nitrile, 100-47-0; 1-cyanobicyclo[3.1.0]hexane, 31357-72-9; 1-cyanocyclohexene, 1855-63-6; cyanocyclohexane, 766-05-2; heptanenitrile, 629-08-3; octanenitrile, 124-12-9; decanenitrile, 1975-78-6; undecanenitrile, 2244-07-7; dodecanenitrile, 2437-25-4; tetradecanenitrile, 629-63-0.

Supplementary Material Available: Tables containing the names and heats of vaporization of the 433 compounds used to generate the constants in Table I and a comparison of the literature and estimated values (34 pages). Ordering information is given on any current masthead page.

Kinetics of Ozonation. 6. Polycyclic Aliphatic Hydrocarbons

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The reaction of ozone with norbornane, adamantane, and bicyclo[2.2.2]octane has been studied, including kinetics and product studies as well as the determination of activation parameters for the ozonation of norbornane. This work was carried out to distinguish between hydride abstraction and a concerted insertion mechanism for the ozonation of C–H bonds. Kinetically, norbornane behaves like a secondary hydrocarbon and lacks the rate acceleration expected if a carbocation intermediate were involved in a hydride abstraction mechanism. We interpret this and other results as supporting a 1,3-dipolar insertion mechanism for the reaction of ozone with C–H bonds.

Several mechanisms have been proposed for the reaction of ozone with carbon-hydrogen bonds,[1-3] including hydride abstraction,[4] hydrogen-atom abstraction,[5,6] and a concerted C–H insertion.[3,7,8] All of these routes form hydrotrioxides, 1, which are observable at low temperatures[9,10] but decompose above −40 °C to form alcohols and carbonyl compounds, as shown in Scheme I. Evidence has been presented against all three of the pathways.

We consider the evidence against the hydrogen-atom abstraction mechanism[1,4,5] to be conclusive. Evidence against a hydride abstraction mechanism,[1,5,6,9] most notably the retention of stereochemistry in the products,[5,6,9] also appears to be sound unless tight ion pairs are involved. Although Nangia and Benson have presented thermochemical arguments against an insertion mechanism and have favored a hydride abstraction,[4] their arguments were based on very approximate relative rate data and are not consistent with the reported absolute rates.[1,11]

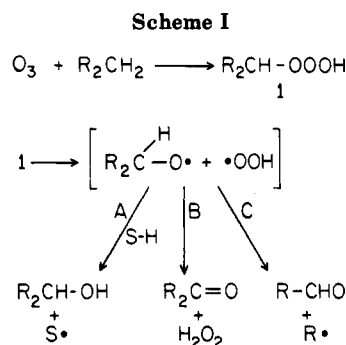We have sought a system that can distinguish in a less ambiguous way between hydride abstraction and a con-

Scheme I

Table I. Typical Product Analyses for the Reaction of Norbornane with Ozone in CCl₄[a]

% conv[b]	norcamphor	*exo*-OH	*endo*-OH	Cl[c]
		product ratios, %		
0.8	14	86	nd[d]	nd
3.1	34	62	2	2
9.6	57	37	1	5
19.2	75	17.5	0.4	7
30.6	87	5	nd	8

[a] Aliquots of 0.18 M norbornane in CCl₄ (5 mL) were bubbled with a stream of ozone at ambient temperature and were then analyzed by GC. Percentages are based on peak areas and are not corrected for relative response. [b] These values on peak areas of norbornane relative to the areas of norbornane plus products. [c] This value is for the sum of *endo*- and *exo*-2-chloronorbornane. [d] None detected.

certed insertion in the ozonation of C–H bonds. Norbornane, 2, has been reported to react with ozone 1.3 times faster than does cyclohexane, and the only products observed were *exo*-norborneol and norcamphor.[5] Due to the stability of the 2-norbornyl cation,[12,13] one would predict norbornane to exhibit higher reactivity toward ozone if a hydride abstraction mechanism were operative. Hamilton

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et al. have interpreted the 1.3-fold rate increase for nor-bornane as supporting an insertion mechanism with a high degree of radical character.[5] Similarly, in an early study of the ozonation of adamantane,[14] the ratio of products appears to be inconsistent with a hydride abstraction mechanism; a hydrogen-atom abstraction pathway was proposed.[14]

In light of more recent evidence against the hydrogen-atom abstraction mechanism,[1,4] we have examined the ozonation of norbornane, adamantane, 3, and bicyclo-[2.2.2]octane, 4, including product analyses and kinetics,
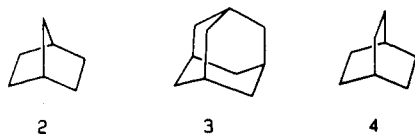
and determined activation parameters for the ozonation of norbornane and cyclopentane. We believe a comparison of these systems provides a distinction between the remaining two mechanisms.

