonation of 3-*t*-butylcyclohexene was determined to be 3.36×10^{-3} l./mole sec., representing a decrease of only *ca.* 70% from the rate for the 4-*t*-butyl isomer. Clearly, an effect of this order is not to be identified with such sudden change in transition state structure occasioned, for example, by moving a *t*-butyl group from a *m*- to an *o*-position on the aromatic ring.

One possible explanation of the variability in the nature of the alkyl group inductive effect is: The field effect of the unsolvated alkyl group, transmitted through unsolvated intramolecular space, is actually the electron-attracting effect of the hydrogens lying on the periphery of the freely rotating and vibrating group. The net effect is a spherical dipole which is positive at its periphery and negative at its core.³⁹ Under these circumstances it behaves as a positive layer interposed in a low dielectric space between a remote reaction site and the negative carbon contra-layer.

On the other hand, the inductive effect of the methylenes in the relatively rigid trimethylene norbornene substituent is focused at the negative carbon centers of the group and may be transmitted *via* a chain of atoms as an electron-releasing influence. Work presently in progress in our laboratories is intended to test these possibilities.

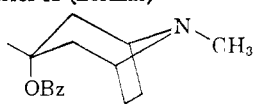
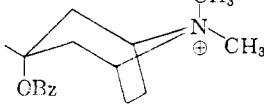
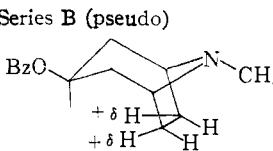
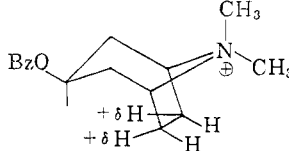
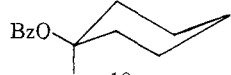
However, mere rigidity cannot determine the magnitude and direction of the alkyl inductive effect. It is possible that a lack of flexibility and free rotation can actually result in the orientation of the C-H dipoles in such fashion as to produce an electron-attracting effect even greater than the effect of an unconstrained methyl group on the rate, as noted above. An example of this can be deduced from data obtainable in the literature⁴⁰ and summarized in Table III.

Therein, it can be perceived that the substitution of methyl on the tropinol nitrogen, which confers a positive charge, has a *ca.* 20-fold greater effect in the series A where the ester is axial and therefore in closer proximity to the inductive center than in series (B) where the ester group is equa-

(39) This assumes that the effective dipole is only the consequence of the ionic character of each carbon-hydrogen bond, which has been characterized as $\mu = 1.53$ D., C-H⁺, by C. A. Coulson, *Trans. Faraday Soc.*, **38**, 433 (1942), rather than the opposing contribution of the covalent bond which is the result of the imbalance of a single *sp*³ orbital of the carbon overlapping with the spherical *s* orbital of the hydrogen.

(40) H. C. Beyerman, C. M. Siegman, F. L. J. Sixma and J. H. Wisse, *Rec. trav. chim.*, **75**, 1445 (1956).

TABLE III
RELATIVE RATES IN TROPINOL BENZOATE HYDROLYSIS IN
DIOXANE-WATER (3:2) SOLVENT MEDIUM AT 25°

Series A (normal)		
Rel. rate	1	2500
Series B (pseudo)		
Rel. rate	63	9300
		10

torial. However, the absolute rate of hydrolyses of corresponding equatorial esters (series B) are from *ca.* 4 to 60 times faster than the axial because of a combination of steric hindrance factors to which the mechanism of hydrolysis of esters is usually very sensitive.

Comparison of the rates of the equatorial esters with that of cyclohexyl benzoate in which the ester function is also equatorial points up the accelerating field effect of the ethylene bridge quite convincingly. For instance, the factor of more than 6 which distinguishes cyclohexyl benzoate from the uncharged pseudo-tropinol ester indicates that the (here) electron-attracting influence of the ethylene bridge is even large enough to overcome the opposing electron-releasing influence of the heteroatom in the ring. As illustrated on the figures in Table III this result may be explained as the effect of the positive hydrogen terminals of the bridges ethylene dipoles projecting (rigidly) into the intraannular space toward the ester function.

Acknowledgment.—The authors are indebted to the National Science Foundation for support of this project under grant NSF-G 6037 and to various people who contributed their assistance in securing several of the compounds used in the kinetic measurements; Mr. Harold Feller, Dr. A. N. Hoffman, Mr. T. McCaffrey, Mr. P. McGrath and Dr. P. v. R. Schleyer.