

On the Mechanism of Alkane Oxidation by Ozone in the Presence and Absence of FeCl_3 ¹

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Abstract: The characteristics of the reaction of ozone with alkanes at ambient temperatures have been investigated further. When O_2 is replaced by N_2 as the O_3 carrier gas the following characteristics are not altered significantly: the ratio (0.3) of ketone to alcohol products formed from cyclohexane; the stereochemistry (60–70% net retention of configuration) of tertiary alcohol formation; and the relative reactivities (1:13:110) of primary, secondary, and tertiary carbon–hydrogen bonds. The stereochemical results are unchanged by performing the ozonation in polar solvents, but a somewhat higher (82%) net retention of configuration is observed in an alkane solvent (octadecane) of higher viscosity, and lower per cent retentions are observed when additives or solvents with which O_3 reacts are present. When the ozonations are performed in the presence of FeCl_3 , alcohols are formed with virtually 100% retention of configuration. Alkyl halides with essentially 100% inversion of configuration are also formed under such conditions. The effects of FeCl_3 , diphenylamine, and combinations of the two on the ratios of products (ketone, alcohol, and alkyl halide) formed on ozonation of cyclohexane were also determined. The Hammett ρ for the oxidation of substituted toluenes was found to be -2.07 . The mechanism which best fits the data is one in which the ozone and alkane react to give either singlet O_2 and the alcohol with retention of configuration, or triplet O_2 and a triplet solvent-caged radical pair. The latter is either trapped by FeCl_3 to give alkyl halide, or the radicals diffuse apart and react further to give the other observed products.

Recently, there has been considerable interest in the mechanism of oxidation of carbon–hydrogen bonds by ozone. Thus, studies on the ozonation of aldehydes,^{2,3} ethers,^{4,5} acetals,⁶ alcohols,⁷ and amines,⁸ as well as alkanes,^{7,9–12} have been reported. The alkane ozonation is of particular interest because this reaction may be occurring in polluted atmospheres, and it is probably contributing to the degradation of organic materials in contact with polluted atmospheres. In addition, the reaction's characteristics seem related to those of biological alkane oxidations,^{13–16} and an understanding of the ozone reaction mechanism might clarify the mechanism of the biological reactions. For these reasons we have been investigating the mechanism of alkane ozonation in detail.

From the results reported in our earlier paper⁹ it was

concluded that the first step in the alkane ozonation has some characteristics of a radical reaction and some of an insertion reaction. This was indicated especially by stereochemical results which showed that reaction proceeds with considerable but not complete retention of configuration.¹⁷ Some further characteristics of the reaction have now been determined and are reported here. The results lead to a further clarification of the mechanism of the reaction.

Experimental Section

Materials. Unless otherwise described, commercial materials, which were usually redistilled and which were shown by gas chromatography to be free of interfering impurities, were used throughout. Pure *trans*-1,2-dimethylcyclohexanol and a mixture of the *cis* and *trans* alcohols were prepared as previously described;⁹ on preparative gas chromatography of the mixture a small sample of the pure *cis*-1,2-dimethylcyclohexanol was obtained.

The *cis*- and *trans*-1,2-dimethylcyclohexyl chlorides were obtained by conversion of a mixture of *cis*- and *trans*-1,2-dimethylcyclohexanols to the chlorides by a method similar to that suggested by Fieser for conversion of *tert*-butyl alcohol to *tert*-butyl chloride.²⁰ The chloride mixture was purified by preparative gas chromatography; the mixture contained greater than 90% of the chloride with the shorter retention time and less than 10% of the chloride with the longer retention time (referred to as X and Y, respectively, in the following discussion). About 1.5 g of X and 100 mg of Y (*Anal.* Calcd for $\text{C}_8\text{H}_{15}\text{Cl}$: C, 65.43; H, 10.32; Cl, 23.46. Found for X: C, 67.09; H, 9.85; Cl, 23.07. Found for Y: C, 66.81; H, 9.93; Cl, 22.89) were isolated as clear liquids. The poor correlation between the calculated elemental composition and that found is attributed to the facile elimination of HCl from the alkyl chlorides. The lability toward elimination reactions of compounds very closely related to these 1,2-dimethylcyclohexyl chlorides is well documented.²¹ The proton magnetic resonance (pmr) spectra of X and Y indicated that no olefins were present

(1) (a) Presented in part at the 157th National Meeting of the American Chemical Society, Minneapolis, Minn., Apr 1969, Abstracts, ORGN-71; (b) taken from the Ph.D. Thesis of T. M. H., The Pennsylvania State University, 1970.

