Tricyclo[3.2.1.0^{3,6}]octan-7-yl Derivatives. Synthesis, Chemistry, and Solvolytic Studies[1]

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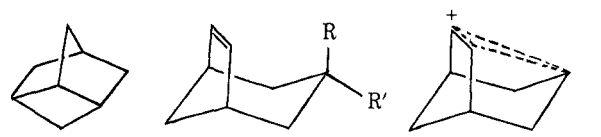
An intramolecular, base-catalyzed ring closure of *exo*-bicyclo[3.2.1]octan-6-on-3-yl tosylate (**6**) furnished the symmetrical ketone, tricyclo[3.2.1.0^{3,6}]octan-7-one (**4**), in good yield. The bicyclic precursor **6** was prepared from dehydronorcamphor by the sequence: dichlorocarbene addition and ring expansion, reductive removal of the two chlorine atoms, and introduction of the exo-C_3 oxygen atom by hydroboration–oxidation. The stereoselective and regioselective nature of the hydroboration reaction was established unambiguously. Wolff–Kishner reduction of ketone **4** gave the known parent hydrocarbon. Baeyer–Villiger oxidation of **4** gave a single lactone resulting from formal migration of the cyclobutane ring. Product distribution and deuterium label scrambling results suggest that solvolysis of tricyclo[3.2.1.0^{3,6}]octan-7-yl tosylate proceeds through a symmetrical, degenerate tricyclic cation to yield both tricyclic and bicyclic products.

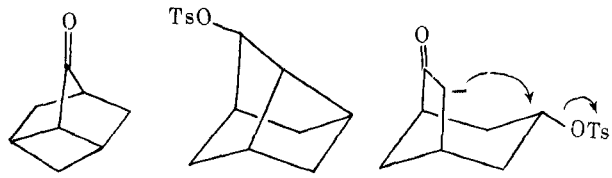
Concurrent interest in synthetic approaches to polycyclic skeletons common to naturally occurring systems and in the nature of cationic interconversions within the tricyclooctane–bicyclooctene carbon systems led to an examination of C_7-functionalized derivatives of tricyclo[3.2.1.0^{3,6}]octane (**1**). Considerable attention has been focused on the nature and scope of carbonium ion rearrangements in the various bicyclooctene systems.[2-5] In particular, the possibility of remote (homoallylic) double bond participation during solvolysis of *exo*- (and *endo*-) bicyclo[3.2.1]oct-6-en-3-yl tosylate (**2**) to give cation **3** as an intermediate has been examined.[6] No evidence for the postulated participation, however, was observed in these systems.[6] In contrast, ionization of C_7-substituted derivatives of **1** provides a direct route to the potentially degenerate tricyclic cation **3**. Herein we report the synthesis and some reactions of the symmetrical tricyclo[3.2.1.0^{3,6}]-octan-7-one (**4**) and the solvolytic behavior of the C_7 tosylate **5**.

Since the known synthetic entries[7-10] into the tricyclo[3.2.1.0^{3,6}]octane system are not suited for the preparation of C_7-functionalized derivatives, our initial synthetic efforts were directed toward the preparation of the key bicyclic intermediate, *exo*-bicyclo[3.2.1]-octan-6-on-3-yl tosylate (**6**). Formation of the tricyclic skeleton of **4** was then envisioned *via* a base-catalyzed intramolecular[11] ring closure (see arrows, **6**), a process requiring the exo-C_3 leaving group shown.[12]

As a first step, the carbonyl group of dehydronorcamphor (**7**) was protected by acid-catalyzed conversion to the ethylene ketal **8**. The possibility

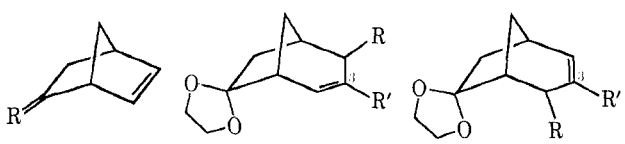


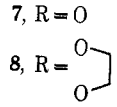
1 **2a**, R = H; R′ = OTs **3**
b, R = OTs; R′ = H



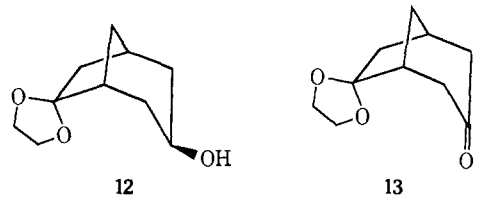
4 **5** **6**

of cationic skeletal rearrangements during ketal formation was excluded by reconversion to ketone **7**. Dichlorocarbene addition to ketal **8** followed by ring expansion[13] of the unstable dichlorocyclopropane adduct during distillation then yielded the isomeric dichlorides **9**. Sequential removal of the chlorine atoms by treatment with lithium aluminum hydride in tetrahydrofuran to give **10** and by lithium in liquid ammonia furnished the isomeric olefins **11**.



7, R = O
8, R = 

9, R = R′ = Cl
10, R = H; R′ = Cl
11, R = R′ = H



12 **13**

Examination of the bicyclo[3.2.1] skeleton of **11** suggested that an addition reaction sensitive to steric environment would ensure both the regioselectivity and the stereoselectivity required for the conversion of **11** to the C_3 exo derivative **12**. Since the C_3 position

(1) Financial support of this research by the Robert A. Welch Foundation is gratefully acknowledged.

(2) H. L. Goering and D. L. Towns, *J. Amer. Chem. Soc.*, **85**, 2295 (1963) and references cited therein.

(3) N. A. LeBel and J. E. Huber, *ibid.*, **85**, 3193 (1963).

(4) H. Kwart and J. L. Irvine, *ibid.*, **91**, 5541 (1969).

(5) J. A. Berson, J. J. Gajewski, and D. S. Donald, *ibid.*, **91**, 5550 (1969), and subsequent papers and references cited therein.

(6) N. A. LeBel and R. J. Maxwell, *ibid.*, **91**, 2307 (1969).

(7) (a) R. R. Sauers, R. A. Parent, and S. B. Damle, *ibid.*, **88**, 2257 (1966); (b) R. R. Sauers and J. C. Oppelt, *Tetrahedron*, **25**, 613 (1969); (c) P. K. Freeman and V. N. M. Rao, *Chem. Commun.*, 511 (1965).

