solved in 20 ml of ethanol-O-d_1 (>98% OD) containing the sodium ethoxide from 35 mg (1.5 mg-atoms) of sodium was refluxed for 24 hr and recovered by acidification with deuterium chloride.

Registry No.—I (S = 7), 774-05-0; I (S = 8), 4017-56-5; II (S = 7), 13347-95-0; II (S = 8), 13347-96-1; III (S = 8), 13347-97-2; IVa (S = 7), 13347-98-3; IVb (S = 7), 13347-99-4; Va (S = 7), 13348-00-0; Vb (S = 7), 13348-01-1; VI, 13348-02-2; VIII (S = 7), 13348-03-3; VIII (S = 8), 13348-04-4; IX (S = 7), 13348-05-5; IX (S = 8), 13348-06-6; X (S = 7), 13348-07-7; X (S = 8), 13348-08-8; XI, 4242-18-6; XII, 13348-10-2; XIII, 13348-11-3; XIII (2,4-dinitrophenylhydrazone), 13348-12-4; XIV, 13348-13-5.

Direct Oxidation of Alkenes to Ketones Using Peroxytrifluoroacetic Acid–Boron Fluoride[1,2]

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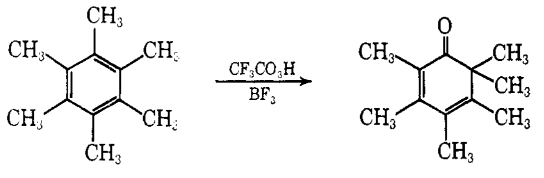
Peroxytrifluoroacetic acid-boron fluoride etherate is shown to be a satisfactory oxidant for effecting a one-step transformation of a number of alkenes to ketones. The products can be explained as the result of attack of positive hydroxyl on the double bond, followed by Wagner–Meerwein rearrangement, to yield the corresponding ketone. The products are shown to be the result of hydrogen, methyl, acyl, chlorine, or bromine migration, as well as of ring contraction.

Previous reports[1] from this laboratory have described the use of peroxytrifluoroacetic acid–boron fluoride as an electrophilic oxidant of substituted aromatic compounds. With hexaalkylbenzenes, hexaalkylcyclohexadienones were obtained in good yields by electrophilic attack of the oxidant, followed by a Wagner–Meerwein rearrangement and proton loss. For example, hexamethylbenzene (**1**) was converted into hexamethyl-2,4-cyclohexadienone (**2**)[3] in 88% yield.



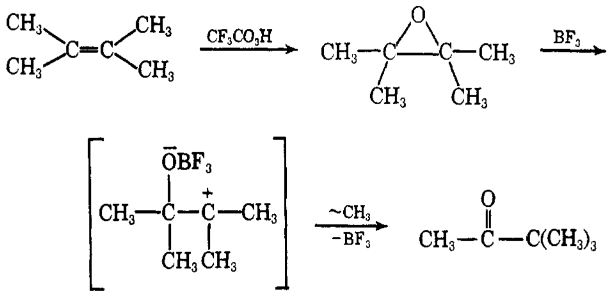
1 2

Since epoxidation of olefins by organic per acids is also believed to proceed by attack of "positive hydroxyl,"[4] and since boron fluoride catalyzes epoxide ring opening to carbonyl compounds *via* Wagner–Meerwein rearrangements,[5] we believed that the oxidation of alkenes with peroxytrifluoroacetic acid–boron fluoride might combine both reactions in sequence and lead to a one-step synthesis of ketones. This paper reports the results of a number of such oxidations.

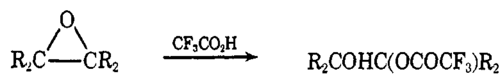
Results and Discussion

The alkenes investigated were either oxidized at 0–8° or allowed to warm to reflux[6] with peroxytrifluoroacetic acid in methylene chloride. Boron fluoride was most conveniently added in the form of its etherate, concurrent with the addition of the peracid dissolved in methylene chloride. The reactions were complete within 15 min after mixing the reagents. Table I summarizes the results.

Oxidation of 2,3-dimethyl-2-butene was expected to give pinacolone, assuming the oxidation and rearrangement occurs as in eq 1. The major product was formed, as predicted, in 75% yield. An intermediate other than the epoxide could be involved since it has been shown by Emmons[7] that the initially formed epoxide, from the oxidation of olefins with peroxytrifluoroacetic acid, further reacts with the trifluoroacetic acid present to give hydroxytrifluoroacetates. To test whether such a trifluoroacetate might be the precursor of pinacolone, the oxidation was run without boron fluoride. The yield of pinacolone was reduced to 16%, and the major product was the hydroxytrifluoroacetate **3**, which on treatment with boron fluoride gave pinacolone quantitatively, possibly as envisioned in eq 2.



