

## CHEMICAL EFFECTS OF STERIC STRAINS—XIV

### THE EFFECT OF RING SIZE ON THE RATE OF REACTION OF THE CYCLANONES WITH SODIUM BOROHYDRIDE

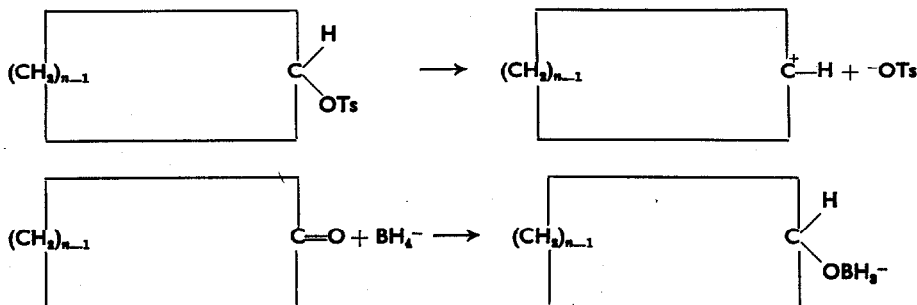
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**Abstract**—The rates of reaction of sodium borohydride with a number of cyclanones (4-, 5-, 6-, 7-, 8-, 9-, 10-, 11-, 12-, 13-, 15-, and 17-ring members) were determined at several temperatures in order to ascertain the effect of ring size on the reactivity of the carbonyl group. *Cyclobutanone* is the most reactive of the ketones examined, followed closely by *cyclohexanone*. *Cyclopentanone* is considerably less reactive, followed a sharp drop in reactivity in the 7-, 8-, 9-, and 10-ring derivatives. The rate reaches a minimum in the 10-ring and then increases with the larger rings to the value exhibited by the open-chain derivative, di-*n*-hexylketone. The trends in reactivity are very similar to those observed in the equilibrium constants for cyanohydrin formation and in other reactions of ring derivatives. The results agree with the predicted effects of ring size on the magnitude of the internal strains (I-strain).

THE reactivities of ring compounds exhibit a remarkable dependence upon the size of the rings.<sup>1,2</sup> This dependence of the reactivity upon the size of the ring has been attributed to the changes in internal strain accompanying the formation or breaking of a bond to the ring atom in the rate-determining stage.<sup>3-5</sup>

According to this proposal, opposite effects of ring size should be observed in reactions involving the breaking of a bond, such as in the acetolysis of tosylates, and in reactions involving the making of a bond, such as in the reduction of ketones.



Data on the effect of ring size on the rate of solvolysis of cyclanyl tosylates are now available.<sup>6,7</sup> However, rate data for the reactions of ketones are available only for the

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<sup>1</sup> V. Prelog *J. Chem. Soc.* 420 (1950).

<sup>2</sup> J. D. Roberts and V. C. Chambers *J. Amer. Chem. Soc.* 73, 5034 (1951).

<sup>3</sup> H. C. Brown, R. S. Fletcher, and R. B. Johannesen *Ibid.* 73, 212 (1951).

<sup>4</sup> H. C. Brown and M. Borkowski *Ibid.* 74, 1894 (1952).

<sup>5</sup> P. D. Bartlett *Bull. Soc. Chim.* C100 (1951).

<sup>6</sup> R. Heck and V. Prelog *Helv. Chim. Acta.* 38, 1541 (1955).

<sup>7</sup> H. C. Brown and G. Ham *J. Amer. Chem. Soc.* 78, 2735 (1956).

TABLE 1. RATE CONSTANTS AND DERIVED DATA FOR THE REACTION OF THE CYCLANONES WITH SODIUM BOROHYDRIDE IN ISOPROPYL ALCOHOL SOLUTION