Results

Products. Table I presents results for a series of reactions in which samples of norbornane were treated with ozone in CCl_4 as solvent for varying times. Only products resulting from reaction at C-2 of norbornane are formed: *exo-* and *endo*-norborneol and norcamphor. Initially (when less than 1% of the norbornane has been consumed) the major product is *exo*-norborneol (75–85%). Norcamphor (15–25%) and traces of *endo*-norborneol, *exo*-2-chloronorbornane, and another chloronorbornane, presumably the 2-endo isomer, also are present. At 30% conversion the product mixture is 87% norcamphor, 4.6% *exo*-norborneol, and 8.2% chloronorbornanes.

At low conversions the reaction of 7-bicyclo[2.2.1]heptanol with ozone produces the C-7 ketone as the only product. Norcamphor is the only product from the reaction of either *endo*- or *exo*-norborneol. The exo isomer is 8- to 10-fold and the endo isomer 250–300 times more reactive than is norbornane. Other products, observed at high conversions, account for less than 0.5% of the products and are not identified.

The reaction of 3 with ozone in CCl_4 affords 1-adamantanol, 1-chloroadamantane, 2-adamantanone, and 2-chloroadamantane in a ratio of 10:8:2:1, respectively; these ratios are the same at 2%, 4%, and 50% conversion. At 50% conversion 5–10 minor products also are observed. The C-2 alcohol is not observed.

The major product of the ozonation of 4 is the C-2 ketone, 2-bicyclo[2.2.2]octanone, which accounts for 70–75% of the product mixture. The C-1 alcohol accounts for 8–9% of the product mixture. This alcohol was identified by its MS fragmentation, particularly by the lack of a fragment at m/e 109, representing a loss of OH. The remainder of the product mixture consists of two monochlorinated products in a ratio of ca. 5 to 1. The same product ratios are obtained at 5%, 10%, and 24% conversion.

Rates. Our rate data are presented in Tables II and III. The rate constant for reaction of a typical secondary C–H bond with ozone is about 0.001 M^{-1} s^{-1} and that for a tertiary C–H bond is about 0.1 M^{-1} s^{-1}.[1] Dodecane, norbornane, bicyclo[2.2.2]octane, and adamantane react with ozone with relative rate constants of 0.3:0.4:0.5:1.0, respectively.

Table II. Rates of Reaction of Ozone with Saturated Hydrocarbons[a]

substrate	T, °C	k, M^{-1} s^{-1}	E_a, kcal/mol	log A per H
cyclopentane	5.0	0.005 ± 0.001	13.0 ± 0.2	6.9
	10.0	0.007 ± 0.001		
	21.2	0.018 ± 0.001		
	25.0	0.023 ± 0.001		
	30.0	0.032 ± 0.002		
	40.0	0.066 ± 0.002		
norbornane	9.8	0.007 ± 0.001	13.6 ± 0.5	7.6
	15.0	0.011 ± 0.002		
	20.0	0.022 ± 0.002		
	25.0	0.031 ± 0.003		
	30.0	0.035 ± 0.003		
	40.0	0.075 ± 0.004		
	49.9	0.155 ± 0.005		
	60.0	0.290 ± 0.060		
cyclohexane[b]	25.0	0.01	14.6	7.7
2,3-dimethyl-butane[b]	25.0	0.2	11.4	7.3

[a] All values were collected by stopped-flow spectroscopy in CCl_4; temperatures are ±0.1 °C. [b] These values are taken from ref 1.

Table III. Rates of Reaction of Ozone with Saturated Hydrocarbons[a]

substrate	k, M^{-1} s^{-1}
2,3-dimethyl-2-butane	0.2[b]
primary C–H	3.2 × 10⁻⁶ per H[c]
cyclohexane	0.01[b]
cyclopentane	0.023
norbornane	0.031 (0.40 ± 0.02)
bicyclo 2.2.2 octane	0.038[d] (0.50 ± 0.02)
adamantane	0.077[d] (1.00)
n-dodecane	0.020 (0.26 ± 0.03)

[a] These values were determined in CCl_4 at 25 °C. Parenthetic values were determined relative to adamantane at ambient temperature. [b] This value is taken from ref 1. [c] This value is taken from ref 12. [d] These absolute rates were not measured directly but were calculated from the relative rate values. The relative and absolute rates of norbornane and n-dodecane as well as the anticipated rate constant for n-dodecane are in good agreement with each other.