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(8) P. S. Bailey, J. E. Keller, and T. P. Carter, *J. Org. Chem.*, **35**, 2777 (1970), and references therein.

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(12) L. G. Galimova, V. D. Komissarov, and E. T. Denisov, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 307 (1973).

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(15) G. A. Hamilton, J. R. Giacin, T. M. Hellman, M. E. Snook, and J. W. Weller, *Ann. N. Y. Acad. Sci.*, **212**, 4 (1973).

(16) G. A. Hamilton in "Molecular Mechanisms of Oxygen Activation," O. Hayaishi, Ed., Academic Press, New York, N. Y., 1974, p 405.

(17) Previous results by others^{18,19} with less accurate analytical procedures had indicated a greater degree of retention.

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(19) W. P. Long, Jr., Ph.D. Thesis, Harvard University, 1955.

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(21) G. S. Hammond and T. D. Nevitt, *J. Amer. Chem. Soc.*, **76**, 4121, 4124 (1954); G. S. Hammond and C. H. Collins, *ibid.*, **82**, 4323 (1960).

immediately after isolation. Gas chromatographic analysis of either X or Y, however, showed, in addition to the chloride peaks, three peaks with the same retention times as the isomeric olefins formed on elimination of HCl. These peaks accounted for *ca.* 30% of the total area. It is believed that these olefins are formed by the elimination of HCl from the chlorides in the injector port (temperature, 165°) of the gas chromatograph. In addition to peaks corresponding to the alkanes, the gas chromatogram of pmr-pure X showed a peak at the retention time of Y with an area 8–10% of the area of X. This indicates that some isomerization as well as elimination occurs in the injector port. Thus, the values for the isomer distributions of the tertiary chlorides listed in Table III indicate that the chlorides are probably formed with complete inversion of configuration.

The assignment of configurations to X and Y could not be made on the basis of their mass spectra (which are essentially identical) or pmr spectra^{1b} (which are different but the differences could not be definitively interpreted in terms of the two structures). Compound X was assigned the *trans* configuration and Y the *cis* configuration on the basis of the following criteria. (1) The *trans* isomer is expected to be the thermodynamically more stable isomer and the method of synthesis should give the thermodynamically more stable isomer in greater amounts. (2) Only X could be isolated from a reaction involving the addition of HCl gas to 1,2-dimethylcyclohexene under conditions similar to those used in related reactions where the *trans* isomer was shown to predominate.²¹ (3) Since the compounds should have similar polar characteristics, the compound (X) with the shorter retention time on gas chromatography should have the lower boiling point, and studies with related compounds show the *trans* isomer to have the lower boiling point.²¹ (4) Under E2 elimination conditions (2 *N* sodium ethoxide²¹) the only alkene formed in significant amounts from X is 1,2-dimethylcyclohexene (the isomeric alkenes do not isomerize under the reaction conditions); only the *trans* isomer can give 1,2-dimethylcyclohexene by an E2 elimination.

Gas Chromatographic Methods. Perkin-Elmer Series 800 gas chromatographs equipped with dual flame ionization detectors were used for all quantitative analyses. Chromatographic peaks were identified both by comparison of retention times with those of authentic compounds and by adding known compounds to mixtures being analyzed. The relative amounts of the products formed in a given reaction were calculated by multiplying the observed peak areas by conversion factors determined (immediately prior to each analysis) using known amounts of the products. N₂ at a flow rate of *ca.* 25 ml/min was used throughout as carrier gas. The columns and conditions utilized were: 12 ft × 1/8 in. 20% polypropylene glycol on Chromosorb W (Perkin-Elmer designation R), temperature, 140° for analyses of products from cyclohexane ozonation, 145–160° for analyses of alcohol and chloride products from *cis*- and *trans*-1,2-dimethylcyclohexane ozonations, and 80° for analyses of products from 2-methylbutane ozonations; 8 ft × 1/8 in., 20% Carbowax 20M on Gas Chrom Z at temperatures from 180 to 215° for analyses of products from the ozonations of substituted toluenes. Several product identifications were checked using a 12 ft × 1/8 in. fluorinated silicone oil column (Perkin-Elmer designation FS-1265).

All preparative gas chromatography was performed using a Varian Aerograph A90-P3 chromatograph equipped with a thermal conductivity detector. Helium was used as carrier gas and the column containing silicone gum rubber (SE-30) measured 20 ft × 0.25 in.