(8) (a) R. R. Sauers, K. Kelly, and B. Sickles, 158th National Meeting of the American Chemical Society, New York, N. Y., Sept 1969, ORGN 74; (b) R. R. Sauers and B. R. Sickles, *Tetrahedron Lett.*, 1067 (1970).

(9) R. R. Sauers and R. J. Kiesel, *J. Amer. Chem. Soc.*, **89**, 4695 (1967).

(10) P. Yates and A. G. Fallis, *Tetrahedron Lett.*, 2493 (1968); F. D. Lewis and R. A. Ruden, *ibid.*, 715 (1971).

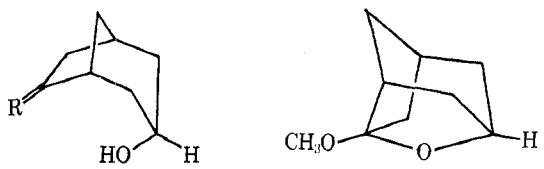
(11) *Cf.* C. H. Heathcock, R. A. Badger, and J. W. Patterson, Jr., *J. Amer. Chem. Soc.*, **89**, 4133 (1967); J. E. McMurry, *ibid.*, **90**, 6821 (1968).

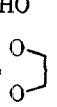
(12) A preliminary report of part of this work has appeared: S. A. Monti and S.-S. Yuan, *Tetrahedron Lett.*, 3627 (1969).

(13) C. D. Gutsche and D. Redmore, "Carbocyclic Ring Expansion Reactions," Academic Press, New York, N. Y., 1968, pp 127–155.

of **11** is the less hindered sp^2-hybridized carbon atom in both isomers and addition to the double bond should occur from the less hindered exo face,[14] both isomeric olefins **11** should yield the desired product **12**.

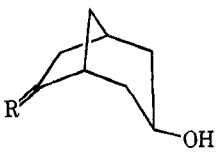
As anticipated, treatment of the olefin mixture **11** with disiamylborane,[15] followed by alkaline hydrogen peroxide oxidation, gave the C_3-exo ketal alcohol **12** in 84% yield. The skeletal position of the hydroxyl group was verified by careful oxidation[16] of **12** to give a *single* ketal ketone **13**. Exposure of **13** to deuterium oxide–potassium carbonate resulted in the incorporation of *four* deuterium atoms (mass spectrum). Thus the anticipated position selectivity was established since boron addition to C_2 or C_4 would lead ultimately to a ketal ketone (mixture) that would incorporate only two deuterium atoms. The exo orientation of the hydroxyl group in **12** was confirmed as follows. Lithium aluminum hydride reduction of ketal ketone **13** gave, as the major product, a new ketal alcohol **14**. The endo hydroxyl group assignment is based on the assumption that hydride addition will occur predominantly from the less hindered exo face.[14] This assignment was substantiated by conversion of the endo keto alcohol **15**, obtained from **14** by mild aqueous acid hydrolysis, to the cyclic ketal **16** upon treatment with anhydrous methanol,m agnesium sulfate, and a catalytic amount of *p*-toluenesulfonic acid.[17] The original exo ketal alcohol **12** was converted to keto alcohol **17** and then to the dimethyl ketal **18** when subjected to a similar reaction sequence.



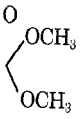
14, R = 

15, R = O

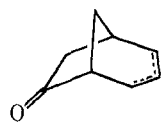
16



17, R = O

18, R = 

With the relative disposition of the functional groups now secure, the exo keto alcohol **17** was converted to tosylate **6**, the initial synthetic objective. The proposed intramolecular cyclization occurred smoothly upon treatment of a dilute benzene solution of **6** with potassium *tert*-butoxide to yield tricyclo[3.2.1.0^{3,6}]octan-7-one (**4**) in 62% yield. The spectral properties of this highly volatile solid were in complete accord with the proposed structure (see Experimental Section). Two additional products were also isolated from this reaction and they became the major products when cyclization was attempted in more concentrated solutions. Preliminary data indicate both possess at least a dimeric composition although structure elucidation is not complete. The two potential elimination products **19** (authentic samples were prepared from ketals **11**) were not formed during base treatment of tosylate **6** as judged by vpc analysis of the crude cyclization mixture. In addition, the absence of **20** or related monocyclic derivatives suggests that base-catalyzed fragmentation of **6** is not competitive with intramolecular cyclization.[18]



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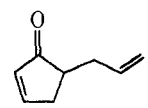

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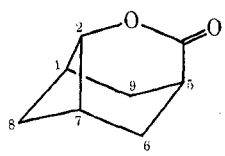
Wolff–Kishner reduction[6] of ketone **4** to the known parent hydrocarbon[7] **1** furnished final confirmation of the tricyclo[3.2.1.0^{3,6}]octane skeleton.

In connection with studies directed toward the total synthesis of cyclobutanoid terpenes, the Baeyer–Villiger oxidation of ketone **4** was examined. In theory, two lactones **21** and **22** are possible and both are derived by migration of a secondary alkyl group. Oxidation of **4** with buffered trifluoroperacetic acid yielded a single lactone in 98% yield. The general spectral properties of this material (see Experimental Section) were in accord with either formulation, **21** or **22**. An unambiguous structure assignment for the lactone was made using nmr spectroscopy.



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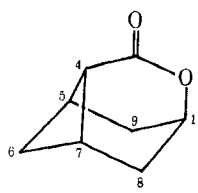

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Four distinct regions of absorptions were observed in the nmr spectrum of the lactone: δ 1.24 (1 H, doublet, J = 10 Hz), 2.0 (5 H, multiplet), 2.7 (3 H, multiplet), and 4.78 ppm (1 H, triplet, J = 5 Hz). The crucial difference between the two possible structures is that for **21**, the C_2 proton α to the oxygen atom (4.78 ppm) is coupled to the two equivalent bridgehead protons at C_1 and C_7 (2.7 ppm). For **22**, this proton (4.78 ppm) is coupled to *one* of the equivalent methylene proton pairs at C_8 and C_9 (2.0 ppm) (see respective figures for numbering). Spin decoupling at 2.7 ppm resulted in collapse of the 4.78-ppm signal to a sharp singlet; irradiation at 2.0 ppm did not affect the multiplicity of the 4.78-ppm signal but, as expected, did result in collapse of the 1.24-ppm doublet (exo proton at C_8) to a singlet. Thus, Baeyer–Villiger oxdation of the rigid ketone **4** results in preferential migration of the cyclobutyl group to yield lactone **21**.