| $(\text{CH}_2)_{n-1} \text{C}=\text{O}$ | Temp.<br>(°C) | Rate constant<br>$k_2 \times 10^4$<br>(l. mole <sup>-1</sup> sec <sup>-1</sup> ) | $E_{\text{act.}}$<br>(kcal<br>mole <sup>-1</sup> ) | log $A$ , | $\Delta H^\ddagger$<br>(kcal<br>mole <sup>-1</sup> ) | $\Delta S^\ddagger$<br>(e.u.) |
|---|---------------|--|--|-----------|--|-------------------------------|
| 4                                       | -24.1         | 56.9   | 8.6  | 5.4       | 8.1  | -36.4                         |
|   | -14.5         | 115  |  |           |  |                               |
|   | 0.1           | 266  |  |           |  |                               |
| 5                                       | 0.0           | 7.01   | 9.8  | 4.7       | 9.3  | -38.8                         |
|   | 25.0          | 31.8   |  |           |  |                               |
|   | 35.1          | 54.1   |  |           |  |                               |
| 6                                       | -23.7         | 61.7   | 5.8  | 2.9       | 5.1  | -48.1                         |
|   | -9.2          | 115  |  |           |  |                               |
|   | 0.0           | 161  |  |           |  |                               |
| 7                                       | 0.0           | 1.02   | 10.2   | 4.1       | 9.6  | -41.6                         |
|   | 25.0          | 4.90   |  |           |  |                               |
|   | 35.1          | 8.54   |  |           |  |                               |
| 8                                       | 0.0           | 0.0781   | 11.9   | 4.4       | 11.3   | -41.2                         |
|   | 25.0          | 0.411  |  |           |  |                               |
|   | 35.1          | 0.963  |  |           |  |                               |
| 9                                       | 25.0          | 0.203  | 12.2   | 4.3       | 11.6   | -41.4                         |
|   | 35.1          | 0.381  |  |           |  |                               |
|   | 45.0          | 0.732  |  |           |  |                               |
| 10                                      | 25.0          | 0.103  | 13.1   | 4.6       | 12.6   | -43.5                         |
|   | 35.1          | 0.218  |  |           |  |                               |
|   | 45.0          | 0.416  |  |           |  |                               |
| 11                                      | 25.0          | 0.152  | 12.0   | 4.0       | 11.4   | -42.4                         |
|   | 35.1          | 0.290  |  |           |  |                               |
|   | 45.1          | 0.537  |  |           |  |                               |
| 12                                      | 25.0          | 1.05   | 11.3   | 4.3       | 10.7   | -41.0                         |
|   | 35.1          | 1.98   |  |           |  |                               |
|   | 45.1          | 3.42   |  |           |  |                               |
| 13                                      | 0.0           | 0.194  | 11.8   | 4.7       | 11.1   | -39.2                         |
|   | 25.0          | 1.22   |  |           |  |                               |
|   | 35.0          | 2.22   |  |           |  |                               |
| 15                                      | 0.0           | 0.420  | 11.5   | 4.9       | 10.8   | -38.9                         |
|   | 25.0          | 2.41   |  |           |  |                               |
|   | 35.1          | 4.61   |  |           |  |                               |
| 17                                      | 0.0           | 0.583  | 10.7   | 4.4       | 10.2   | -40.5                         |
|   | 25.0          | 3.07   |  |           |  |                               |
|   | 35.0          | 5.56   |  |           |  |                               |
| Di- <i>n</i> -hexyl<br>ketone           | 25.0          | 2.67   | 11.5   | 4.9       | 10.8   | -38.8                         |
|   | 35.1          | 5.05   |  |           |  |                               |
|   | 45.0          | 9.00   |  |           |  |                               |

5- and 6-membered rings.<sup>9</sup> The reaction of sodium borohydride with aldehydes and ketones is a kinetically simple reaction which promises to be of considerable utility in examining the reactivity of these compounds.<sup>9</sup> It appeared desirable therefore, to undertake a detailed study of the rates of reaction of sodium borohydride with a wide range of cyclic ketones.

### RESULTS

The cyclanones (4-, 5-, 6-, 7-, 8-, 9-, 10-, 11-, 12-, 13-, 15- and 17-ring members) were either commercially available products or were synthesized by recognized literature procedures. In each case the compounds were carefully purified prior to use. The rates of reaction were run in *isopropyl* alcohol solution by the procedure previously described.<sup>9</sup>

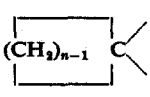
For comparison of the rates observed for the large rings with those anticipated for related open-chain structures, di-*n*-hexyl ketone was included in the study.

The results are summarized in Table 1.

### DISCUSSION

To facilitate ready comparison, the rate constants at 0° for the borohydride reduction reaction are listed in Table 2. Previously available data for the solvolysis of the 1-chloro-1-methylcycloalkanes,<sup>4</sup> the cyclanyl tosylates,<sup>6,7</sup> and the dissociation of the cyclic cyanohydrins<sup>10</sup> are also included.