(1)



$R_2COHC(OCOCF_3)R_2$

Since even without boron fluoride a 16% yield of pinacolone was found, direct attack of positive hydroxyl on the olefin is a third possibility, where boron fluoride enhances the heterolytic cleavage of peroxytrifluoroacetic acid as in eq 3. Equation 3 is similar

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(1) Paper IX in a series on Oxidations with Peroxytrifluoroacetic Acid–Boron Fluoride; for paper VIII, see H. Hart and R. K. Murray, Jr., *J. Org. Chem.*, in press.

(2) We are grateful to the National Science Foundation and the Army Research Office (Durham) (DA-31-124-ARO-D-157) for financial support of this research.

(3) H. Hart, P. M. Collins, and A. J. Waring, *J. Am. Chem. Soc.*, **88**, 1005 (1966).

(4) For a review, see D. Swern, *Org. Reactions*, **7**, 378 (1953).

(5) For a review, see R. E. Parker and N. S. Isaacs, *Chem. Rev.*, **59**, 737 (1959).

(6) The yields for oxidations run at reflux were as good as or better than those run at 0–8° for the olefins studied at both temperature ranges. The latter temperature range has been generally used for the oxidation of aromatic compounds (see ref 1).

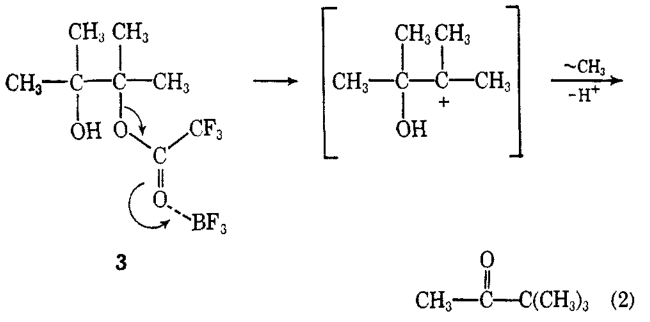
(7) W. D. Emmons, A. S. Pagano, and J. P. Freeman, *J. Am. Chem. Soc.*, **76**, 3472 (1954); W. D. Emmons and A. S. Pagano, *ibid.*, **77**, 89 (1955).

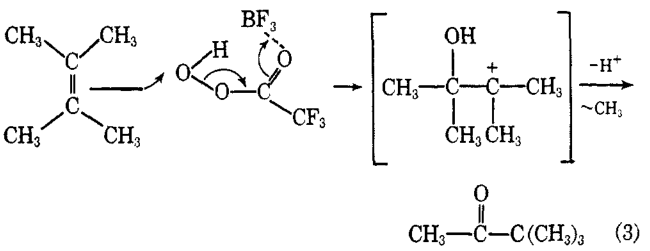
TABLE I

OXIDATION OF ALKENES WITH PEROXYTRIFLUOROACETIC ACID–BORON FLUORIDE

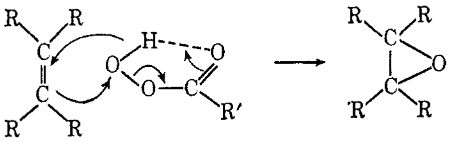
Alkene	Product	Yield,[a] %	Procedure[b]
2,3-Dimethyl-2-butene	3,3-Dimethyl-2-butanone (pinacolone)	72, 75, 75, 16	A–D
2-Methyl-2-butene	3-Methyl-2-butanone	53	A
cis-3-Methyl-2-pentene	3-Methyl-2-pentanone	63	A
trans-3-Methyl-2-pentene	3-Methyl-2-pentanone	70	A
1-Methylcyclohexene	2-Methylcyclohexanone (**4**)[c]	8, 41, 8	A–C
1,2-Dimethylcyclohexene	1-Acetyl-1-methylcyclopentane (**8**)	76	A
$\Delta^{9,10}$-Octalin	Spiro[4.5]decan-6-one (**11**)	86	A
3-Chloro-2-methyl-2-butene	3-Chloro-3-methyl-2-butanone (**12**)	77	B
3-Bromo-2-methyl-2-butene	3-Bromo-3-methyl-2-butanone (**16**)	79	B
2,3-Dibromo-2-butene	3,3-Dibromo-2-butanone (**17**)	61	B
3,4-Dimethyl-3-penten-2-one	3,3-Dimethyl-2,4-pentanedione (**18**)	81	B
2-Cyclopentylidenecyclopentanone	Spiro[4.5]decane-6,10-dione (**22**)	43	B