(14) (a) R. T. LaLonde, J.-Y. Ding, and M. A. Tobias, *J. Amer. Chem. Soc.*, **89**, 6651 (1967), and references cited therein; (b) C. W. Jefford, S. N. Mahajan, and J. Gunsher, *Tetrahedron*, **24**, 2921 (1968).

(15) D. J. Pasto and F. M. Flein, *J. Org. Chem.*, **33**, 1468 (1968); E. F. Knights and H. C. Brown, *J. Amer. Chem. Soc.*, **90**, 5281 (1968); S. P. Acharya and H. C. Brown, *J. Org. Chem.*, **35**, 196 (1970).

(16) R. H. Cornforth, J. W. Cornforth, and G. Popjak, *Tetrahedron*, **18**, 1351 (1962).

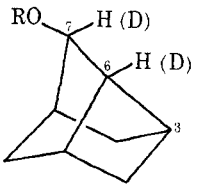
(17) The tricyclic ether skeleton of **16** is known: see ref 6 and P. Brun, M. Pally, and B. Waegall, *Tetrahedron Lett.*, 331 (1970).

(18) P. C. Mukharji and T. K. Das Gupta, *Tetrahedron*, **25**, 5275 (1969), and references cited therein.

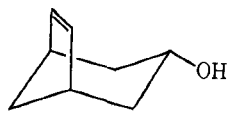
Reduction of the symmetrical ketone **4** with lithium aluminum hydride furnished the tricyclic alcohol **23** in good yield. The nmr spectra of the corresponding tosylate **5** and acetate **24** displayed clean, one-proton triplets (δ 4.50 ppm, J = 1.5 Hz, and 4.75 ppm, J = 1.5 Hz, respectively) for the proton on the hydroxyl-bearing carbon.

Solvolysis of tosylate **5** was examined in unbuffered acetic acid and in 80% acetone–water. Although decomposition accompanied solvolysis in acetic acid, no significant decomposition was observed in acetone–water. In order to facilitate analysis, the acetolysis products were saponified prior to analysis. The individual products were then identified by comparison of vpc retention times with those of authentic samples[19] and confirmed by peak enhancement experiments. Both the structures of the products and the composition of the mixtures were similar for the two solvent systems.

Three major products were obtained: tricyclic alcohol **23** and two bicyclic alcohols, *exo*-bicyclo[3.2.1]-oct-6-en-3-ol (**25**) and *exo*-bicyclo[3.2.1]oct-2-en-7-ol (**26**) in a ratio of *ca.* 10:10:1. Since decomposition accompanies solvolysis in acetic acid, the kinetic formation of other products cannot be excluded. During the very early stages of acetolysis, vpc analysis indicated the presence of small amounts of two additional products, **27** and **28**. These minor products disappeared rapidly and the composition ratio of major products remained essentially constant throughout the remainder of the acetolysis.[20] In acetone–water only the three major alcohol products were observed and their ratio remained constant with time.[21] Careful vpc analysis of the final product mixtures from both solvent systems showed that the endo alcohol **29** was not present.[22]



23, R = H
24, R = Ac
5, R = Ts



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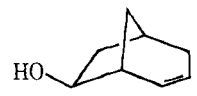

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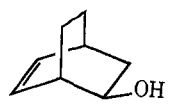

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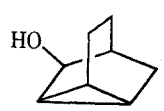

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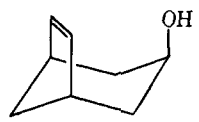

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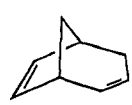
Acetolysis of the deuterium-labeled substrate **5** (C_7-*d*) was examined in order to ascertain the extent of rearrangement. The reappearance of a signal in the nmr spectrum corresponding to the proton on the hydroxyl-bearing carbon of, first, tosylate **5** (δ 4.50 ppm, doublet) and then tricyclic acetate **24** (δ 4.75 ppm, doublet) indicated that a scrambling process had occured.[23] The doublet multiplicity of the CHOR signal in both **5** and **24** confirmed that only a 1,2-C,C shift of the C_3–C_6 (or C_5–C_6) bond had occurred on ionization. Integration of the final reaction mixture indicated that the tricyclic acetate **24** was completely scrambled. Since the rate of internal return to give scrambled tosylate was greater than the rate of solvolysis, direct ionization of **5** to give scrambled acetate is not demanded. In separate control experiments it was established that **5** did not yield bicyclic tosylate **2** by internal return and that the C_7-labeled acetate **24** (C_7-*d*) was not scrambled under the solvolysis conditions.

The symmetrically bridged species **3** or its equivalent of two rapidly equilibrating classical ion pairs appears to be the most economical intermediate to account for both the product distribution and the specific label scrambling results observed in the solvolysis of tosylate **5**. Solvent attack (or internal return) at the equivalent C_6 and C_7 sites in cation **3** clearly results in scrambled, tricyclic products, while attack at C_3, with inversion, accounts for the stereospecific formation of exobicyclic product **25**. As shown by LeBel[6] (for acetolysis), the minor bicyclic product **26** is not a primary solvolysis product but results from acid-catalyzed addition to bicyclo[3.2.1]octa-2,6-diene (**30**). Diene **30** is derived readily from **3** by deprotonation. The possible intermediary of the bicyclic cation **31** in product formation appears to be excluded by the observed product distribution. LeBel found[6] that solvolysis of both exo and endo bicyclic tosylates **2** occurred without double bond participation; exo tosylate **2a** yielded C_3 endo acetate (**29**, OH = OAc), and endo tosylate **2b** (possibly the more appropriate model for the case in hand) gave both exo and endo C_3 acetates (**25** and **29**, OH = OAc); and the major products from both epimers (64–73%) were derived from either a 1,2-hydride shift to give the C_2 cation **32** or deprotonation to give diene **30**. The absence of both the endobicyclic product **29** and significant hydride shift products (*e.g.*, **27** and **28**) appear to rule out the bicyclic cation **31** as an intermediate. An examination of molecular models provides a possible explanation for the difference in behavior between the tricyclic cation **3** and the bicyclic species **31**. In **31** the axial



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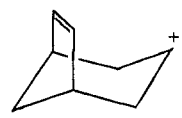

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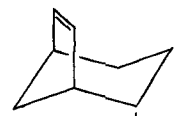

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hydrogens at C_2 are favorably disposed for hydride shift and/or elimination since their bond axes are parallel to the empty p orbital. The corresponding axial hydrogens in **3**, however, cannot achieve this optimum geometry for overlap due to the molecular distortions present in the tricyclic skeleton.