TABLE 2. EFFECT OF RING SIZE ON RATE AND EQUILIBRIUM CONSTANTS OF CYCLIC DERIVATIVES

|  | Borohydride <sup>(a)</sup><br>reduction<br>$k_2 \times 10^4$<br>(l. mole <sup>-1</sup> sec <sup>-1</sup> ) | Cyanohydrin <sup>(b)</sup><br>dissociation, 22-23°<br>(keq., mole l. <sup>-1</sup> ) | Solvolysis <sup>(c)</sup><br>of tosylates, 70°<br>( $k_1 \times 10^8$ sec <sup>-1</sup> ) | Solvolysis <sup>(d)</sup> of<br>1-chloro-1-methyl-<br>cycloalkanes, 25°<br>( $k_1 \times 10^8$ hr <sup>-1</sup> ) |
|--|--|--|---|---|
| <i>n</i>   |  |  |   |   |
| 4  | 264  |  | 26.7  | 0.224   |
| 5  | 7.01   | 0.021  | 32.2  | 132   |
| 6  | 161  | 0.001  | 2.37  | 1.06  |
| 7  | 1.02   | 0.13   | 60.0  | 115   |
| 8  | 0.0781   | 0.86   | 452   | 303   |
| 9  | 0.0316 <sup>(e)</sup>  | 1.70   | 408   | 46.5  |
| 10   | 0.0132 <sup>(e)</sup>  |  | 891 <sup>(e)</sup>  | 18.8  |
| 11   | 0.0235 <sup>(e)</sup>  | 1.12   | 116   | 12.7  |
| 12   | 0.182 <sup>(e)</sup>   | 0.31   | 7.70  |   |
| 13   | 0.194  | 0.26   | 8.30  | 3.02  |
| 14   |  | 0.06   | 3.12  |   |
| 15   | 0.420  | 0.11   | 5.18  | 1.92  |
| 16   |  | 0.09   |   |   |
| 17   | 0.593  | 0.12   | 5.15  | 2.01  |
| R <sub>2</sub> CO  | 0.454 <sup>(e), (f)</sup>  |  | 3.15 <sup>(g)</sup>   | 4.80 <sup>(h)</sup>   |

<sup>(a)</sup> This study. <sup>(b)</sup> Dissociation of cyanohydrin in 96 per cent ethanol (ref. 11). <sup>(c)</sup> Acetolysis of cyclanyl tosylates (ref. 7, 8). <sup>(d)</sup> Solvolysis in 80 per cent aqueous ethanol (ref. 5). <sup>(e)</sup> Calculated from data at other temperatures. <sup>(f)</sup> Di-*n*-hexylketone. <sup>(g)</sup> Di-*n*-octylketone. <sup>(h)</sup> Di-*n*-propylcarbonyl tosylate. <sup>(i)</sup> Di-*n*-amylmethylcarbonyl chloride.

<sup>8</sup> F. P. Price, Jr. and L. P. Hammett *Ibid.* 63, 2387 (1941).

<sup>9</sup> H. C. Brown, O. H. Wheeler, and K. Ichikawa *Tetrahedron* 1, 214 (1957).

<sup>10</sup> V. Prelog and M. Kobelt *Helv. Chim. Acta* 32, 1187 (1949).

It was previously suggested that the normal bond angle for a carbon atom with co-ordination number 3, as in carbonyl derivatives ( $> C=O$ ) and carbonium ions ( $> C^+-H$ ), would be expected to be  $120^\circ$ , as compared to the  $109.5^\circ$  for the normal tetrahedral value. Consequently, the deformation of the angle at the carbonyl carbon atom ( $120^\circ \rightarrow \sim 90^\circ$ ) must be greater than the corresponding deformation for a tetrahedral carbon atom ( $109.5^\circ \rightarrow \sim 90^\circ$ ). It is reasonable to expect that the larger angular deformation will result in a greater strain. Conversion of the carbonyl carbon to a tetrahedral derivative should relieve this additional strain. On this basis it was predicted that reactions of *cyclobutanone* in which the carbonyl carbon atom undergoes transformation from co-ordination number 3 to 4 in the rate-determining step should be strongly favored.<sup>3</sup> In this discussion it is tacitly assumed that the bond oppositions in the *cyclobutane* system are relatively small and may be ignored in view of the large change in angular strain accompanying the change in the configuration of the ring atom.

