acetone, cooled to –78 °C, was added to 10 mL of a 0.1 M solution of TPPO in acetone at –78 °C. The reaction mixture was stirred at –60 °C for 24 h and then quenched by triethylamine. VPC analysis showed that no biadamantylidene dioxetane or epoxide had been formed. A control experiment in which the mixture was warmed from –78 °C to room temperature in a period of 30 min gave 79% dioxetane and 21% epoxide by VPC analysis (6 ft, 5% SE-30; 150 °C for 5 min, linear programming with the temperature rising at 20 °C/min to 220 °C, and then held constant). The reaction gave the same results in dichloromethane.

Molecular Weight of TPPO. It was found that freezing point depressions in chloroform could be determined within the precision shown in Table I by using the apparatus already set up for the low-temperature experiments and a low-temperature thermometer with 1 °C graduations. For each solution 3–5 cooling curves were run, each with about ten points, and extrapolated to yield a freezing point reading. The freezing point of pure chloroform was thus determined by averaging the values –61.1, –61.1, –61.0, –60.9, and –60.8 °C (average –60.98, mean deviation 0.104 °C). A solution of TPPO prepared from 3.72 g (12.0 mmol) of triphenyl phosphite in 30.00 g of chloroform at –55 °C, with the usual precautions to avoid any momentary excess of phosphite, yielded from five cooling curves the freezing points –63.8, –63.5, –63.7, –63.6, and –63.0 °C (average –63.52, mean deviation 0.216 °C). If the deviant last point is excluded, the average of the other four is –63.65 °C, and the mean deviation is 0.10, making the deviation of the last point 6.5 times the mean of the others. Both averages are shown in Table I.

When the TPPO solution was warmed, gas evolution was observed at –30 °C, which became very vigorous at –10 °C. After the gas evolution had ceased, the solution was again cooled, and three more cooling curves were determined, leading to mp –63.5, –63.8, and –63.7 °C (average –63.67 °C, mean deviation 0.11 °C). Thus the freezing point depression produced by TPPO was 94% of that produced by the product phosphate, or 99% if the final point for TPPO is rejected.

The freezing point depression by the product of the TPPO decomposition was checked with a solution of triphenyl phosphate (1.30 g, 4.0 mmol) in 10 g of chloroform. The five cooling curves gave freezing points of –63.8, –64.1, –64.2, –64.0, and –63.8 °C (average –63.98 °C, mean deviation 0.14 °C). The depressions produced by equimolar amounts of triphenyl phosphate with these two histories were within 6% of each other.

Registry No. 1, 29833-83-8; 3, 58594-17-5; 4a, 41850-90-2; 4b, 41850-89-9; 6, 110-87-2; 9, 24350-41-2; 10, 3393-45-1; 11, 23603-63-6; 12, 73789-90-9; 13, 1489-69-6; 14, 1121-37-5; 15, 30541-56-1; 16, 35544-39-9; 17, 29186-07-0; 1,2-dimethylcyclohexene, 1674-10-8; 2-methyl-2-butene, 513-35-9; 1-methyl-2-methylenecyclohexyl hydroperoxide, 54683-51-1; 1,2-dimethyl-2-cyclohexen-1-yl hydroperoxide, 54683-52-2; 2,3-dimethyl-2-cyclohexen-1-yl hydroperoxide, 56201-42-4; 1,2-dimethyl-2-propenyl hydroperoxide, 15315-29-4; 1,1-dimethyl-2-propenyl hydroperoxide, 15315-30-7; O₂, 7782-44-7.