[a] Yields were obtained by vpc analysis. [b] See Experimental Section. [c] 1-Methylcyclohexyl trifluoroacetate was obtained in 15, 9, and 15% yields, respectively; it was identical with an authentic sample prepared from 1-methylcyclohexene, trifluoroacetic acid, and boron fluoride etherate.



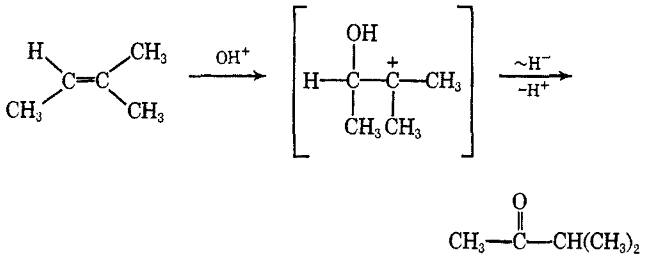


to the mechanism suggested for the epoxidation of olefins[8] where the proton of the per acid, rather than boron fluoride, acts as the electrophile.

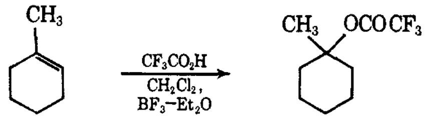


The intermediate postulated in eq 2 and 3 is the same as that postulated for the pinacol rearrangement.[9] At present there is insufficient evidence to choose amongst these or some additional mechanism, so, for simplicity, the attacking species will be represented as OH$^+$.

When 2-methyl-2-butene was oxidized, the exclusive product was 3-methyl-2-butanone, as would be expected by initial attack of the electrophile to form the most stable carbonium ion, followed by hydride migration. Similarly, oxidation of either *cis*- or *trans*-3-methyl-2-pentene gave 3-methyl-2-pentanone in good yield.



A serious side reaction was found in the oxidation of 1-methylcyclohexene. When the oxidation was carried out at 0°, two volatile products were detected. They were identified as 2-methylcyclohexanone (**4**) and 1-methylcyclohexyl trifluoroacetate (**5**) obtained in 8 and 15% yield, respectively. By carrying out the oxidation at reflux, the yield of **4** was improved to 41%, while the yield of **5** dropped to 9%. Compound **5** was undoubtedly formed by the addition of trifluoroacetic acid to 1-methylcyclohexene; **5** was the only product when the per acid was omitted.



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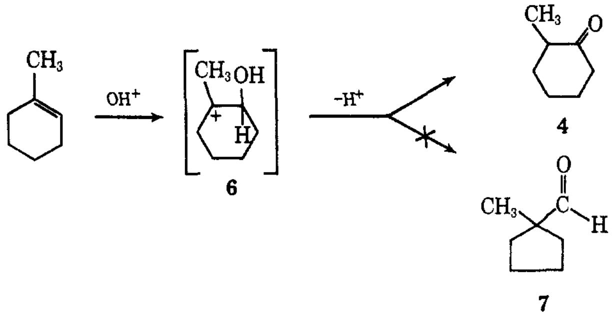
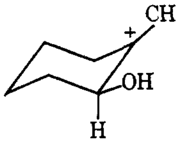
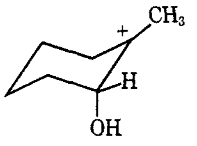
The expected oxidation intermediate **6** might give two products, 2-methylcyclohexanone (**4**) by hydrogen migration or aldehyde **7** by ring contraction, but only **4** was observed. **6a** and **6b** are the two possible carbonium ion intermediates. Either **6a** or **6b** could lead to ring contraction, but only **6a** leads to hydrogen migration. Ion **6a**, with the equatorial hydroxyl, should