Kinetic examination of tosylate **5** in unbuffered acetic acid and in 80% acetone–water yielded approximate first-order constants of $k_{112°}$ (HOAc) = 8.4 × 10^{-6}

(19) We are most grateful to Professor N. A. LeBel for generously providing authenic samples; see ref 6.

(20) Isolated material balances in acetolysis were *ca.* 60–70%.

(21) Control experiments showed that acetate **24** and the acetate derived from alcohol **25** did not interconvert under solvolysis conditions although both did undergo some decomposition.

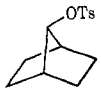
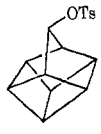
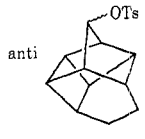
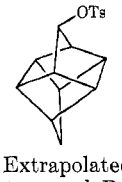
(22) Small amounts (*ca.* 5%) of unidentified, nonpolar materials were observed in both solvent systems.

(23) For analogous rearrangements in more complex polycyclic systems, see (a) P. v. R. Schleyer, J. J. Harper, G. L. Dunn, V. J. DiPasquo, and J. R. E. Hoover, *J. Amer. Chem. Soc.*, **89**, 698 (1967); (b) J. C. Barborak and R. Pettit, *ibid.*, **89**, 3080 (1967); (c) W. L. Dilling, R. A. Plepys, and R. D. Kroening, *ibid.*, **91**, 3404 (1969); (d) W. L. Dilling, C. E. Reineke, and R. A. Plepys, *J. Org. Chem.*, **34**, 2605 (1969).

sec^{-1} and $k_{113°}$ (acetone–H_2O) = 4.8×10^{-6} sec^{-1}. The rate of solvolysis of **5** is comparable to similar polycyclic systems and accelerated in comparison to simple 7-norbornyl tosylate (see Table I). Considera-

TABLE I

SOLVOLYSIS RATE CONSTANTS FOR SOME RELATED 7-NORBORNYL TOSYLATES (IN ACETIC ACID)

Compd	Rate	Ref
	$k_{110°} = 6.34 \times 10^{-9}$ in 0.1 M potassium acetate	*a*
	$k_{125°} = 4.75 \times 10^{-3}$	23a
	Syn, $k_{120°} = 2.82 \times 10^{-4}$ Anti, $k_{120°} = 5.07 \times 10^{-5}$	23c,d 23c,d
	$k_{120°} = 6.86 \times 10^{-5}$	*b*

[a] Extrapolated value from S. Winstein, M. Shatavsky, C. Norton, and R. B. Woodward, *J. Amer. Chem. Soc.*, **77**, 4183 (1955). [b] Quoted in ref 23d.

tion of the series of structurally related 7-norbornyl systems shown in Table I suggests that anchimeric assistance on ionization (relief of strain) is a significant contributor to the observed rate acceleration. In the absence of an unassisted reference model system (such as the 2-adamantyl system for unstrained secondary systems[24]), however, the relative contributions of nucleophilic solvent assistance (k_s) and anchimeric assistance (K_Δ) to the observed rate cannot be evaluated accurately.

Experimental Section

Melting points were determined on a Mel-Temp apparatus and are uncorrected. Infrared spectra were obtained on a Perkin-Elmer Model 237B grating infrared spectrometer; nmr spectra were measured on a Varian Associates Model A-60 or HA-100 spectrometer. High-resolution mass spectra were obtained using CEC Model 21-100 mass spectrometer. The microanalytical determinations were done by the Chemalytics, Inc., Tempe, Ariz.

Bicyclo[2.2.1]hept-5-en-2-one Ketal (8).—A mixture of bicyclo[2.2.1]hept-5-en-2-one,[25] **7** (228.3 g, 2.11 mol), ethylene glycol (290 g), and *p*-toluenesulfonic acid (1 g) in benzene (750 ml) was refluxed for 20 hr with continuous separation of water (42 ml, 2.3 mol). Upon cooling, sodium bicarbonate (10 g) was added, and the glycol layer was separated and then extracted with ether (400 ml). After drying ($MgSO_4$) and evaporation of the solvent, the residue was distilled to give pure ketal **8**: 286.3 g (89%); bp 95–100° (30 mm); ir (film) 1200–1000 cm^{-1} (COC); nmr (CCl_4) δ 1.1–1.2 (m, 4, CH_2), 2.5–2.9 (m, 2, bridgehead), 3.8 (m, 4, OCH_2CH_2O), 6.0 (dd, 1, J = 5.5 and 3.5 Hz, C_5), and 6.25 ppm (dd, 1, J = 5.5 and 3 Hz, C_6); mol wt, calcd for $C_9H_{12}O_2$, 152.0837 (found m/e, 152.0840).

Anal. Calcd for $C_9H_{12}O_2$: C, 71.02; H, 7.95. Found: C, 71.04; H, 7.97.

2,3- (and 3,4-) Dichlorobicyclo[3.2.1]oct-3- (and -2-) en-6-one Ketal (9).—Under a nitrogen atmosphere, ethyl trichloroacetate (546 g, 2.86 mol) was added over a 6-hr period to an ice-cold mixture of ketal **8** (86.8 g, 0.57 mol) and sodium methoxide (200 g, 3.7 mol) in pentane (500 ml). After stirring for an additional 6 hr at 0° and 12 hr at room temperature, the mixture was diluted with water (200 ml) and extracted with pentane. The combined organic extracts were dried ($MgSO_4$) and concentrated. Distillation of the residue yielded pure product **9**: 104.4 g (77%); bp 120–130° (0.6 mm); ir (film) 1635, 1200–1000 cm^{-1}; nmr (CCl_4) δ 1.5–2.8 (m, 6), 3.89 (m, 4), 4.23 (d, 0.33, J = 2.5 Hz, CHCl), 4.50 (d, 0.67, J = 2.5 Hz, CHCl), 6.0 (dd, 0.33, J = 8.5 and 1 Hz), and 6.18 ppm (dd, 0.67, J = 8 and 1 Hz); mol wt, calcd for $C_{10}H_{12}O_2Cl_2$, 234.0214 (found m/e, 234.0222). The compound decomposed in air; microanalytical data were not reproducible.