Discussion

This work is in part a reinvestigation of the reactions of norbornane[5] and adamantane[14] with ozone. Our product data are largely consistent with earlier work;[5,14] however, there are some points worthy of note.

Chlorinated products account for up to 40% of the products observed in this study. Earlier, Whiting et al. observed the formation of 1-chloro- and 1-bromo-adamantane in the ozonation of 3 in the presence of CCl_3Br.[14] The formation of these products appears to be indicative of free-radical intermediates. Our solutions are saturated with dioxygen, so one might expect carbon-centered radicals to be trapped by oxygen rather than by reaction with solvent. However, other authors have observed large amounts of halogenated products in the presence of oxygen[15] as well as higher-than-expected ratios of chlorination to bromination (as observed by Whiting et al.[14]) of bicyclic radicals.[16] Thus, although we consider the evidence against H-atom abstraction to be strong,[1,4] alkyl radicals do appear to be present; we attribute their production to the decomposition of the initial hydrotrioxide products and reaction of the resulting oxy radicals with the hydrocarbon. While this aspect of the ozonation

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of alkanes deserves further attention, it is beyond the scope of this work and it will not be considered here.

The exo/endo ratio of the norborneols might not accurately reflect the ratio of initial hydrotrioxides formed. Since a significant amount of norcamphor is present even at less than 1% conversion, it cannot be formed solely from the further ozonation of the alcohol products; some ketone must be formed from the decomposition of either the exo or the endo hydrotrioxide, or both. The observed exo/endo ratio is high, but a high ratio would be expected for all three of the proposed mechanisms.[12,13,17]

In the reaction of ozone with **3** and **4**, products arise from reaction of ozone at C-1 (bridgehead) and C-2 (secondary) C-H bonds. From adamantane the C-1 alcohol and the C-2 ketone are formed in a ratio of 5 to 1; an earlier study reported a 3.5 to 1 ratio.[14] In the ozonation of **4**, reaction at secondary positions is favored by a factor of 9. These product ratios are not inconsistent with what would be expected for either a hydride abstraction[13] or a hydrogen-atom abstraction mechanism[16,21,22] and might be consistent with an insertion mechanism. Adamantane, **3**, should react primarily at C-1 in the radical pathway; the two positions should be similar in reactivity in a cationic process, but we have found no direct comparison of reactivity of the two positions in this system. The bicyclooctane **4** should react mainly at C-2 by either mechanism, although the preference should be greater for hydride abstraction. Thus, while these product studies appear to be more consistent with a hydrogen-atom abstraction mechanism, they do not serve to positively discount a hydride abstraction pathway.

Unlike the study of products, the rate data do provide a distinction between the possible mechanisms. If the reaction of a C-H bond with ozone were to proceed via a hydride abstraction as the rate-determining step, norbornane should react at a rate comparable to a tertiary hydrocarbon. The stability of the norbornyl cation is similar to that of a *tert*-butyl cation,[12,18] and solvolysis data indicate that 2-norbornyl and *tert*-butyl derivatives should react at comparable rates for reactions proceeding via a cationic intermediate.[19] On the basis of rates of tosylate[13] or bromide[20] solvolyses, **4** would be expected to be less reactive than norbornane but more reactive than either adamantane or substrates containing only typical secondary C-H bonds. In fact, norbornane reacts with ozone at a rate only slightly faster than cyclopentane.