The rate constant for the reaction of *cyclobutanone* with sodium borohydride is far larger than that for an open-chain compound, such as acetone, and indeed is larger than that of any other ring compound here examined. This result supports the proposed role of angular strain in controlling the reactivity of 3- and 4-membered ring derivatives.<sup>3</sup>

If the change from co-ordination number 3 to co-ordination number 4 is favored in 4-ring systems, the reverse change should be resisted. This prediction is supported by the low rate of solvolysis of 1-chloro-1-methyl*cyclobutane*.<sup>4</sup> It has been pointed out that the solvolysis of *cyclobutyl* tosylate is far greater than would be anticipated on the basis of the considerations here discussed.<sup>3</sup> However, this compound solvolyzes with rearrangement, and it is probable that the solvolysis proceeds directly to the formation of a carbonium ion more stable than the *cyclobutyl* cation. The theory cannot be applied to such a case; it should be restricted to cases where the rate-determining stage depends primarily upon a simple change in the number of bonds formed by the ring atom undergoing reaction.

In the 5- and 7-ring compounds the bond angles are presumably near the tetrahedral values and angle strain is not believed to be a major factor. The strains in *cyclopentane* and *cycloheptane*, which are indicated by heats of combustion studies,<sup>11</sup> are believed to arise from bond opposition forces. On this basis, a change in co-ordination number from 4 to 3 should reduce the number of bond oppositions and the resulting strain in 5- and 7-ring systems. Such reactions should be favored in these ring systems. Conversely, *cyclopentanone* and *cycloheptanone* should resist reactions in which the carbonyl carbon is converted into a tetrahedral derivative in the rate-determining stage.

On the other hand, in *cyclohexane* all of the carbon-to-hydrogen bonds are nicely staggered and there are no bond opposition effects, whereas in *cyclohexanone* both the angle is unfavorable and two of the *alpha* carbon-to-hydrogen bonds are in partial opposition to the carbon-to-oxygen bond. These considerations lead to the conclusion that changes in co-ordination number from 4 to 3 should be favored in the 5- and 7-ring and resisted in the 6-ring systems, whereas the converse should be true for reactions involving changes in co-ordination number from 3 to 4. In confirmation of

<sup>11</sup> K. S. Pitzer *Science* 101, 672 (1945); J. E. Kilpatrick, K. S. Pitzer, and R. Spitzer *J. Amer. Chem. Soc.* 69, 2483 (1947).

this conclusion, the reduction of *cyclohexanone* is faster than that of any ring ketone other than *cyclobutanone*, with the rate for *cyclopentanone* and *cycloheptanone* being much smaller (Table 2).

The available evidence indicates that the medium rings (8- to 12-members) are highly strained,<sup>1</sup> with the strain reaching a maximum in the 10-ring compounds. These strains are believed to arise from both bond opposition forces and compressions of van der Waals radii. Consequently, these ring systems should favor reactions in which bonds to a ring atom are broken and resist reactions in which additional bonds are made. The low rate of reaction with borohydride ion, with a minimum in rate at *cyclodecanone*, is in agreement with this interpretation.

The large rings exhibit reactivities which are considerably lower than that of acetone ( $k_2$  at 0° is  $15.1 \times 10^{-4}$  l. mol.<sup>-1</sup> sec.<sup>-1</sup>), but which are comparable to the higher aliphatic ketones, such as di-*n*-hexyl ketone.

In general, the enthalpies of activation parallel the rate constants. Only in the case of *cyclohexanone* and *cyclobutanone* do the entropies of activation exhibit a wide variation from the average value of approximately -40 e.u. The higher value for *cyclobutanone*, -36.4, can be accounted for in terms of the relatively high rigidity and order of this ring system.<sup>9</sup> On this basis, the lower value for *cyclohexanone* might be attributed to a low degree of order in the parent ketone, or to a highly ordered structure in the transition state, or both.

The close similarity in the effects of ring size in the various reactions is indicated in Figs. 1-4. In order to facilitate comparison, the ordinates have been fixed so as to place the points for the 4- and 6-ring systems (either the most reactive, or the least reactive compounds) at the bottom of the diagrams. The remarkable similarity in the effects of ring size on chemical behavior argues for a common factor. This common factor is believed to be the change in internal strain accompanying the change in the co-ordination number of the ring atom undergoing reaction.