Reaction and Analysis Procedures. These were similar to those previously described⁹ unless otherwise noted. The method of Bailey and Reader²² was used for removing O₂ from the O₃ and replacing it with N₂. With O₂ as carrier gas, ozone at the rate of *ca.* 1 mg/min was bubbled through the reaction solutions (12–20 ml). With N₂ as carrier gas the rate could not be controlled with accuracy but the amount of ozone added was determined using a stream splitter and iodometric titration. The ozonations were carried out at room temperature (0° for 2-methylbutane to minimize evaporation) for periods up to 2 hr.

When FeCl₃ was not present, small aliquots of the cyclohexane and 1,2-dimethylcyclohexane reaction mixtures were injected directly into the gas chromatograph for analysis. With FeCl₃ present, the reaction mixtures following ozonation were mixed with an equal volume of water (to remove the FeCl₃), and an aliquot of the

organic layer was injected into the gas chromatograph. Control experiments using known amounts of products indicated that the organic layer had the same molar ratio of cyclohexanol to cyclohexanone or *cis*- to *trans*-1,2-dimethylcyclohexyl alcohols and chlorides as the original reaction mixture.

Following the ozonations of 2-methylbutane and the binary solutions of the toluenes, the product mixtures were reduced with LiAlH₄^{1b,9} to simplify the quantitative product analysis. Control experiments with known amounts of the probable alcohol, aldehyde, ketone, and acid products indicated that less than 5% of any alcohol is lost by this procedure and greater than 95% of the other products are converted to the corresponding alcohols.

Results

Effect of Carrier Gas: O₂ or N₂. In the earlier work⁹ O₂ was used as carrier gas for the ozone. In Table I are shown some representative experiments

Table I. Effect of Carrier Gas (O₂ or N₂) on the Characteristics of Some Alkane Ozonations

Compd ozonized ^a	Carrier gas	Relative yield of products ^b		
		% cyclohexanol	% cyclohexanone	
Cyclohexane	O ₂	75	25	
Cyclohexane	N ₂	79	21	
		Relative yield of tertiary alcohols ^c		
		% <i>cis</i>	% <i>trans</i>	
<i>cis</i> -DMC ^d	O ₂	85	15	
<i>cis</i> -DMC	N ₂	86	14	
<i>trans</i> -DMC	O ₂	21	79	
<i>trans</i> -DMC	N ₂	19	81	
		Relative reactivity per hydrogen ^e		
		Primary	Secondary	Tertiary
2-Methylbutane	O ₂	1	13	110
2-Methylbutane	N ₂	1	10	100

^a For reaction and assay conditions, see the Experimental Section and the earlier report.⁹ ^b Extrapolated to zero time, reproducibility ± 5%. ^c Reproducibility ± 2%. ^d DMC means 1,2-dimethylcyclohexane. ^e Reproducibility ± 5%.

comparing the effect of N₂ as carrier gas with that of O₂. Since cyclohexanol is oxidized to cyclohexanone under the reaction conditions,⁹ the values given for the relative yields of cyclohexanol and cyclohexanone are those obtained after extrapolation of the observed relative yields at various times to time zero (when the ozonation began). The relative yields of tertiary alcohols formed from the isomeric 1,2-dimethylcyclohexanes (DMC), and the relative reactivity per hydrogen obtained using 2-methylbutane as reactant, are invariant with time for ozonations up to 3 hr.

The results shown in Table I clearly indicate that the carrier gas has little if any effect in the experiments listed. This is true for most other characteristics determined during this work also. There may be a slight enhancement in the absolute amounts of products formed with O₂ as carrier gas. Thus, when 1.0 mmol of ozone was added over *ca.* 45 min to cyclohexane with O₂ as carrier, 0.30 mmol of cyclohexanone, 0.20 mmol of cyclohexanol,²⁵ and 0.06 mmol of peroxides²⁴ are formed.

(23) The ratio of cyclohexanol to cyclohexanone is different from that shown in Table I because some of the alcohol is oxidized by ozone to the ketone after 45 min.

(24) Analyzed as described by C. D. Wagner, R. H. Smith, and E. D. Peters, *J. Anal. Chem.*, **19**, 976 (1947).

(22) P. S. Bailey and A. M. Reader, *Chem. Ind. (London)*, 1063 (1961).