3-Chlorobicyclo[3.2.1]oct-2- (and -3-) en-6-one Ketal (10).—Lithium aluminum hydride (3.9 g, 0.102 mol) was stirred in refluxing tetrahydrofuran (200 ml) under nitrogen. The dichloride **9** (7.5 g, 0.032 mol) was dropped into the suspension and heated for 1.5 hr. With ice cooling, water (7.5 ml) was added slowly to the reaction mixture and the resultant slurry was filtered through Celite. The solid collected on the funnel was washed with tetrahydrofuran and the combined solution was dried ($MgSO_4$) and evaporated. Distillation of the residue gave 5.3 g of product **10** (83%): bp 72–76° (0.06 mm); ir (film) 1648, 1120–1000 cm^{-1}; nmr (CCl_4) δ 1.5–3.0 (m, 8), 3.8 (m, 4), and 5.7–6.1 ppm (m, 1); mol wt, calcd for $C_{10}H_{13}O_2Cl$, 200.0604 (found m/e, 200.0615).

Anal. Calcd for $C_{10}H_{13}O_2Cl$: C, 59.86; H, 6.53. Found: C, 59.97; H, 6.57.

Bicyclo[3.2.1]oct-2- (and -3-) en-6-one Ketal (11).—A solution of vinyl chloride **10** (12 g, 0.06 mol) in 5 ml of ether was added dropwise to a solution of lithium (1.2 g, 0.2 mol) in liquid ammonia (200 ml) and then stirred for 1 hr. Ammonium chloride (15 g) was added and the ammonia was evaporated. Water (70 ml) was added and the mixture was extracted with ether. The ether solution was dried ($MgSO_4$) and concentrated. The residue was distilled to give 7.2 g of **11** (71%): bp 122–127° (30 mm); ir (film) 1100–1000 cm^{-1}; nmr (CCl_4) δ 1.4–2.6 (m, 8), 3.8 (m, 4), and 5.2–6.1 ppm (m, 2); mol wt, calcd for $C_{10}H_{14}O_2$, 166.0994 (found m/e, 166.0998).

Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.00; H, 8.60.

***exo*-Bicyclo[3.2.1]octan-3-ol-6-one Ketal (12).**—A solution of diborane in tetrahydrofuran (0.1 M solution, 145 ml) was injected *via* a hypodermic syringe into a stirred solution of 2-methyl-2-butene (28 g, 0.4 mol) in tetrahydrofuran (300 ml) at 0° under a nitrogen atmosphere. This mixture was stirred for 2 hr. The ketal **11** (30.8 g, 0.18 mol) was then added at 0° and the mixture was stirred at room temperature for 3.5 hr. The solution was heated to 50°, a solution of sodium hydroxide (6 N, 100 ml) was added, and then a solution of hydrogen peroxide (30%, 130 ml) was added. The resulting mixture was stirred at 50° for 2 hr. The aqueous layer was separated and extracted with ether (200 ml). After drying ($MgSO_4$) and evaporation, the residue was distilled to give 26.8 g (77%) of pure alcohol **12**: bp 90–95° (0.04 mm); ir (film) 3400, 1100–1000 cm^{-1}; nmr (CCl_4) δ 1.0–2.4 (m, 10) and 3.6–4.3 ppm (m, 6); mol wt, calcd for $C_{10}H_{16}O_3$, 184.1099 (found m/e, 184.1109).

Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75. Found: C, 64.69; H, 8.79.

Bicyclo[3.2.1]octane-3,6-dione 6-Ketal (13).—Chromium trioxide (2 g, 20 mmol) was dissolved in 2 ml of water and added to pyridine[16] (20 ml). The alcohol **12** (1.1 g, 5.95 mmol) in pyridine (10 ml) was added and this mixture was stirred at room temperature for 3 days. The solution was quenched with water (50 ml), filtered through Celite, and extracted with ether. After drying ($MgSO_4$) and evaporation, the residue was chromatographed on a silica gel column (hexane–ether 3:1, v/v) to give 1.0 g (90%) of crystalline ketone **13**: mp 58–60°; ir (CCl_4) 1718 (C=O), 1120–1000 cm^{-1}; nmr (CCl_4) δ 1.6–2.7 (m, 10) and 3.7–4.1 ppm (m, 4); mol wt, calcd for $C_{10}H_{14}O_3$, 182.0943 (found m/e, 182.0941).

Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 65.58; H, 7.47.

Deuterium Incorporation of Bicyclo[3.2.1]octane-3,6-dione 6-Ketal (13).—A mixture of ketone–ketal **13** (59 mg, 0.32 mmol) and potassium carbonate (51 mg) in ether (3 drops) and deuterium oxide (0.5 ml) was stirred for 90 hr. The organic ma-

(24) J. M. Harris, D. J. Raber, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 5729 (1970), and references cited therein.

(25) P. K. Freeman, D. M. Balls, and D. J. Brown, *J. Org. Chem.*, **33**, 2211 (1968).

terial was extracted with carbon tetrachloride and evaporated to give 50 mg (85%) of deuterated **13**: nmr (CCl_4) diminished peaks δ 2.15, 2.25, 2.45, and 2.60 ppm (integration indicated a loss of 3.3 hydrogens); ir (CCl_4) 2200, 2130 cm^{-1}; mass spectrum *m/e* (rel intensity) 183 (2), 184 (5), 185 (10), 186 (7.5), and 187 (2); mol wt of **11**-d_0, 182.

***endo*-Bicyclo[3.2.1]octan-6-on-3-ol Ketal (14).**—To a boiling suspension of lithium aluminum hydride (140 mg, 3.69 mmol) in tetrahydrofuran (20 ml) under nitrogen was added the ketone-ketal **13** (672 mg, 3.69 mmol) in 5 ml of tetrahydrofuran. The reflux was maintained for 8 hr and then 5 drops of water were added. The resultant slurry was filtered through Celite and the collected solid was washed with tetrahydrofuran. The combined organic phase was dried ($MgSO_4$) and concentrated. The residue was chromatographed on a silica gel column (ether–chloroform 1:1, v/v). The first fractions gave the liquid endo alcohol **14**, 500 mg (74%); the latter fractions yielded the exo alcohol **12**, 140 mg (20%). Pure[26] endo **14** showed ir (CCl_4) 3510, 1200–1000 cm^{-1}; nmr ($CDCl_3$) δ 1.2–2.5 (m, 10) and 3.7–4.1 ppm (m, 6).

Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75. Found: C, 64.56; H, 8.66.