Direct Epoxy Alcohol Synthesis from Cyclic Olefins Using O₂ and VO(acac)₂–AIBN Catalyst System

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The vanadium-catalyzed oxidation of cyclic olefins with molecular oxygen is examined. The VO(acac)₂–AIBN system is an efficient catalyst for epoxy alcohol synthesis. Chloro hydrocarbons such as 1,2-dichloroethane and 1,1,2-trichloroethane are suitable solvents for the epoxidation reaction. Cyclohexene (1), methylcyclohexene (2), and cyclododecene (5) give the corresponding epoxy alcohols in good yields; in the case of 2 with the VO(acac)₂–AIBN system, the selectivity to epoxy alcohol reaches over 70%. 1,4-Cyclooctadiene (7) is oxidized to give 9-oxabicyclo[3.3.1]non-3-en-*exo*-2-ol (6a) via the rearrangement of *cis*-2,3-epoxycyclooct-4-en-1-ol. Exceptional is cyclooctene (4), which gives exclusively cyclooctene oxide (4b).

Olefins with hydrogen on the α-carbon undergo autoxidation to give allylic hydroperoxides. Soluble transition metals decompose catalytically the hydroperoxides.[1] Iron, cobalt, and manganese compounds accelerate the autoxidation and the homolytic cleavage of the hydroperoxide forms allylic alcohol and α,β-unsaturated ketone (path A, Scheme I). With molybdenum and tungsten compounds, the oxygen transfer from the hydroperoxide to the starting olefin occurs by the heterolytic cleavage of the hydroperoxide and then both epoxide and allylic alcohol are formed (path B).[2] Furthermore, vanadium compounds are prone to the formation of epoxy alcohol because they epoxidized the allylic alcohol much faster than the parent olefin (path C).[3]

To our knowledge, three groups, Allison,[4] Lyons,[5] and Noels,[6] have reported the epoxy alcohol formation from olefins. For example, Lyons has succeeded in 65% selective formation of epoxycyclohexanol (1a) from the reaction of cyclohexene (1) using CpV(CO)₄ (Cp = cyclopentadienyl) catalyst. In these reactions, 1 has been often used as a representative reactant. Because of the potential significance of epoxy alcohols in general,[7] it is important to examine the scope and limitation of their formation from various olefins with molecular oxygen.

(1) Hiatt, D. "Organic Peroxides"; Wiley: New York, 1971; Vol. II, p 1.

(2) (a) Gould, E. S.; Rado, M. *J. Catal.* 1969, *13*, 238. (b) Fusi, A.; Ugo, R.; Zanderighi, G. M. *Ibid.* 1974, *34*, 175. (c) Arzoumanian, H.; Blanc, A.; Hartig, U.; Metzger, J. *Tetrahedron Lett.* 1974, 1011.

(3) (a) Lyons, J. E. *Adv. Chem. Ser.* 1974, *132*, 64. (b) Itoh, T.; Kaneda, K.; Teranishi, S. *Bull. Chem. Soc. Jpn.* 1975, *48*, 1337.

(4) Allison, K.; Johnson, P.; Foster, G.; Sparke, M. B. *Ind. Eng. Chem. Prod. Res. Dev.* 1966, *5*, 166.

(5) Lyons, J. E. *Tetrahedron Lett.* 1974, 2737.

(6) Noels, A. F.; Hubert, A. J.; Teyssie, P. *J. Organometal. Chem.* 1979, *166*, 79.

(7) (a) Sheng, M. N.; Zajacek, J. G. *J. Org. Chem.* 1970, *35*, 1839. (b) Sharpless, K. B.; Michaelson, R. C. *J. Am. Chem. Soc.* 1973, *95*, 6136. (c) Tanaka, S.; Yamamoto, H.; Nozaki, H.; Sharpless, K. B.; Michaelson, R. C.; Cutting, J. D. *Ibid.* 1974, *96*, 5254. (d) Demuth, M. R.; Garrett, P. E.; White, J. D. *Ibid.* 1976, *98*, 634. (e) Yamada, S.-I.; Mashiko, T.; Terashima, S. *Ibid.* 1977, *99*, 1988. (e) Michaelson, R. C.; Palermo, R. E.; Sharpless, K. B. *Ibid.* 1977, *99*, 1990.