Table II. Effects of Solvent and Various Additives on the Relative Ratios of Some Products Formed on Ozonation of Cyclohexane and *cis*-DMC^a

Additive (mol %)	Rel amounts ^b of cyclohexanol and cyclohexanone formed from cyclohexane		Rel amounts ^c of tertiary alcohols formed from <i>cis</i> -DMC	
	% alcohol	% ketone	% <i>cis</i>	% <i>trans</i>
None	75	25	85	15
Alkane ^d (90)	75	25	87	13
Nitrobenzene (90)	76	24	87	13
Acetic acid (90)			85-90 ^e	15-10 ^e
Octadecane (90)	80	20	91	9
Ethyl acetate (90)	40	60	78	22
Acetone (90)	33	67	65	35
Acetonitrile (90)	32	68	74	26
Cumene (12)			85	15
2,4-Di- <i>tert</i> -butylphenol (9)			73	27
Diphenylamine (5)	69	31	69	31
Chloroform (10)			85	15
CBrCl ₃ (16)	72	28	80	20
Iodine (7)			70	30

^a The products obtained from cyclohexane, and the tertiary alcohols formed from *cis*-DMC, were determined in separate experiments. The results reported were obtained with O₂ as carrier gas for the ozone, but most were also run with N₂ as carrier gas and no detectable differences were noted. ^b Extrapolated to zero time; reproducibility $\pm 5\%$. ^c Reproducibility $\pm 2\%$. ^d The added alkane was cyclopentane for the experiment where the products from cyclohexane were determined, and was cyclohexane for the experiment where the products from *cis*-DMC were determined. ^e For technical reasons the accuracy here is less than in the other experiments.

rated hydrocarbon solvents to more polar solvents such as nitrobenzene or acetic acid. Increasing the solvent viscosity (octadecane) results in a significant increase in the retention of configuration in the *cis*-DMC ozonation, and probably a decrease in the relative amount of cyclohexanone to cyclohexanol produced in the ozonation of cyclohexane. The final group of solvents (ethyl acetate, acetone, and acetonitrile) lowers the retention of configuration and increases the relative amount of cyclohexanone. These latter results are probably due to the reaction of ozone with the solvents to produce radical species which subsequently react with *cis*-DMC and cyclohexane to produce different ratios of the reaction products. It was observed that these solvents react readily with ozone to produce a number of unidentified products.

The last group of additives in Table II are those which are known to act as free radical traps. In no case do these compounds increase the per cent retention of configuration; the changes which are observed are probably again due to subsequent reactions of radicals produced on reaction of ozone with these additives.

Effects of FeCl₃. In Table III are shown the effects of various FeCl₃ concentrations on the isomer distribution of tertiary alcohols produced during the ozonation of *cis*- and *trans*-DMC in 80 vol % acetone (added for solubility reasons). Since alkyl chlorides are also formed during the ozonation in the presence of FeCl₃, Table III also gives the isomer distribution of tertiary chlorides. Control experiments showed that the alkyl chlorides are not formed from the tertiary alcohols

Table III. The Effect of Ferric Chloride on the Isomer Distributions of Tertiary Alcohols and Tertiary Chlorides Formed upon Ozonation of *cis*- and *trans*-DMC^a

Molarity of FeCl ₃	Configuration of DMC ozonized	O ₃ carrier gas	Isomer distribution of tertiary alcohols		Obsd ^b isomer distribution of tertiary chlorides	
			<i>Cis</i>	<i>Trans</i>	<i>Cis</i>	<i>Trans</i>
0.00	<i>Cis</i>	O ₂	70	30		
0.00	<i>Cis</i>	N ₂	70	30		
0.06	<i>Cis</i>	O ₂	77	23		
0.06	<i>Cis</i>	N ₂	84	16		
0.12	<i>Cis</i>	O ₂	92	8		
0.12	<i>Cis</i>	N ₂	90	10	<8	>92
0.24	<i>Cis</i>	O ₂	97	3		
0.24	<i>Cis</i>	N ₂	98	2		
0.36	<i>Cis</i>	O ₂	98	2		
0.36	<i>Cis</i>	N ₂	98	2		
0.00	<i>Trans</i>	N ₂	35	65		
0.12	<i>Trans</i>	N ₂	25	75	>90	<10
0.24	<i>Trans</i>	N ₂	9	91	>91	<9
0.36	<i>Trans</i>	N ₂	3	97	>93	<7

^a In 80 vol % acetone at room temperature. ^b Uncorrected for isomerization in the injector port.

With N₂ as carrier gas, 0.19 mmol of cyclohexanone, 0.16 mmol of cyclohexanol,²⁰ and 0.03 mmol of peroxides are formed from 1 mmol of ozone. The small amount of reaction with O₂ probably arises from reactions with radicals formed during the ozonation (see Discussion). However, the results of Table I strongly indicate that under the reaction conditions used in this research the alkane oxidation is primarily the result of a direct reaction of ozone with the alkane, and is not due to some long chain autoxidation process.

Effects of Solvent and Various Additives. As shown in Table II, the relative ratios of hydrocarbon ozonation products are unaffected by changing from satu-

(which are stable to the FeCl₃ solution under the reaction conditions), nor are they formed in the reaction mixture in the absence of ozone.