For reactions involving H-atom abstraction in the rate-determining step,[16,21,22] the order of reactivity is **4** > **3** = **2**, and the rates vary only 5-fold from **4** to **2**. In the ozonation of these substrates we determine the relative rates to be **3** > **4** > **2**, with the rates differing by less than a factor of 3. We do not consider this difference great enough to exclude the possibility of an H-atom abstraction mechanism. Additionally, we follow the loss of starting material to determine relative rates, so that competing reactions such as the pathway resulting in the formation of chlorinated products (presumably an H-atom abstrac-

Scheme II
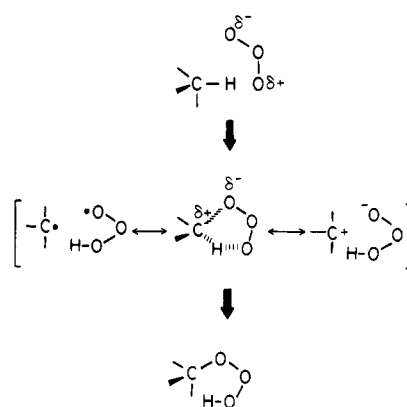
tion) may interfere. Calculating the relative reactivities excluding the chlorinated products makes **3** and **4** similar in reactivity and 25–50% more reactive than **2**. This is closer still to the reactivity pattern observed for authentic H-atom abstractions. However, earlier work presented by ourselves[1] and others[4,5] is in clear disagreement with an H-atom abstraction pathway.

A close parallel is found when our data are compared with relative reactivities of nitrene insertions[23] or with the more limited data available for carbene insertion reactions.[23,24] In both of these insertion reactions, bicyclo[2.2.2]octane is more reactive than is norbornane. While data for the carbene insertion into adamantane C-H bonds are not available, adamantane is about twice as reactive toward the nitrene as is **4**.[23] We consider these rate data to be inconsistent with the development of a significant degree of positive charge character in the transition state for these insertion reactions and to suggest that the ozonations of the substrates we have studied also proceed by a concerted insertion into the C-H bond.

The range of pathways that have been considered for the ozonation of C-H bonds is illustrated in Scheme II, in which possible transition states are pictured as resonance forms. The central structure, representing a concerted insertion, is shown with the O-H bond formation preceding C-O bond formation; the asymmetry of the transition state serves to relax the energy requirements of five-membered ring and pentavalent carbon formation invoked by Nangia and Benson[4] and to increase the preexponential term of log A = 6.5 suggested by those authors.[4]

The transition states of the three possible mechanisms need not be resonance forms. In the transition state of the cationic (or radical) mechanism the oxygen bearing the negative charge (or odd electron) need not be constrained in a cyclic configuration as shown. In the eyes of several authors,[2,5,6] hydride abstraction and H-atom abstraction may be viewed as extremes in a spectrum of transition states of a concerted insertion. Hamilton et al. have described the transition state as that of an insertion reaction with a high degree of radical character,[5] and Bailey favors a dipolar insertion with carbocation character.[2] Scheme II encompasses both of these viewpoints, which vary only in the relative contributions to the transition state of the three resonance forms illustrated.

Conclusions. Our present data are inconsistent with a high degree of carbocation character in the transition

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state for ozonations of C–H bonds, and our earlier work[1] rules out a radical H-atom abstraction mechanism. Therefore we favor a concerted insertion mechanism, the central path of Scheme II, with little contribution from either of the other resonance forms.

Experimental Section

All materials were of the highest purity commercially available. CCl_4 was treated with ozone prior to use; all other materials were used as received. Gas chromatography was carried out on a Varian 3700 chromatograph with an FID detector and both DB1 and DB17 columns. GC/MS was carried out on a Hewlett-Packard 5890 chromatograph with a 5970 Series mass selective detector, equipped with either a 30- or a 50-m DB1 column.

Procedure for Product Analysis: Norbornane. A 5-mL portion of a solution of the substrate (0.1–0.25 M in CCl_4) was bubbled with a stream of ozone in oxygen (ca. 1%) at 23 °C for times ranging from 3 to 280 min. The reaction mixture was allowed to stand for several minutes and was then degassed and analyzed by GC or GC/MS. This resulted in from 0.3% to 30% of the substrate being consumed. Products were identified by their mass spectra and retention times in comparison to authentic samples of **2**, norcamphor, *endo*- and *exo*-norborneol, and 7-bicyclo[2.2.1]heptanol. Amounts of products formed are reported in Table I. Note that in the low-conversion runs potential errors in quantitation are greater, particularly in the minor products. Thus, the apparent increase in the relative amount of chlorinated products with increased reaction may not be significant. *exo*- and *endo*-2-chloronorbornane were identified by their mass spectra. The exo isomer was the larger of the two, m/e (relative intensity) 132, 130 (M⁺, 11, 32); 103, 101 (M – C_2H_5, 33, 100); 95 (M – Cl, 100). The mass spectrum of the lesser component lacks the M – 29 fragment but contains a prominent M – C_2H_4Cl: m/e (relative intensity) 132, 130 (M⁺, 6, 19); 95 (M – Cl, 34); 67 (M – C_2H_4Cl, 100). Spiking experiments showed that amounts of the C-7 alcohol as low as the concentrations of the endo alcohol could have been detected.