The internal strain is made up of several types of interactions: (1) compression of van der Waals radii, (2) the distortion of bond angles, and (3) bond opposition forces.<sup>7</sup> Reactions which proceed with a net decrease in internal strain in the transition state should be favored; those which proceed with a net increase in such strain will be hindered. Ideally, the effect of making or breaking a bond to one of the ring atoms should be analyzed in terms of each of the above strain factors. In actual fact, such an analysis is not possible at the present time. The individual strains are not mutually independent, nor can they be estimated separately with any accuracy at the present time.

On the other hand, the net change in internal strain accompanying the making or breaking of a bond to a ring atom can be estimated with considerable precision. Consequently, it appears desirable to discuss the effect of ring size on chemical behavior in terms of the net change in internal strain accompanying the reaction (I-strain).

It should be recognized that I-strain effects will not be the only factor influencing chemical behavior of ring compounds. It is only claimed that it is an important factor, and in the simple systems here examined it appears to be a dominant factor.

In three of the four reactions considered in Table 2, the maximum or the minimum in the behavior of the system appears at the 10-ring derivative. This behavior is in accord with the evidence that the internal strain is a maximum in the 10-ring compounds.

It is of interest to explore the exception, the solvolysis of the 1-chloro-1-methylcyclohexanes, where the maximum in rate appears at the 8-ring compound.

Examination of molecular models of the medium rings suggest that compression of van der Waals radii may be involved in the internal strain as well as the bond opposition

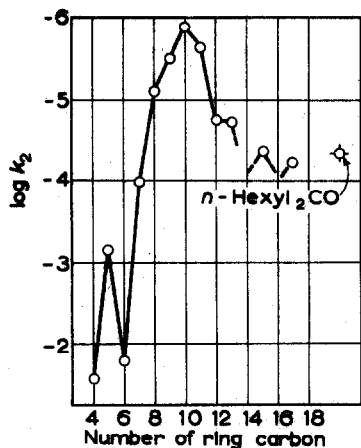


FIG. 1. Effect of ring size on the rate of reaction of sodium borohydride with the cyclanones in isopropyl alcohol at 0°.

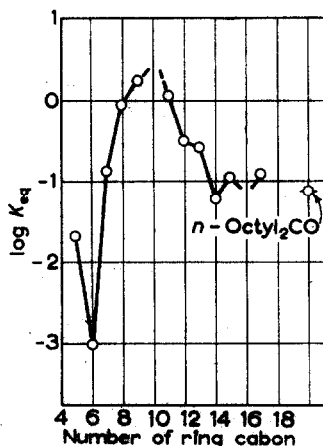


FIG. 2. Effect of ring size on the equilibrium constant for the dissociation of the cyclic cyanohydrins in 96 per cent ethanol at 22-23°.

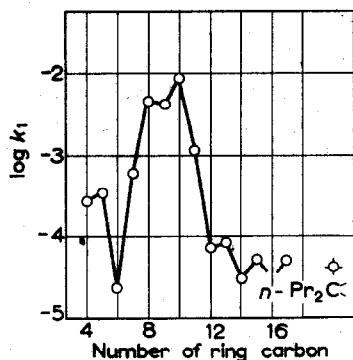


FIG. 3. Effect of ring size on the acetolysis of the cyclanyl tosylates at 70°.

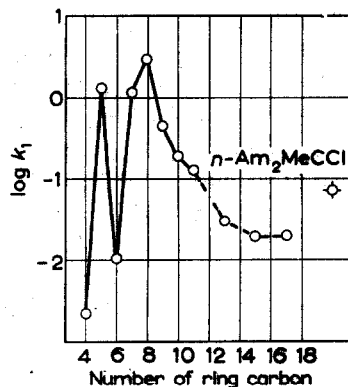


FIG. 4. Effect of ring size on the solvolysis of the 1-chloro-1-methyl-cyclohexanes in 80 per cent aqueous ethanol at 25°.

forces. On this basis, the introduction of both a methyl group and a chlorine atom on the same carbon atom of a given cyclane molecule may be expected to alter both the internal compressions and the bond opposition forces. There is no reason to expect that both these forces will be equally affected, and the relative magnitude of each effect may vary considerably with the size of the ring and the steric requirements of the substituents.