The results summarized in Table III indicate that with high concentrations of FeCl₃ the tertiary alcohols are formed with virtually complete retention of configuration; this is the first documented example of an essentially stereospecific ozonation of alkanes to alcohols. Again, changing the carrier gas from O₂ to N₂ has no significant effect on the isomer distributions. The isomer distribution of the tertiary chlorides is also surprising; the results indicate that the tertiary chlorides are formed with essentially complete inversion of configuration.

The small observed percentage of isomerized chloride is probably the result of some isomerization occurring in the injector port of the gas chromatograph during the analysis procedure (see Experimental Section). The relative yield of tertiary chlorides (cis and trans) to tertiary alcohols (cis and trans) is 0.3–0.4 when the FeCl_3 concentration is 0.35 M .

The formation of alkyl chloride, in addition to the normal ozonation products, was also observed on ozonizing cyclohexane in the presence of FeCl_3 . In Table IV are summarized the relative amounts of these

Table IV. The Effects of Ferric Chloride, Carrier Gas, and Diphenylamine on the Relative Yields of Products Formed upon Ozonation of Cyclohexane^a

FeCl_3, M	Diphenyl- amine, M	O_3 carrier gas	Molar ratios of products ^b	
			$\text{R}=\text{O}^c/\text{ROH}$	$\text{RCl}/(\text{ROH} + \text{R}=\text{O})$
0	0	O_2	2.0	
0	0	N_2	1.5	
0.49	0	O_2	1.1	4.3
0.49	0	N_2	0.14	23
0	0.49	O_2	0.30	
0	0.49	N_2	0.25	
0.49	0.49	O_2	0.14	0.89
0.49	0.49	N_2	0.11	2.4

^a In 80 vol % acetone at room temperature. ^b Abbreviations used are: $\text{R}=\text{O}$, cyclohexanone; ROH , cyclohexanol; RCl , cyclohexyl chloride. ^c Extrapolated to zero time.

products obtained with FeCl_3 present as well as those obtained when a good hydrogen atom donor such as diphenylamine is present. It can be seen that the relative amount of chlorocyclohexane is decreased when O_2 is used as carrier gas and when diphenylamine is present. All of FeCl_3 , N_2 carrier gas, and diphenylamine decrease the ketone to alcohol ratio and the effects seem to be additive. In this solvent (80 vol % acetone) with diphenylamine present and no FeCl_3 , the ketone to alcohol ratio is about the same as that in pure alkane solvent (Table I). Thus, it is likely that the diphenylamine is mainly trapping radicals produced from the ozonation of acetone. Consequently, the products formed with diphenylamine and FeCl_3 present are probably a better indication of the FeCl_3 effect on the direct ozonation of cyclohexane. Under such conditions very little ketone is formed and the chlorocyclohexane and cyclohexanol are formed in comparable amounts.

Effects of Substituents. The polar characteristics of the transition state leading to the initial intermediate in the ozonation of alkanes were investigated by determining (from competition experiments) the effects of substituents on the side-chain ozonation of substituted toluenes. Thus, known amounts of two different toluenes, present in large excess (no solvent), were ozonized simultaneously. The side-chain products were reduced to the benzyl alcohols by lithium aluminum hydride under conditions that were shown to effect at least 95% reduction of any aldehyde or acid present. Also, any benzyl alcohol subjected to the reduction procedure could be recovered in over 95% yield. The relative yields of the benzyl alcohols are thus a direct measure of the relative reactivity toward ozone of the methyl groups of the substituted toluenes. Figure 1 shows a plot of $\log(A_x/A_0)$ vs. the Hammett σ

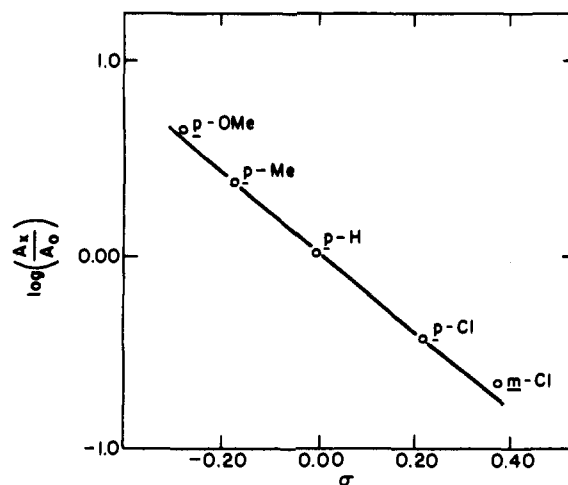


Figure 1. σ - ρ plot for the side-chain ozonation of toluenes. For definition of the coordinates, see the text.