6a



6b

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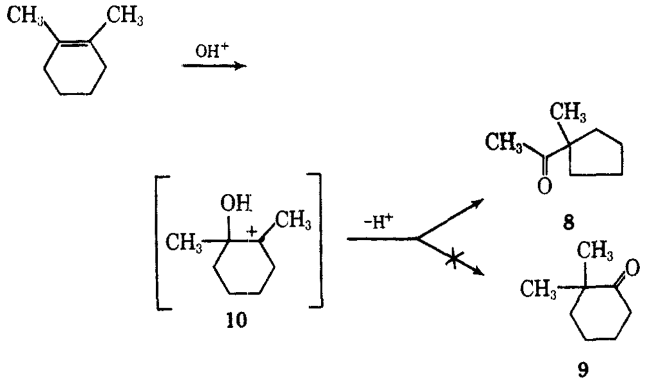
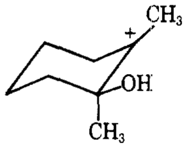
[8] (a) B. M. Lynch and K. H. Pausacker, *J. Chem. Soc.*, 1525 (1955); (b) K. D. Bingham, G. D. Meakins, and G. H. Whitham, *Chem. Commun.*, 445 (1966).

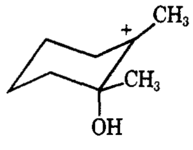
[9] For a review, see C. J. Collins, *Quart. Rev.* (London), **14**, 357 (1960).

be the more stable of the two. From our results **6a** is the preferred intermediate and rearranges exclusively by hydrogen migration.

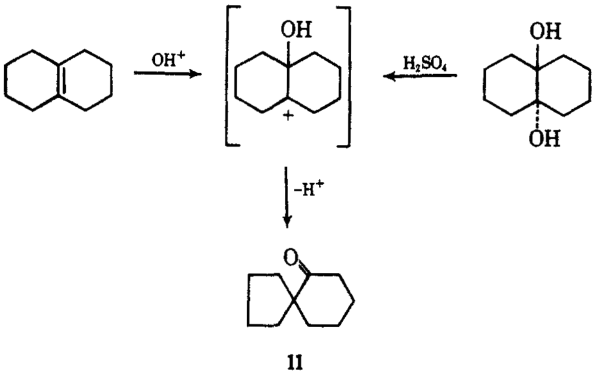
Interestingly, oxidation of 1,2-dimethylcyclohexene gave exclusively the ring-contraction product, 1-acetyl-1-methylcyclopentane (**8**), rather than 2,2-dimethylcyclohexanone (**9**), which would result from methyl migration. In the pinacol rearrangement of the corresponding *cis*[10] and *trans*[11] glycols in sulfuric acid, the only product formed was also **8**, presumably through the same intermediate **10**. When the glycol rearrangement was carried out in $HClO_4$ at various temperatures,[12] the amount of **8** in the rearranged product was found always to be greater than 90%. Bunton and Carr suggest that of the two possible intermediates **10b** should be more stable than **10a** since the carbonium ion center can be stabilized by participation of the hydroxyl group.[13] **10b** can only lead to ring contraction.



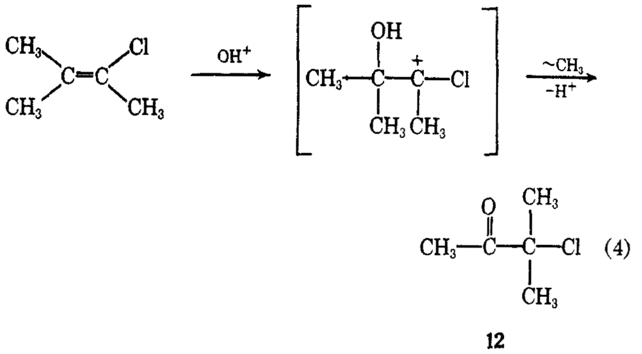

10a

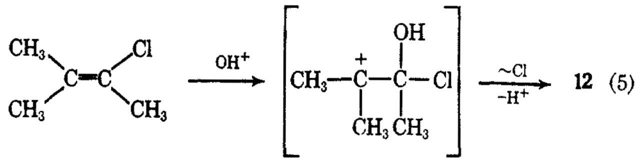

10b

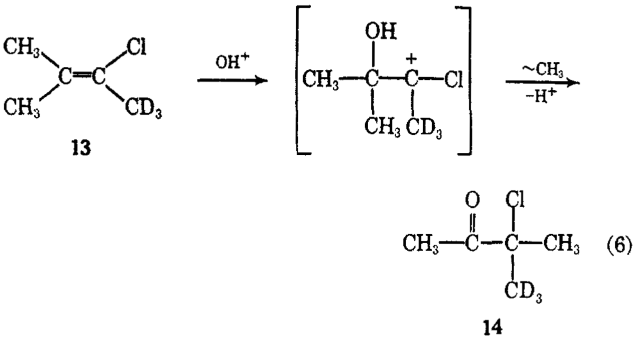
Oxidation of $\Delta^{9,10}$-octalin afforded an additional comparison with the pinacol rearrangement of the corresponding *trans* glycol.[14] As expected, $\Delta^{9,10}$-octalin gave the same spiro ketone (**11**) as the glycol, in 86% yield.