Table I. Cyclohexene Oxidation Catalyzed by Vanadium Catalysts[a]

catalyst	induction period, h	O$_2$ absorption rate, mL of O$_2$/ min·mol	% conversion[b]	% yield[c]	% selectivity[d] 1a	1b	1c	1d
CpV(CO)$_4$[e]	1.5	6.3	17	11	36	33	17	14
CpV(CO)$_4$	0.4	57	29	16	6	17	37	40
VO(acac)$_2$[f]				no reaction				
VO(acac)$_2$ + AIBN[g]	2.5	16.5	24	19	41	28	15	16
V$_2$O$_5$[h]	7.5	11	36	8	41	24	12	23

[a] Reaction conditions: cyclohexene (20 mmol), catalyst (0.1 mmol), O$_2$ (1 atm), 60 ± 1 °C, GLC (OV-17). [b] Based on O$_2$ absorption. [c] Total volatile products, based on O$_2$ absorption. [d] Products: 1a, 2,3-epoxycyclohexanol; 1b, 1,2-epoxycyclohexane; 1c, cyclohex-2-en-1-ol; 1d, cyclohex-2-en-1-one. [e] CpV(CO)$_4$ (0.01 mmol). [f] No reaction within 24 h. [g] VO(acac)$_2$ (0.01 mmol), AIBN (0.1 mmol). [h] Heterogeneous system.

In this paper, we study the epoxidation of a series of cyclic olefins (1–7) with vanadium catalysts and report that many olefins, except cyclooctene (4) which hardly forms the allylic hydroperoxide (4e) as an intermediate, can be taken to the corresponding epoxy alcohols in good yields by one-pot oxidation.

Results and Discussions

Oxidation of Cyclohexene with Vanadium Catalysts. In order to clarify the unique catalysis of vanadium compounds for epoxy alcohol formation, we reexamined the oxidation of 1 with various metal compounds under an oxygen atmosphere. Expectedly, only vanadium compounds gave epoxycyclohexanol (1a) (Table I). As re-


ported by Lyons,[5] the monovalent vanadium compound CpV(CO)$_4$ was an excellent catalyst with a short induction period and moderate selectivity to 1a. In the absence of solvent, VO(acac)$_2$ complex did not show the catalytic activity even after 24 h of reaction. But in the presence of solvents such as 1,2-dichloroethane and benzene, the catalytic activity appeared and the epoxy alcohol 1a was formed after a long induction period, which will be mentioned in a later section. The addition of α,α'-azobis(isobutyronitrile) (AIBN) to VO(acac)$_2$ complex gave 41% of 1a at a faster rate than in the case of CpV(CO)$_4$ catalyst. Heterogeneous V$_2$O$_5$ catalyst gave a larger quantity of nonvolatile products, but no significant difference in the distribution of volatile products was observed between heterogeneous and homogeneous systems.[2a]
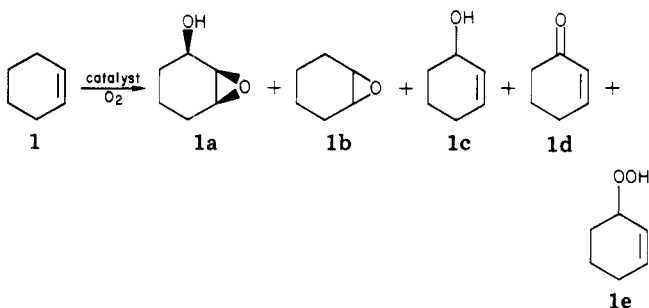
The VO(acac)$_2$–AIBN catalyst system is more advantageous for the present epoxidation than the CpV(CO)$_4$ catalyst because of its handling convenience and low price. It has been reported that the mixed catalyst of rhodium(II) carboxylates and vanadium compounds yielded selectively 1a.[6] However, after the oxidation the separation of two soluble metal compounds seems to be difficult. So we think that this VO(acac)$_2$–AIBN system is a convenient catalyst.
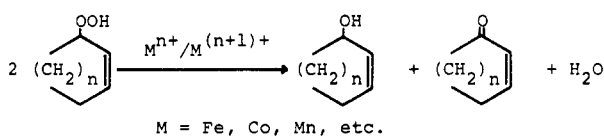
The stereochemistry of 1a was determined to be more than 99% cis by NMR spectroscopy. This high stereoselectivity is comparable to that in our previous reports using a t-BuOOH/VO(acac)$_2$ system.[8]