It would appear that the larger the ring the greater should be its possibilities for modifying its conformation and minimizing the magnitude of the atomic compressions. The maximum observed in the solvolysis of 1-chloro-1-methylcyclo-octane may therefore be attributed to relatively large strains arising from the conflicting steric requirements of the two substituents and the ring hydrogen atoms, superimposed upon the usual bond opposition forces. These atomic compressions are presumably also present in the 10- and 9-ring derivatives, but are reduced to a greater extent than in the smaller ring by modification of the conformation. Conceivably, the maximum in rate could be shifted down as far as the 7-ring, or even further, by a suitable increase of the steric requirements of the substituents.

In general, linear free-energy relationships, such as those pointed out by Hammett for *meta* and *para* aromatic derivatives,<sup>12</sup> are rarely encountered in other than the rigid aromatic systems. The similarity in the structural effects in these ring compounds (Figs. 1-4), encourages an examination of the data from this point of view.

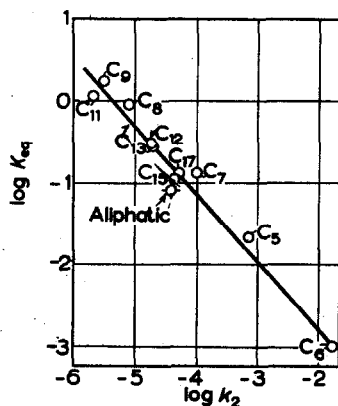
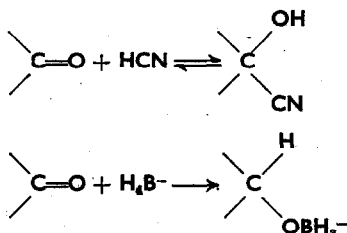


FIG. 5. Free-energy relationship between the equilibrium constants for the dissociation of the cyclic cyanohydrins and the rate constants for the reaction of the cyclanones with sodium borohydride.

Comparison of the equilibrium data for the dissociation of the cyanohydrins with the rate data for the borohydride reaction reveals a reasonably good linear relationship (Fig. 5). The fit is unexpectedly good for systems of this kind and presumably should be attributed to the similarity in the two reactions under comparison.



Comparison of the rate data for the acetolysis of the cyclic tosylates with the rate data for the borohydride reaction also reveals a rough linear relationship for the 5- to 10-ring derivatives (Fig. 6). Larger rings deviate from this relationship and so do

<sup>12</sup> L. P. Hammett *Physical Organic Chemistry* McGraw-Hill, New York (1940).

related aliphatic compounds. The two reactions under comparison must have significantly different steric requirements, so that the deviations are not unexpected.

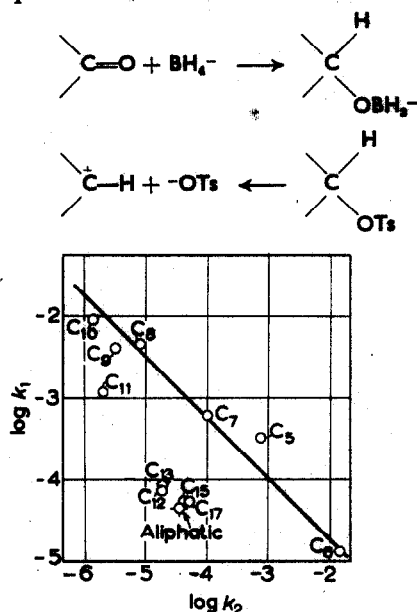


FIG. 6. Free-energy relationship between the rate constants for the acetolysis of the cyclic tosylates and the rate constants for the reaction of the cyclanones with sodium borohydride.

It is the existence of a limited linear relationship for the six consecutive ring systems, 5- through 10-, which must be considered unexpected. The fit, rough as it is, appears to be too good to be considered purely fortuitous. It may be that the fit arises from the fact that the rings from 5- through 10-members are relatively rigid, with comparatively fixed conformations, resembling the aromatic structures in that characteristic, whereas the larger rings possess greater mobility of conformation and more closely resemble aliphatic derivatives.

Carrying the comparison further to the tertiary chlorides, we observe that no linear relationship is indicated (Fig. 7). Presumably this is the result of the much larger steric requirements of the methyl and chlorine substituents in the smaller rings, giving rise to larger strains and enhanced solvolysis rates.