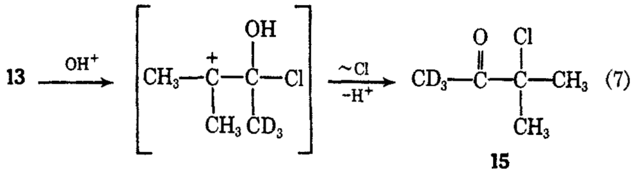


Oxidation of 3-chloro-2-methyl-2-butene offered the interesting possibility for methyl or chlorine migration. The less common chlorine migration has been reported in another olefinic system.[15] The only oxidation product of 3-chloro-2-methyl-2-butene was 3-chloro-3-methyl-2-butanone (**12**), whose structure was assigned on the basis of nmr and infrared spectra (see Experimental Section). This product could arise from two possible intermediates, one in which a methyl group migrates (eq 4) and one in which chlorine migrates (eq 5). To decide between these alternatives, 2-chloro-3-methyl-2-butene-1,1,1-d_3 (**13**) was prepared and oxidized. The product isolated had an nmr spectrum consisting of one singlet at τ 8.36. If methyl migration had occurred the product **14** would have had two singlets (eq 6). The actual product must have arisen, therefore, from chlorine migration (eq 7), where the expected ketone (**15**) would have only a single absorption in the nmr.









To determine whether other halogens might migrate as well, 3-bromo-2-methyl-2-butene was oxidized. The major product was the expected 3-bromo-3-methyl-2-butanone (**16**), identified by its infrared and nmr spectra. Since a suitably labeled bromobutene could

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[10] H. Meerwein, *Ann.*, **542**, 123 (1939).

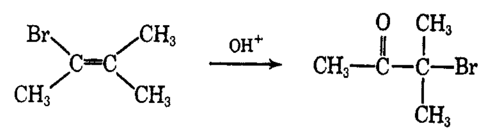
[11] S. Nametkin and others?

[12] C. A. Bunton and M. D. Carr, *J. Chem. Soc.*, 5854 (1963).

[13] In addition, **10b** would also be favored on steric grounds; the methyl group, rather than the smaller hydroxyl group, would be in the equatorial position.

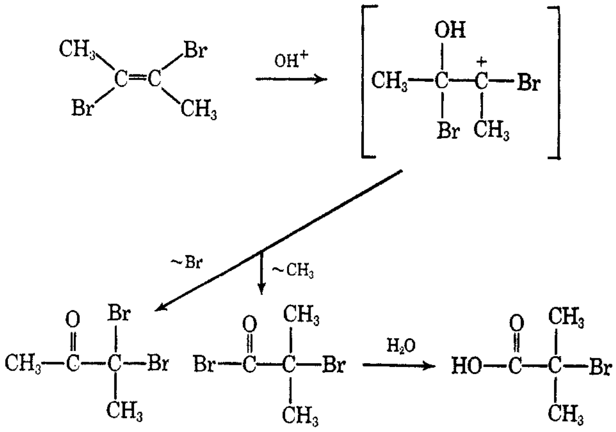
[14] W. Hückel, R. Danneel, A. Schwartz, and A. Gucke, *Ann.*, **474**, 121 (1929).

[15] R. N. McDonald and P. A. Schwab, *J. Am. Chem. Soc.*, **85**, 820, 4004 (1963).



16

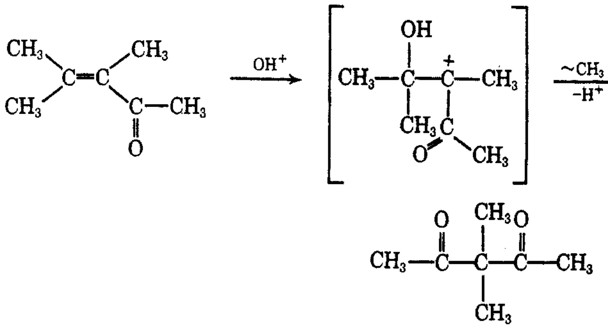
not easily be made, to test whether methyl or bromine migration had occurred we turned our attention to 2,3-dibromo-2-butene where different products would be obtained for bromine and methyl migration (eq 8).