***endo*-Bicyclo[3.2.1]octan-3-ol-6-one (15).**—A solution of ketal **14** (94 mg, 0.51 mmol), one crystal of *p*-toluenesulfonic acid monohydrate, and 1 ml of water in tetrahydrofuran (20 ml) was heated at reflux for 3.5 hr. The solution was cooled and washed with saturated potassium carbonate solution. The organic layer was dried ($MgSO_4$) and concentrated. The residue was purified by column chromatography (silica gel, ether–hexane 1:1, v/v) to give 72 mg of glassy product[26] **15** (100%): ir (CCl_4) 3590, 3410, 1740, 1080 cm^{-1}; nmr (CCl_4) δ 1.7–2.7 (m, 10), 2.9 (s, 1), and 4.1 ppm (m, 1, CHOH); mass spectrum *m/e* (rel intensity) 140 (80, molecular ion), 122 (78), 81 (90), and 79 (100).

3-Methoxy-2-oxatricyclo[3.2.1.$1^{3,7}$]nonane (16).—A mixture of ketone–alcohol **15** (151 mg, 1.08 mmol), one crystal of *p*-toluenesulfonic acid monohydrate, and anhydrous magnesium sulfate (0.1 g) in methanol (25 ml) was heated at reflux for 6 hr. Then potassium carbonate (0.2 g) was added and the solution was filtered. The solvent was removed to give 120 mg of liquid product[26] **16** (71%): ir (CCl_4) 2930, 1325, 1080 cm^{-1}; nmr (CCl_4) δ 1.2–2.5 (m, 10), 3.3 (s, 3), and 4.4 ppm (m, 1); mol wt, calcd for $C_9H_{14}O_2$, 154.0994 (found *m/e*, 154.0994).

Anal. Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 69.59; H, 9.09.

***exo*-Bicyclo[3.2.1]octan-3-ol-6-one (17).**—A mixture of ketal–alcohol **12** (2.1 g, 11 mmol), one crystal of *p*-toluenesulfonic acid monohydrate, and 0.2 ml of water in tetrahydrofuran (100 ml) was heated at reflux for 12 hr. After drying ($NaHCO_3$–$MgSO_4$) and evaporation, the residue was chromatographed on a silica gel column (ether) to give 1.3 g (81%) of pure ketone–alcohol **17**: mp 150–151°; ir ($CHCl_3$) 3400, 1740, 1040 cm^{-1}; nmr ($CDCl_3$) δ 1.2–2.8 (m, 10), 2.9 (s, 1, OH), and 3.6–4.2 ppm (m, 1, CHOH); mol wt, calcd for $C_8H_{12}O_2$, 140.0837 (found *m/e*, 140.0842).

Anal. Calcd for $C_8H_{12}O_2$: C, 68.55; H, 8.63. Found: C, 68.27; H, 8.79.

***exo*-6,6-Dimethoxybicyclo[3.2.1]octan-3-ol (18).**—A mixture of ketone–alcohol **17** (171 mg, 1.2 mmol), one crystal of *p*-toluenesulfonic acid, and 0.2 g of anhydrous magnesium sulfate in 10 ml of methanol was heated at reflux for 18 hr. Then potassium carbonate (0.1 g) was added and the solution was filtered and concentrated. The residue was chromatographed on a silica gel column (hexane, then ether) to give 110 mg of liquid product[26] **18** (50%): ir ($CHCl_3$) 3580, 3400, 1100–1000 cm^{-1}; nmr ($CDCl_3$) δ 1.1–2.7 (m, 11), 3.15 (s, 3, OCH_3), 3.25 (s, 3, OCH_3), and 3.7–4.3 ppm (m, 1, CHOH); mass spectrum *m/e* (rel intensity) 186 (22, molecular ion), 169 (60), 168 (25), 155 (20), and 122 (100).

***exo*-Bicyclo[3.2.1]octan-6-on-3-yl Tosylate (6).**—A solution of alcohol–ketone **17** (1.2 g, 8.6 mmol) and *p*-toluenesulfonyl chloride (2.2 g, 11.5 mmol) in 10 ml of dry pyridine was stirred at 0° for 3 hr. Then 100 g of ice was added. The crude product was filtered and was recrystallized from ether–benzene to give 2.4 g (90%) of product **6**: mp 81–82.5°; ir $CHCl_3$) 1740, 1600, 1190, 1160 cm^{-1}; nmr ($CDCl_3$) δ 1.5–2.8 (m, 3-CH_3 at 2.45), 4.2–4.8 (m, 1), 7.3 (d, 2, J = 8 Hz), and 7.8 ppm (d, 2, J = 8 Hz); mol wt, calcd for $C_{15}H_{18}SO_4$, 294.0926 (found *m/e*, 294.0932).

Anal. Calcd for $C_{15}H_{18}SO_4$: C, 61.20; H, 6.16; S, 10.87. Found: C, 61.48; H, 6.36; S, 10.70.

Tricyclo[3.2.1.$0^{3,6}$]octan-7-one (4).—The tosylate **6** (2.4 g, 8.15 mmol) in benzene (20 ml) was dropped into a stirred slurry of potassium *tert*-butoxide (1.5 g, 13.2 mmol) in benzene (30 ml) under nitrogen. After 3 hr, water (30 ml) was added and the two layers were separated. The aqueous solution was extracted with ether. The combined organic phases were dried ($MgSO_4$) and the solvent was removed by careful distillation. The oily residue was purified by "sublimation" (70°, 60 mm) to yield crystalline **4**: 611 mg (62%); mp 99–100.5° (sealed capillary); ir (CCl_4) 2930, 2860, 1763, 1150 cm^{-1}; nmr (CCl_4) δ 1.5–2.7 ppm (complex); mol wt, calcd for $C_8H_{10}O$, 122.0732 (found *m/e*, 122.0739).

Anal. Calcd for $C_8H_{10}O$: C, 78.65; H, 8.25. Found: C, 78.46; H, 8.04.

The 2,4-dinitrophenylhydrazone had mp 175–177°.

Anal. Calcd for $C_{14}H_{14}N_4O_4$: C, 55.63; H, 4.67; N, 18.53. Found: C, 55.46; H, 4.76; N, 18.50.

The residue remaining after sublimation (232 mg) was chromatographed on a silica gel column ($CHCl_3$) to give two substances: A (50 mg) [mp 197–200°; ir ($CHCl_3$) 2950, 1270, 1100–1000 cm^{-1}] and B (110 mg) [mp 138–140°; ir ($CHCl_3$) 3560, 2940, 2860, 1745, 1050 cm^{-1}; nmr ($CDCl_3$) δ 1.3–2.8 ppm (complex); mass spectrum *m/e* 244 (molecular ion)].