As was pointed out, these effects should be less in the larger rings. Presumably these steric interactions result in the points for the 5-, 6-, 7-, and 8-rings being considerably higher than they would otherwise appear in the plot and thereby destroy the linear relationship which might exist in the absence of this effect.

The existence of a limited linear relationship for the solvolysis of the cyclic tosylates and the reaction of the cyclanones with borohydride may have important consequences. A number of strained substances are known which exhibit enhanced rates of solvolysis. In some cases the enhanced rates have been attributed to relief of steric strain.<sup>13</sup> In others, the enhanced rates have been attributed to the formation of unusually stable "non-classical" ions.<sup>14</sup> A rigorous test of the relative importance of these factors in

<sup>13</sup> H. C. Brown *J. Chem. Soc.* 1248 (1956).

<sup>14</sup> S. Winstein *Bull. Soc. Chim.* 18, 55 (1951).



various systems has been rendered difficult by the transient nature of these carbonium ions.

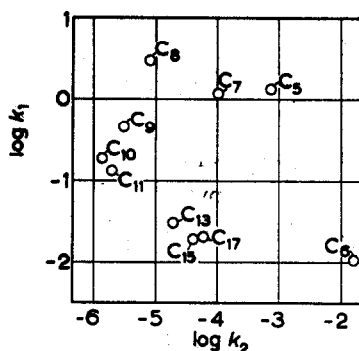


FIG. 7. Free-energy relationship between the rate constants for the solvolysis of the 1-chloro-1-methylcycloalkanes and the rate constants for the reaction of the cyclanones with sodium borohydride.

Conceivably, the carbonyl derivatives may provide relatively stable models of carbonium ions of related structures.

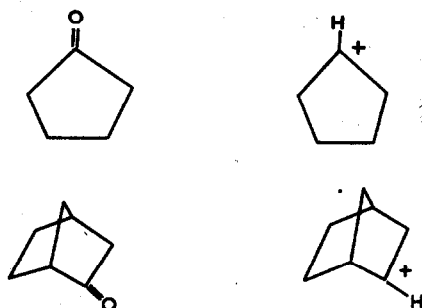
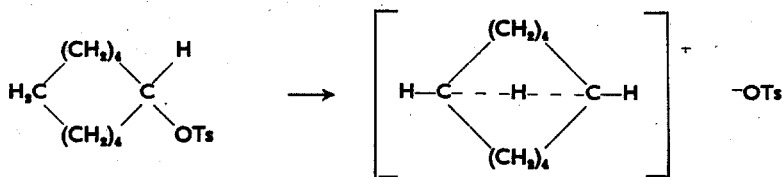


FIG. 23a.

For example, we have attributed the high rate of solvolysis of *cyclodecyl* tosylate to relief of internal strain accompanying the ionization. On the other hand, the alternative possibility that the high rate is due to the formation of a relatively stable "non-classical" *cyclodecyl* cation has been considered.<sup>6</sup>



Such a structure would, of course, provide a reasonable explanation for the facile transannular hydride shifts which are observed in this ring system.<sup>15</sup>

However, from Fig. 6 it appears that the high rate of solvolysis of *cyclodecyl* tosylate is not out of line with the low reactivity of *cyclodecanone*. Since "non-classical" structures for this cyclic ketone are of questionable importance, it does not

<sup>15</sup> V. Prelog and K. Schenker *Helv. Chim. Acta* 35, 2044 (1952).  
V. Prelog, K. Schenker, and W. Kung *Ibid.* 36, 471 (1953).

appear desirable in the absence of additional evidence to attribute the high reactivity of cyclodecyl tosylate to this type of stabilization of the cyclodecyl cation.

We are presently investigating this experimental approach, utilizing the carbonyl compounds as models for related carbonium ions, in the hope of attaining a more complete understanding of the factors influencing the rates of formation and the stability of carbonium ions.

#### EXPERIMENTAL PART

*Materials.* The purifications of isopropyl alcohol and sodium borohydride have been described previously.<sup>9</sup> The carbonyl compounds were either commercial samples, carefully purified, or were synthesized by standard procedures. The physical properties of the cyclic ketones used in the rate measurements are summarized in Table 3.