17 (8)

Vpc analysis showed only one product from the oxidation of 2,3-dibromo-2-butene, which was identified as 3,3-dibromo-2-butanone (**17**) by its infrared and nmr spectra, elemental analysis, and independent synthesis (see Experimental Section). Therefore, bromine migration must have taken place. Although bromine migrations in other carbonium ion rearrangements have been reported,[16] we believe these are the first examples of a pinacol-type rearrangement with bromine as the migrating group.

Oxidation of 3,4-dimethyl-3-penten-2-one was of interest, since products could be formed by either methyl or acyl migration. The latter has been observed by House[17] in the boron fluoride rearrangement of a number of α,β-epoxy ketones. The only product detected from this oxidation had spectral and physical properties consistent with the structure 3,3-dimethyl-2,4-pentanedione (**18**) (see Experimental Section). This product could have arisen from either methyl (eq 9) or acyl (eq 10) migration.



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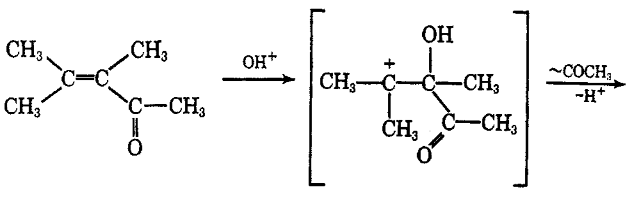
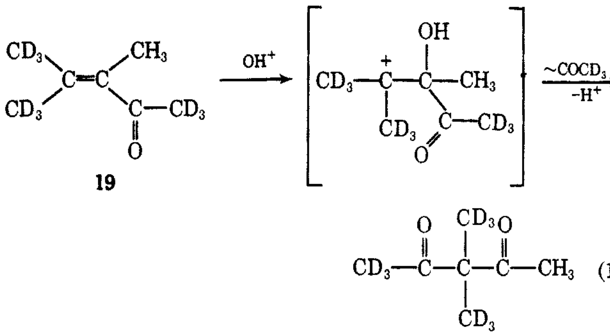


18 (10)

In order to decide between the two paths, 4-methyl-d_3-3-methyl-3-penten-2-one-1,1,1,5,5,5-d_6 (**19**) was prepared and oxidized. The resulting deuterated diketone **20** showed a single peak in the nmr at τ 7.93. Acyl migration (eq 11) must have taken place, since if a methyl group had migrated (eq 12) the resulting diketone **21** would have had a single nmr absorption at higher field (*ca.* τ 8.7).



(11)

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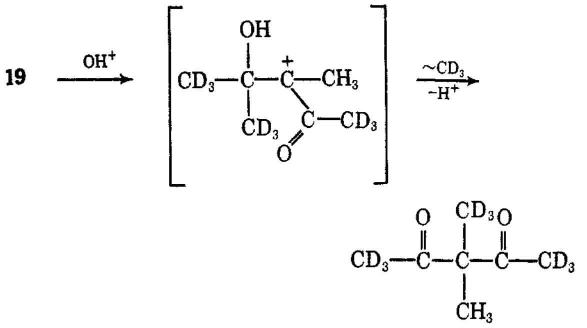

(12)

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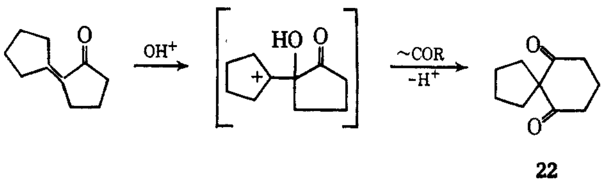
An additional example of acyl migration was found in the oxidation of 2-cyclopentylidenecyclopentanone which gave spiro[4.5]decane-6,10-dione (**22**) in 27% yield. Surprisingly, **22** does not seem to have been previously prepared. Its structural assignment rests on spectral data and chemical transformations. It had infrared carbonyl bands at 1720 and 1695 cm^{-1}. The nmr spectrum showed a triplet (4 H) at τ 7.38 (methylene protons α to the carbonyl) and multiple absorption between τ 7.65 and 8.60 (10 H). Compound **22** was converted with base to 5-cyclopentyl-5-oxopentanoic acid (**23**), whose semicarbazone had a melting point in agreement with the reported value.