Bicyclo[3.2.1]oct-2- (and -3-) en-6-one (19).—The olefin–ketal **11** (3.5 g, 21 mmol) was dissolved in acetone (30 ml) containing 3 ml of 10% hydrochloric acid and was stirred at room temperature for 6 hrs. This solution was neutralized with sodium bicarbonate and extracted. The concentrated liquid was chromatographed on a silica gel column (ether–hexane 1:8, v/v) to give 2.0 g of pure liquid **19** (77%): ir (CCl_4) 1730, 1630 cm^{-1}; nmr (CCl_4) δ 1.7–2.9 (m, 8) and 5.3–6.2 ppm (m, 2); mass spectrum *m/e* (rel intensity) 122 (50), 80 (34), 79 (100), 78 (93), and 77 (21).

Anal. Calcd for $C_8H_{10}O$: C, 78.65; H, 8.25. Found: C, 78.86; H, 8.39.

Tricyclo[3.2.1.$0^{3,6}$]octane (1).—A mixture of ketone **4** (334 mg, 27 mmol), ethylene glycol (10 ml), and hydrazine hydrate (1.4 g, 274 mmol) was heated to 140°. Sodium methoxide (296 mg, 54.8 mmol) in 1 ml of methanol was added and the mixture was heated to 180° over a 3-hr period. Water (30 ml) was added, and the aqueous layer was separated and extracted with *n*-pentane. The pentane solution was dried ($MgSO_4$) and the solvent was distilled. The residue from distillation (100 mg) was sublimed at 50° (100 mm) to give 31 mg of pure hydrocarbon **1** (11%): mp 118–119° (sealed capillary) (lit.[7] mp 111–112°); ir (CCl_4) 2930, 2850, 1450, 1330, 1270, 1090 cm^{-1}; nmr (CCl_4) δ 1.3 and 1.6 (m, 6), 2.2, 2.45, and 2.85 ppm (m, 6); mass spectrum *m/e* (rel intensity) 108 (9), 79 (45), 67 (43), 66 (100). These data are in agreement with the literature.[7]

3-Oxatricyclo[3.3.1.$0^{2,7}$]nonan-4-one (22).[27]—Trifluoroacetic anhydride (1.02 g, 7 mmol) was added slowly to a vigorously stirred suspension of 90% hydrogen peroxide (Shell Chemical Co.) (0.16 g, 6 mmol) in methylene chloride (10 ml) at 0° and then stirred for 30 min. The peracid solution was then added slowly to a stirred mixture of disodium acid phosphate (1.6 g) and ketone **4** (511 mg, 4.9 mmol) in methylene chloride (10 ml) at 0°. The reaction mixture was stirred at room temperature for 6 hr and then it was filtered. The filtrate was washed with 10% sodium carbonate solution, dried ($MgSO_4$), and evaporated. The residue was chromatographed on a silica gel column ($CHCl_3$) to give 670 mg of lactone **22** (98%): mp 136–138°; this material was homogeneous on tlc (silica gel) and on two vpc columns (SE-30 and FFAP); ir (CCl_4) 1770, 1150–1000 cm^{-1}; nmr (CCl_4), see text; mol wt, calcd for $C_8H_{10}O_2$, 138.0681 (found *m/e*, 1.38.0682).

Tricyclo[3.2.1.$0^{3,6}$]octan-7-ol (23).—A solution of ketone **4** (569 mg, 4.6 mmol) in ether (5 ml) was added dropwise to a stirred suspension of lithium aluminium hydride (175 mg, 4.6 mol) in ether (5 ml) under nitrogen. After the mixture was heated for 4 hr, dilute hydrochloric acid (10%) was added carefully to dissolve all the solid present. The aqueous layer was separated and extracted with ether. The ethereal solutions

(26) This compound was judged homogeneous by silica gel tlc in chloroform and hexane–ether. Since a satisfactory combustion analysis was not obtained, the physical constants should be interpreted accordingly.

(27) This procedure is that previously described by E. E. Smissman, J. F. Muren, and N. A. Dahle, *J. Org. Chem.*, **29**, 3517 (1964).

were combined and dried ($MgSO_4$). The residue, after concentration, was sublimed at 70° (60 mm) to give 526 mg of waxy crystalline **23** (91%): mp 158–159°; ir (CCl_4) 3650, 3320, 2950, 1090, 1050 cm^{-1}; nmr (CCl_4) δ 1.1–2.7 (m, 10), 2.9 (s, 1), and 3.95 ppm (m, 1); mol wt, calcd for $C_8H_{12}O$, 124.0888 (found *m/e*, 124.0888).

Anal. Calcd for $C_8H_{12}O$: C, 77.37; H, 9.74. Found: C, 76.93; H, 9.85.

7-Deuteriotricyclo[3.2.1.0^{3,6}]octan-7-ol (**23**, C_7-*d*) was prepared as described above using lithium aluminum deuteride: ir ($CHCl_3$) 3600, 3400, 2940, 2140, 1130, 1060 cm^{-1}; nmr ($CDCl_3$) δ 1.1–2.7 (m, 10) and 1.8 (s, 1); mass spectrum *m/e* 125 (molecular ion).

Tricyclo[3.2.1.0^{3,6}]octan-7-yl *p*-Toluenesulfonate (**5**).—A solution of **23** (184 mg, 1.5 mmol) and *p*-toluenesulfonyl chloride (563 mg, 2.9 mmol) in 5 ml of dry pyridine was stirred at 0° for 2 hr. The solution was then stored at −5° for 12 hr until precipitation of pyridine hydrochloride was complete. The mixture was poured into ice–water (20 ml) and was extracted with ether. The ethereal solution was washed with dilute hydrochloric acid and then dried ($MgSO_4$) and concentrated. Column chromatography (silica gel) with ether–pentane (1:6, v/v) gave 323 mg of **5** (88%): mp 30–32°; ir ($CHCl_3$) 3020, 2950, 1600, 1370, 1180, 1160, 1100 cm^{-1}; nmr ($CHCl_4$) δ 1.2–2.8 (m, 10), 2.4 (s, 3, Ar CH_3), 4.5 (t, 1, J = 1.5 Hz), 7.3, and 7.7 ppm (two d's, 4, J = 8 Hz, aromatic H's); mass spectrum *m/e* 278 (molecular ion).