values²⁵ where A_x/A_0 is the ratio of the amount of the benzyl alcohol formed from the substituted toluene to the amount formed from toluene itself (corrected for equimolar amounts of reactants and by a statistical factor of 2 for *p*-xylene). The observed ρ value of -2.07 has a correlation coefficient of 0.995, calculated by least-squares analysis.²⁶ A plot of $\log(A_x/A_0)$ vs. the Brown σ^+ substituent constants²⁷ gave a much poorer correlation and a ρ value of approximately -1.35 (correlation coefficient, 0.955). A change from hydrocarbon solvent to methanol results in no change in the observed ρ value. The deuterium isotope effect for the side-chain ozonation of toluene, determined by competition studies, is 4.0.

Discussion

Two of the more interesting observations of the present investigation of alkane ozonation are that alcohols are formed with virtually complete retention of configuration when FeCl_3 is present, and that alkyl chlorides with essentially complete inversion of configuration are formed under the same conditions. The formation of the inverted alkyl chloride, and the effects of FeCl_3 on the relative amounts of the other products, indicate that the FeCl_3 is not just complexing with the ozone to change its reactivity, but rather is trapping some intermediate in the reaction. The observation,^{1b} that the relative reactivity of primary, secondary, and tertiary hydrogens is not altered significantly when FeCl_3 is present, is further evidence that FeCl_3 does not change the ozone reactivity.

The intermediate which FeCl_3 traps is presumably an incipient alkyl radical; alkyl radicals are known to react by chlorine atom transfer with FeCl_3 .²⁸ Furthermore, there seems little doubt that some alkyl radicals are involved in the ozonation reaction in the absence of FeCl_3 .⁹ Well-known reactions of such radicals with

(25) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, N. Y., 1940, Chapter VII.

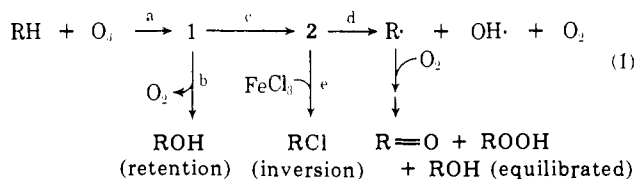
(26) M. G. Natrella, "Experimental Statistics," Handbook 91, U. S. Dept. of Commerce, National Bureau of Standards, 1963.

(27) H. C. Brown, J. A. Brady, M. Grayson, and W. H. Bonner, *J. Amer. Chem. Soc.*, **79**, 1897 (1957).

(28) (a) J. K. Kochi, *Rec. Chem. Progr.*, **27**, 207 (1966); (b) J. K. Kochi in "Free Radicals," Vol. 1, J. K. Kochi, Ed., Wiley-Interscience, New York, N. Y., 1973, p 591.

O₂²⁹ yield many of the observed ozonation products, namely, equilibrated alcohol, ketone, peroxide, etc. The decrease in the relative yields of these products (Tables III and IV) when FeCl₃ is present, and the observed differences between the results obtained with O₂ and N₂ as the ozone carrier gas, are consistent with this interpretation. However, since O₂ is produced in the alkane ozonation reaction, some of the products characteristic of the R· + O₂ reaction are observed even with N₂ carrier gas. When acetone is present (necessary to solubilize the FeCl₃) some of the results are complicated by the reaction of O₃ with the solvent; this solvent reaction apparently leads in the absence of FeCl₃ to some ill-defined radical reactions giving increased amounts of equilibration and ketone products. When FeCl₃ is present, the FeCl₃ apparently traps the radicals formed from the acetone-ozone reaction before they react with the alkane; the stereochemical results listed in Table III indicate that this must occur. Thus, in discussing the mechanism of the direct reaction of O₃ with alkanes, it seems legitimate to compare the relative yields of alkane oxidation products formed in the absence of acetone with those formed in the presence of acetone as long as FeCl₃ is present.

The simplest overall alkane ozonation mechanism, which is consistent with the results reported here and earlier,⁹ is that shown in eq 1, where 1 and 2 are inter-



mediates, although 1 could possibly be a combination of two transition states (see later). In the absence of FeCl₃ the competition between steps b and c would determine the products formed, and at least for oxidation at a tertiary position, the reaction occurs mainly by step b (60–70% net retention of configuration). The formation of alkyl chloride with inverted configuration indicates that FeCl₃ reacts with some intermediate prior to the formation of the "free" alkyl radical, R·.³⁰ Thus intermediate 2 must be on the pathway which leads in the absence of FeCl₃ to equilibrated alcohol product, but the alcohol with retention of configuration cannot arise from the same intermediate because FeCl₃ changes the ratio of the two types of alcohol. Thus, there must be two intermediates (1 and 2) as illustrated in eq 1, or possibly the alkane and ozone react by two paths, one to give 2 directly (step c') and the other to give the alcohol with retention of configuration directly (step b'). In most of the following discussion the general mechanism of eq 1 will be assumed, but if steps c' and b' account for the formation of 2 and alcohol with retention of configuration, respectively, very similar comments would apply.