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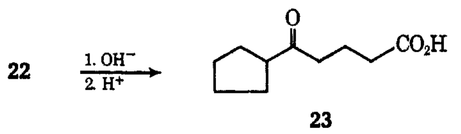

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[16] For example, see H. L. Goering and L. L. Sims, *J. Am. Chem. Soc.*, **79**, 6270 (1957).

[17] H. O. House and G. D. Ryerson, *ibid.*, **83**, 979 (1961), and references therein.

It can be concluded from these results that peroxytrifluoroacetic acid–boron fluoride etherate is a useful oxidant for forming ketones from substituted olefins in one step and for the study of migratory aptitudes in the Wagner–Meerwein rearrangements which lead to the observed products. Alkenes with other functional groups are presently under investigation.

Experimental Section

All spectra are in CCl_4. Nmr chemical shifts are τ values measured from tetramethysilane as an internal standard. Elemental analyses are by Spang Microanalytical Laboratories, Ann Arbor, Mich. Melting points and boiling points are uncorrected.

Starting Materials.—The following alkenes were obtained commercially: 2,3-dimethyl-2-butene,[18] 2-methyl-2-butene,[18] *cis*- and *trans*-3-methyl-2-pentenes,[18] 1-methylcyclohexene,[18] and 2,3-dibromo-2-butene.[19] The following alkenes were prepared by procedures in the literature: $\Delta^{9,10}$-octalin,[20] 3-chloro-2-methyl-2-butene,[21] 3-bromo-2-methyl-2-butene,[22] 3,4-dimethyl-3-penten-2-one,[23] 2-cyclopentylidenecyclopentanone,[24] and 1,2-dimethylcyclohexene.[25] The purity of all starting materials was checked by vpc.

Oxidation of 2,3-Dimethyl-2-butene.[26] **A.**—A methylene chloride solution of peroxytrifluoroacetic acid[27] was prepared by mixing 15.3 g (0.073 mole) of trifluoroacetic anhydride, 20 ml of methylene chloride, and 1.78 ml (0.066 mole) of 90% hydrogen peroxide at 0°. The peracid was added dropwise to a stirred solution of 7.09 ml (0.060 mole) of 2,3-dimethyl-2-butene in 100 ml of methylene chloride at 0–8° over a period of 20 min, during which time 8.3 ml (0.066 mole) of 47% boron fluoride etherate was also added dropwise. The mixture was stirred at 0° for 15 min after addition was completed, then hydrolyzed with 35 ml of water. The organic layer was washed consecutively with two 35-ml portions of water, three 35-ml portions of saturated sodium bicarbonate, and two 35-ml portions of water, then dried over anhydrous magnesium sulfate and the solvent partially evaporated. The residue was diluted with methylene chloride to exactly 100 ml. A small portion of this solution was used for yield determination by vpc comparison with a standard methylene chloride solution of the product. The solvent was removed from the remainder of the solution and vpc analysis was carried out on a 20-ft SE-30 column at 80°. Only one product peak was detected, and it was identified as pinacolone (72% yield) by comparison of vpc retention time and infrared and nmr spectra with those of an authentic sample.

B.—The above procedure was followed except that the methylene chloride solution of 2,3-dimethyl-2-butene was not cooled, and the rate of addition of reagents was adjusted so that the solution refluxed gently. Addition time of reagents was 10 min and the yield of pinacolone was 75%.

C.—The only alteration from procedure A was replacement of boron fluoride etherate with gaseous boron fluoride. The boron fluoride (0.060 mole) was bubbled into the reaction mixture concurrent with, and at the same rate as, the oxidant addition. The gas volume was determined with a flowmeter. The yield of pinacolone under these conditions was 75%.

D.—Procedure A was followed, but the boron fluoride was omitted. Vpc analysis showed a 16% yield of pinacolone, plus an additional product of longer retention time with principle infrared bands (liquid film) at 3500, 1776, 1196, 1140, and 1074 cm^{-1}, consistent with the structure of the hydroxytrifluoroacetate **3** which is the expected product in the absence of boron fluoride.[7]

The reaction mixture was dissolved in 300 ml of CH_2Cl_2 and 0.060 mole of boron fluoride was bubbled through at 0°. After work-up, vpc analysis showed that **3** had been quantitatively converted into pinacolone.