Products of *endo*- and *exo*-Norborneol. At low conversions the only product noted was norcamphor. At higher conversions several trace compounds with longer retention times were observed.

Products of 7-Bicyclo[2.2.1]heptanol. At low conversions 7-bicyclo[2.2.1]heptanone is the only observed product: m/e (relative intensity) 110 (M⁺, 27); 81 (M – C_2H_5, 16); 67 (M – 43, 100); 54 (M – 56, 60).

Products of Adamantane. Samples of **3** in CCl_4 were allowed to react with ozone until 2–50% of the starting material was consumed, and the samples were analyzed by GC, in comparison to authentic samples of 1- and 2-adamantanol and 2-adamantanone. GC/MS was used to identify other products. These included 1-chloroadamantane [m/e (relative intensity) 170, 172 (M⁺, 2, 0.7); 135 (M– Cl, 100); 93 (18); 67 (6)] and 2-chloroadamantane [m/e (relative intensity) 170, 172 (M⁺, 13, 4); 135 (M – Cl, 34); 134 (M – HCl, 100). At 50% conversion, 5–10 trace

components were observed that appear to be chlorinated products and isomers of the ketone. Two of the samples were evaporated to dryness, taken up in ether, and reanalyzed by GC; this resulted in no change in the ratio of products.

Products of Bicyclo[2.2.2]octane. Solutions of **4** were allowed to react with ozone in CCl_4 until 5–24% was consumed. The reaction mixtures were analyzed by GC/MS (for the identification of products) and GC for quantitative analysis. Product ratios were independent of the extent of reaction. The major product was 2-bicyclo[2.2.2]octanone [m/e (relative intensity) 124 (M⁺, 32); 81 (41); 80 (100); 67 (43)]. Also present was 1-bicyclo-[2.2.2]octanol [m/e (relative intensity) 126 (M⁺, 14); 97 (M – C_2H_5, 77); 70 (100)]. A peak at m/e 109, representing the loss of OH (bridgehead position) was only 0.3% of the parent ion. Two chlorinated products also were present. The larger of the two, eluting first, contained the following major fragments: m/e (relative intensity) 146, 144 (M⁺, 10, 30); 109 (M – Cl, 74); 108 (M – HCl, 54); 79 (100); 67 (53). The mass spectrum of the lesser chlorinated product had significant fragments at m/e (relative intensity) 144, 146 (M⁺, 6, 2); 109 (M – Cl, 24); 108 (M – HCl, 83); 67 (100); and 66 (78).

Absolute Rates. Absolute rate data were collected by stopped-flow spectroscopy, as described earlier,[25] and are presented in Table II. Second-order rate constants for the reactions of *endo*- and *exo*-norborneol with ozone appeared to increase with increasing concentration: the rate constant for *exo*-norborneol in CCl_4 at 30 ± 0.1 °C varied from 0.86 M⁻¹ s⁻¹ at 0.014 M to 1.49 M⁻¹ s⁻¹ at 0.21 M. (Similarly, for 2-butanol in CCl_4 at 30 °C k varied from 2.6 to 9.6 M⁻¹ s⁻¹ as the concentration was varied from 0.02 to 4.0 M.[26] This is believed to be due to the change in the solvent.) At equal concentrations, *endo*-norborneol was 8–10 times more reactive than the exo isomer.

Relative Rates. Relative rates of ozonation of some compounds were determined as follows: Adamantane, one other substrate, and either 1,3,5-trichlorobenzene or *m*-dichlorobenzene (as an internal standard) were dissolved in CCl_4 in a ratio or ca. 2:2:1. The total concentration of substrates in CCl_4 was 3–5%. The solutions were divided into three portions, one of which was analyzed by GC without ozonation. The other portions were bubbled with a stream of ozone in oxygen for up to 30 min. (If more than 50% of the adamantane remained after this time ozonation was continued for another 20–30 min.) All samples were analyzed in quadruplicate by GC, and relative rates were calculated on the basis of on the disappearance of the starting materials.

Registry No. Norbornane, 279-23-2; adamantane, 281-23-2; bicyclo[2.2.2]octane, 280-33-1.

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