The observation, that solvent polarity does not affect the product ratio of equilibrated alcohol to alcohol

(29) W. A. Pryor "Free Radicals," McGraw-Hill, New York, N. Y., 1966; G. A. Russell, *J. Amer. Chem. Soc.*, **79**, 3871 (1957).

(30) Alkyl radicals free in solution equilibrate very rapidly; even O₂ at 1 atm pressure cannot trap them before they are equilibrated.^{31,32}

(31) P. D. Bartlett, R. E. Pincock, J. H. Rolston, W. G. Schindel, and L. A. Singer, *J. Amer. Chem. Soc.*, **87**, 2590 (1965).

(32) G. A. Hamilton and J. R. Giacin, *J. Amer. Chem. Soc.*, **88**, 1584 (1966).

with retention of configuration (Table II), indicates that the transition states for b and c must have similar polar characteristics. The small increase in net retention of configuration (Table II) when the solvent viscosity is increased (octadecane) implies that 2 is a solvent-caged radical pair and that step c is at least partly reversible. Similar viscous solvent effects on the separation of radicals from radical pairs have been observed.³³ The reaction of 2 with FeCl₃ to give alkyl chloride with inversion of configuration is readily understandable if 2 is a solvent-caged radical pair. Thus, 2 would have reactivity like an alkyl radical, and be able to accept a chlorine atom from FeCl₃, but the side of the molecule from which the hydrogen is abstracted would be protected by the accompanying radical. Therefore, the chlorine atom could only come in from the other side to give inverted product.

The following observations define some of the characteristics of step a, the initial step in the reaction: (1) the deuterium isotope effect ($k_H/k_D = 4.0\text{--}4.5$) determined from competition experiments indicates a large amount of carbon-hydrogen bond breaking in the transition state; (2) the observation that the relative reactivities of primary, secondary, and tertiary carbon-hydrogen bonds is 1:13:110³⁴ indicates^{9,15,16} that the transition state for step a has some polar character (relative reactivity differences somewhat greater than for typical radical reactions); (3) the ρ of -2.07 for the ozonation of substituted toluenes is additional evidence for considerable polar character (partial positive charge on the reacting carbon) in the transition state for step a; (4) the observation⁹ that equatorial tertiary hydrogens react seven times more readily than axial tertiary hydrogens suggests that step a has considerable steric requirements.

What is the structure of 1? Although good evidence exists for trioxides (ROOOH) as intermediates in the ozonation of aldehydes, ethers, and alcohols,^{2,5,7,35} it is unlikely that 1 is a trioxide. Whiting and coworkers⁷ could find no evidence for a trioxide intermediate in alkane ozonations under conditions where the trioxide formed on 2-propanol oxidation is readily detected. Since the alkane trioxide should be at least as stable kinetically as that formed from alcohols and ethers,³⁶ the above results imply that a trioxide is not an intermediate in alkane ozonations.

A structure for 1 consistent with all our results is that shown in eq 2 (no specific geometrical relationship is implied in the proposed structure for 1). Bond energy considerations³⁷ indicate that the decomposition of HO₃· to HO· and O₂ is exothermic by 15 kcal/mol. There-

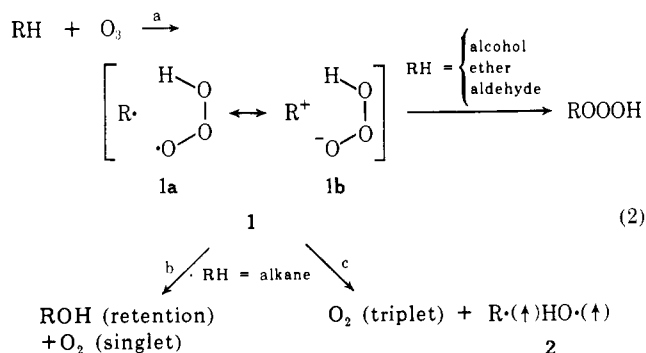
(33) H. Kefer and T. G. Traylor, *J. Amer. Chem. Soc.*, **89**, 6667 (1967); J. C. Martin and S. A. Dombchik, *Advan. Chem. Ser.*, No. 75, 269 (1968); T. Koenig and H. Fischer in ref 28b, p 157.