Other Oxidations and Structure Determinations.—All other oxidations followed one or another of the above procedures, as indicated in Table I. The structures of 3-methyl-2-butanone and 2-methylcyclohexanone were identified by comparison of their infrared and nmr spectra and vpc retention time with those of authentic samples. 3-Methyl-2-pentanone was identified by its nmr spectrum (triplet at τ 9.15 (3 H), doublet at τ 8.97 (3 H), multiplet at τ 8.57 (2 H), singlet at τ 7.97 (3 H), and multiplet at τ 7.63 (1 H), and the identity of its infrared spectrum with a published spectrum.[28]

1-Acetyl-1-methylcyclopentane (**8**) had a $\nu_{C=O}$ at 1700 cm^{-1}, nmr singlets at τ 7.87 and 8.77 (3 H each) and a broad band at τ 7.93–8.85 (8 H), and gave a semicarbazone, mp 138.5–141.0° (lit.[10] mp 141°). Spiro[4.5]decan-6-one (**11**) had $\nu_{C=O}$ at 1700 cm^{-1} and gave a semicarbazone, mp 187–190° (lit.[29] mp 188–190°). 3-Chloro-3-methyl-2-butanone (**12**) had a $\nu_{C=O}$ at 1712 cm^{-1} and an nmr spectrum consisting of two singlets at τ 7.68 (3 H) and 8.33 (6 H).[30] 3-Bromo-3-methyl-2-butanone (**16**) was identified on the basis of its infrared ($\nu_{C=O}$ 1710 cm^{-1}) and nmr (τ 7.63 (3 H) and 8.18 (6 H)) spectra. 3,3-Dibromo-2-butanone (**17**) had infrared ($\nu_{C=O}$ 1715 cm^{-1}) and nmr (two equal singlets at τ 7.33 and 7.50) spectra consistent with the assigned structure; **17** was also synthesized independently following the procedure of Schotte,[31] but using 2-butanone. Three products were obtained, two of which had identical nmr spectra with those published for 3-bromo- and 1,3-dibromo-2-butanones.[32] The third had the same retention time and infrared and nmr spectra as those of **17**. *Anal.* Calcd for $C_4H_6Br_2O$: C, 20.90; H, 2.64; Br, 69.51. Found: C, 21.01; H, 2.76; Br, 69.66.

3,3-Dimethyl-2,4-pentanedione (**18**) had mp 21–22° (lit.[33] mp 21–22°); its nmr spectrum had two singlets of equal intensity at τ 7.93 and 8.70. **Spiro[4.5]decane-6,10-dione** (**22**) had bp 100–103° (0.9 mm) and mp 11.5–12.5° (97% pure by vpc). *Anal.* Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.12; H, 8.60. The infrared and nmr spectra are given in the text. A solution of 2 g of **22** and 12 ml of 6 *N* NaOH in 50 ml of ethanol was refluxed for 30 min. The product, after acidification with HCl, was extracted with ether. After removing the solvent the residue was converted directly to its semicarbazone, mp 180–182° (ethanol). The reported value[34] for the semicarbazone of 5-cyclopentyl-5-oxopentanoic acid is 181–182°. *Anal.* Calcd for $C_{11}H_{19}N_3O_3$: C, 54.76; H, 7.94; N, 17.41. Found: C, 54.62; H, 7.96; N, 17.34.

Oxidation of 2-Chloro-3-methyl-2-butene-1,1,1-d_3 (13).—3-Methyl-2-butanone-1,1,1,4-d_4 was prepared by refluxing 3-methyl-2-butanone with anhydrous K_2CO_3 and excess D_2O overnight. The labeled ketone was converted into **13**[21] which was then oxidized by procedure B. The product had only one singlet in the nmr, at τ 8.36.

Oxidation of 4-Methyl-d_3-3-methyl-3-penten-2-one-1,1,1,5,5,5-d_6 (19).—Compound **19**[35] was oxidized by procedure B. The vpc-collected product showed a single peak in the nmr at τ 7.93 and was therefore assigned the structure **3,3-dimethyl-d_6-2,4-pentanedione-1,1,1-d_3 (20)**.

Registry No.—**3**, 13388-92-6; **8**, 13388-93-7; **11**, 13388-94-8; **12**, 5950-19-6; **16**, 2648-71-7; **17**, 2648-69-3; **18**, 3142-58-3; **20**, 13388-97-1; **22**, 6684-66-8; peroxytrifluoroacetic acid, 359-48-8; boron fluoride, 7637-07-2; 3-methyl-2-pentanone, 565-61-7.

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