Anal. Calcd for $C_{15}H_{18}O_3S$: C, 64.73; H, 6.52; S, 11.50. Found: C, 64.88; H, 6.43; S, 11.55.

7-Deuteriotricyclo[3.2.1.0^{3,6}]octan-7-yl *p*-toluenesulfonate (**5**, C_7-*d*) was prepared from **23** (C_7-*d*) as described above: ir ($CHCl_3$) 3010, 2940, 2200, 1600, 1370, 1180, 1160 cm^{-1}; nmr ($CDCl_3$) δ 4.5 ppm (signal absent).

Solvolysis of Tricyclo[3.2.1.0^{3,6}]octan-7-yl *p*-Toluenesulfonate (**5**). **Acetic Acid.**—Combustion tubes containing tosylate **5** (53 mg, 0.19 mmol) and reagent grade glacial acetic acid with 1% added acetic anhydride (5 ml, 0.03 *M*) were purged with nitrogen, sealed, and then placed in a constant temperature bath at 112 ± 0.5°. After approximately 3–4 hr, the solutions turned dark blue-black and solid gradually appeared; after 10 half-lives a brown precipitate was present. Similar decomposition was observed in buffered (NaOAc) runs and the product composition was the same as in the unbuffered runs (*vide infra*). Tubes were removed after *ca.* 20, 40, 50, 70, and 80% reaction and opened, and the contents were diluted with water (25 ml). The aqueous solution was extracted with ether and, after concentration, the organic phase was saponified with potassium hydroxide in methanol. The resulting products were isolated by continuous pentane extraction of the methanol solution and characterized as described below.

Acetone–Water.—In a similar fashion, combustion tubes containing tosylate **5** and 80% acetone–water (*ca.* 5 ml, 0.03 *M*) were sealed under nitrogen and placed in a constant temperature bath at 113 ± 0.2°. No visual decomposition was observed over a period of *ca.* 10 half-lives. Tubes were removed after *ca.* 15, 30, 50, 80, and 95% reaction and opened, and the products were analyzed directly.

The products from both runs were identified by comparison of vpc retention times with authentic samples[19] using a 25% Dow Polyglycol E20,000 and 60–80 mesh Chromosorb W, 1/8 in. × 3 m column at 130°. In each case, product identity (or absence) was verified by peak enhancement experiments. In order of increasing retention times, the elution of the various products and authentic samples was **30** (1.5 min), **29** (19 min), **25** (31 min), **27** (33 min), **23** (34 min), **26** (36 min), and **28** (38 min). The observed product distributions are described in the text. In both solvent systems *ca.* 5% unknown, nonpolar (short retention time) products were observed.

Deuterium Scrambling.—A sample of C_7-deuterated tosylate **5** (59 mg) in acetic acid (0.4 ml) was heated in a sealed nmr tube at 120°. After 2 hr, nmr analysis of the now blue-black solution showed appearance of a doublet (J = 2 Hz) at δ 4.5 ppm corresponding to the C_7 hydrogen of tosylate **5**. This signal reached maximum intensity at 6 hr and then decreased gradually. A new doublet at 4.75 ppm (J = 2 Hz) corresponding to the C_7 hydrogen of acetate **25** appeared after *ca.* 4 hr and reached constant intensity after *ca.* 10 hr. Using the aromatic protons of the tosylate (and liberated *p*-toluenesulfonic acid) as an internal standard, integration showed that the tosylate **5** was completely scrambled after 6 hr and the product acetate **25** was completely scrambled.

Control Experiments. A.—A sample of C_7-deuterated tricyclic acetate **24**, prepared from C_7-deuterated alcohol **23** with acetic anhydride–pyridine, in acetic acid containing 1 equiv of *p*-toluenesulfonic acid was heated at 120° in a sealed nmr tube. No deuterium scrambling was observed by nmr after 15 hr. Vpc analysis of the resulting product showed only recovered starting material.

B.—The acetic acid solvolysis of tricyclic tosylate **5** was stopped after *ca.* 50% reaction and the unreacted tosylate was isolated by column chromatography. This material was identical with starting tosylate **5** as judged by the ir and nmr.

C.—Treatment of the acetate derived from alcohol[19] **25** with acetic acid containing 1 equiv of *p*-toluenesulfonic acid at 120° led to decomposition, but no tricyclic acetate **24** was formed as judged by vpc.

Kinetics were determined by the classical titrimetric procedures described by LeBel[6] and Winstein.[28] The solutions were prepared using J. T. Baker Co. reagent grade solvents. Glacial acetic acid containing 1% acetic anhydride was used. The acetone was purified by passing through a column of 4-Å molecular sieve and distilled. Methanol was purified by boiling with magnesium metal followed by distillation. In acetic acid solvolysis, titrations were done by the procedure of LeBel.[6] In acetone–water, titration was performed using sodium methoxide in methanol solution to the green end point of bromothymol blue. The infinity titers for acetolysis were poor (*ca.* 50–60% of the theoretical) and the infinity titers used were calculated using the initial tosylate concentrations. The infinity titers for acetone–water were *ca.* 95% of the theoretical and were used without correction. Tosylate concentrations for both solvolyses were *ca.* 0.03 *N*. The solvolyses were followed to 70% completion in acetic acid and to 75% in acetone–water. The rate constants were obtained by a least-squares analysis of eq 1 with the aid of a

$$kt = \ln \frac{[\mathrm{ROTs}]_\infty - [\mathrm{ROTs}]_0}{[\mathrm{ROTs}]_\infty - [\mathrm{ROTs}]_t} \quad (1)$$

computer. The fits to first-order kinetics were within 5% of the computed straight lines for at least 2 half-lives.

Registry No.—**4**, 24730-85-6; **4** 2,4-DNP, 24730-84-5; **5**, 31444-16-3; **6** 2,3-Cl derivative, 31444-17-4; **6** 3,4-Cl derivative, 31489-86-8; **8**, 31444-18-5; **9**, 31444-19-6; **10**, 31444-20-9; **11**, 31444-21-0; **12**, 31444-22-1; **13**, 31444-23-2: **14**, 31444-24-3· **15**, 31444-25-4; **16**, 22532-37-2; **17**, 31444-27-6; **18**, 31444-28-7; **19** (2-ene), 31444-29-8; **19** (3-ene), 31444-32-3; **22**, 31444-30-1; **23**, 31444-31-2.

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(28) *Cf.* C. Poulter, E. Friedrich, and S. Winstein, *J. Amer. Chem. Soc.*, **92**, 4274 (1970).