(34) These values were determined in this and the earlier work⁹ from the analysis of products following the ozonation of 2-methylbutane. Williamson and Cvetanovic¹⁰ found greater differences from direct rate measurements with various alkanes. The reason for this variation is not completely apparent, but the reactivities determined from product analysis might have been affected by the partial involvement of some less selective radicals (HO· and RO·) formed as indicated in eq 1. In any event, the differences are not important to our mechanistic considerations.

(35) R. W. Murray, W. C. Lumma, Jr., and J. W. P. Lin, *J. Amer. Chem. Soc.*, **92**, 3205 (1970).

(36) The alcohols and ethers can decompose to ketone, water (or alcohol), and O₂ by a cyclic six-membered transition state,³⁵ but the alkane trioxide could not decompose by the same mechanism.

(37) S. W. Benson and R. Shaw in "Organic Peroxides," Vol. 1, D. Swern, Ed., Wiley-Interscience, New York, N. Y., 1970, p 105.



fore, if **1a** is by far the major contributor to the structure of **1**, it is expected that oxygen–oxygen bond cleavage should occur very readily. The same energy considerations do not apply to the decomposition of HO_3^- to O_2 and OH^- because of large solvation effects including internal solvation in a structure such as **1b**. Thus, the greater the contribution of structure **1b** to the resonance hybrid, **1**, the more likely it is to collapse directly without oxygen–oxygen bond cleavage to give the trioxide. In all cases where the trioxide has been identified a relatively stable carbonium ion (R^+) is possible. Structure **1b** would contribute less in the alkane ozonation reaction, and thus oxygen–oxygen bond cleavage to give O_2 and other products seems reasonable.

Since the reactants, alkane and O_3 , are both singlet molecules, **1** would have all its electrons paired. However, because the product, O_2 , can exist in two energetically accessible states (singlet and triplet) it is not surprising that **1** could decompose by two pathways to give O_2 . If singlet O_2 is formed, then the other fragments must have their electrons paired (spin conservation rule), and one expects they would collapse directly to alcohol with retention of configuration. On the other hand, if triplet O_2 is formed, the other fragments must have their electrons unpaired and they cannot collapse to give alcohol without spin inversion. Thus, a triplet radical pair (**2**) would be formed which would eventually diffuse apart to give free radicals, or in the presence of FeCl_3 could be trapped to give RCl with inversion of configuration.

The question arises again whether **1** is an actual intermediate or is a combination of transition states for steps b' and c'. As indicated earlier, our results are consistent with either interpretation. Benson³⁸ has

(38) S. W. Benson, *Advan. Chem. Ser.*, No. 77, 74 (1968).

estimated that the reaction: $\text{RH} + \text{O}_3 \rightarrow \text{R} \cdot + \text{HOOO} \cdot$ is endothermic by at least 20 kcal/mol. Thus, unless structures like **1b** contribute greatly to the stability of **1**, it could certainly not be a very stable intermediate. Partial oxygen–oxygen bond breaking as is possible in the transition states for b' and c' could lower the energy barrier considerably from 20 kcal/mol. Since the reaction occurs readily at temperatures below 0° , the activation energy must be less than that. The fact that the reactivity of substituted toluenes correlates better with σ rather than σ^+ might be construed as evidence that the reaction is concerted (step b' transition state would have five groups surrounding the reacting carbon and thus little resonance possibilities with the ring) rather than involving a trigonal intermediate as illustrated for **1** in eq 2. Also, the apparently large steric requirements would be more consistent with a concerted mechanism. In any event, if **1** is an intermediate it is not expected to be much of a depression on the reaction coordinate profile.

The conversion of RH to ROH with retention of configuration is an oxygen atom insertion reaction but one in which a free oxygen atom is not involved. By analogy to related carbenoid reactions it is referred to as an oxygen transfer or oxenoid reaction.³⁹ Many similar oxenoid reactions are believed to occur in biological systems.^{14–16,39} Although it is unlikely that ozone itself is an intermediate in any enzymic reaction, the present work does indicate some of the characteristics expected of enzymic oxenoid reagents. Furthermore, it has recently been suggested^{14,16} that “vinylogous ozone” (ozone with a carbon–carbon double bond between two of the oxygens) is an intermediate in several enzymic oxenoid reactions. Since vinylogous ozone would be expected to have many of the properties of ozone itself, the present work indicates that such a species is a reasonable possibility for an oxenoid reagent.

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(39) G. A. Hamilton, *J. Amer. Chem. Soc.*, **86**, 3391 (1964).