TABLE 3. PHYSICAL PROPERTIES OF CYCLANONES

| $\begin{array}{c} \text{---} \\   \\ \text{---} \end{array} \begin{array}{c} \text{---} \\   \\ \text{---} \end{array} \text{C=O}$ | B.p. (°C/mm) |                           | M.p. (°C) |                      | $n_D^{20}$ |                                |
|--|--------------|---------------------------|-----------|----------------------|------------|--------------------------------|
|  | Obsd.        | Lit.                      | Obsd.     | Lit.                 | Obsd.      | Lit.                           |
| <i>n</i>   |              |                           |           |                      |            |                                |
| 4  | 98.2/743     | 98-100/760 <sup>(a)</sup> |           |                      | 1.4209     | 1.4189(25°) <sup>(a)</sup>     |
| 5  | 130.5/744    | 129.5/761 <sup>(b)</sup>  |           |                      | 1.4363     | 1.4370-<br>1.4373 <sup>c</sup> |
| 6  | 153.8/744    | 155.7/760 <sup>(d)</sup>  |           |                      | 1.4502     | 1.45066(19.3°) <sup>(e)</sup>  |
| 7  | 180.0/744    | 66-70/16 <sup>(f)</sup>   |           |                      | 1.4610     | 1.4608 <sup>(f)</sup>          |
| 8  |              |                           | 43.5      | 43.8 <sup>(g)</sup>  |            |                                |
| 9  | 97.5/15      | 92-95/12 <sup>(h)</sup>   |           |                      | 1.4475     | 1.4730(17°) <sup>(i)</sup>     |
| 10   |              |                           | 24.5-25   | 20-22 <sup>(j)</sup> |            |                                |
| 11   | 106/10       | 108/10 <sup>(j)</sup>     |           |                      | 1.4810     | 1.4786(17°) <sup>(j)</sup>     |
| 12   |              |                           | 61-62     | 60-61 <sup>(k)</sup> |            |                                |
| 13   |              |                           | 29.5-30.5 | 30-32 <sup>(k)</sup> |            |                                |
| 15   |              |                           | 63        | 63 <sup>(l)</sup>    |            |                                |
| 17   |              |                           | 65        | 63 <sup>(l)</sup>    |            |                                |

<sup>(a)</sup> J. D. Roberts and C. W. Sauer *J. Amer. Chem. Soc.* 71, 3925 (1949). <sup>(b)</sup> I. Vogel *J. Chem. Soc.* 2030 (1928). <sup>(c)</sup> E. R. Johnson and W. D. Walters *J. Amer. Chem. Soc.* 76, 6266 (1954). <sup>(d)</sup> J. Timmermans and H. Roland *J. Chem. Phys.* 34, 693 (1937). <sup>(e)</sup> W. Herz and W. Bloch *Z. physik. Chem.* 104, 433 (1923). <sup>(f)</sup> R. H. Cox *J. Amer. Chem. Soc.* 74, 2924 (1952). <sup>(g)</sup> E. P. Kohler, M. Tishler, H. Potter, and H. T. Thompson *Ibid.* 61, 1057 (1939). <sup>(h)</sup> V. Prelog, L. Frenkiel, M. Kobelt, and P. Barman *Helv. Chim. Acta* 30, 1741 (1947). <sup>(i)</sup> L. Ruzicka and W. Brugger *Ibid.* 9, 399 (1928). <sup>(j)</sup> L. Ruzicka, M. Stoll, and H. Schinz *Ibid.* 9, 249 (1928). <sup>(k)</sup> L. Ruzicka, M. Stoll, H. W. Huyser, and H. A. Bockenoogen *Ibid.* 13, 1152 (1930).

*Kinetic measurements.* The experimental procedure was identical with that reported previously.<sup>9</sup> The temperatures were controlled to less than  $\pm 0.02^\circ$  except for temperatures below  $0^\circ$ , where the variation was of the order of  $\pm 0.1^\circ$ . Several individual determinations, with varying initial concentrations of reactants, were carried out for a number of the compounds. In these cases the individual rate constants usually agreed to within 1 per cent. The quality of the agreement realized was similar to that reported in Table 1.<sup>9</sup> Where multiple determinations were available, the mean values of the second-order rate constants are reported in Table 1. For the less accessible ring derivatives, the value of the material made it advisable to restrict our measurements to a single kinetic run at each temperature.