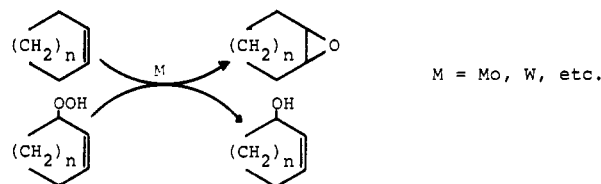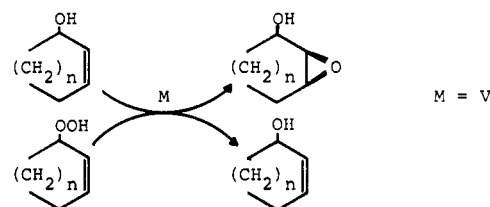### Scheme I

Autoxidation of Cyclic Olefins
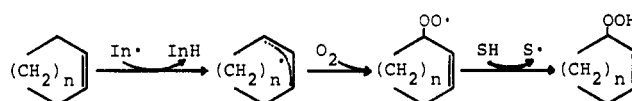
Decomposition of Hydroperoxides (path A)

M = Fe, Co, Mn, etc.

Epoxidation of Cyclic Olefins (path B)

M = Mo, W, etc.

Epoxidation of Cyclic Allylic Alcohols (path C)

M = V

Effect of Solvent on Cyclohexene Oxidation.

Generally there are few discussions about the solvent effect on the selectivity for oxidation products. Since the process of epoxy alcohol formation consists of the following two steps, radical reaction of hydroperoxide formation and ionic oxygen-transfer reaction of hydroperoxide to allylic alcohol, it must be regarded that solvents have a duplicate character in the two steps. First, the oxidation of 1 with VO(acac)$_2$ complex in various solvents was carried out in the absence of AIBN in order to examine the function of solvent in the initial step of hydroperoxide formation. Typical examples are shown in Table II. As mentioned in a previous section, VO(acac)$_2$ complex had no activity for the oxidation of 1 in the absence of solvent. In 1,2-dichloroethane, benzene, or 1,4-dioxane as a solvent, 1a could be formed after a long induction period. Presumably some solvents may induce the fission of a vanadium–acac bond to generate an acetylacetonato radical as an initiator

(8) (a) Itoh, T.; Kaneda, K.; Teranishi, S. *J. Chem. Soc., Chem. Commun.* **1976**, 421. (b) Itoh, T.; Jitsukawa, K.; Kaneda, K.; Teranishi, S. *J. Am. Chem. Soc.* **1979**, *101*, 159.

Table II. Effect of Various Solvents on Cyclohexene Oxidation Catalyzed by VO(acac)₂[a]

solvent	induction period, h	O₂ absorption rate, mL of O₂/ min·mol	% conversion	% yield	% selectivity			
					1a	1b	1c	1d
acetonitrile[b]				no reaction				
DMF	2.5	8.3	38	24	0	18	28	54
ethanol[c]	4.5	65	33	14	0	24	27	49
tert-butanol[b]				no reaction				
1,2-dichloroethane	15	4.6	30	26	56	25	10	9
aniline[b]				no reaction				
benzene	22	3.8	26	18	46	32	10	12
1,4-dioxane	26	5.3	35	21	43	32	13	12
n-hexane[b]				no reaction				

[a] Reaction conditions: VO(acac)₂ (0.01 mmol), solvent (2.0 mL), others are the same as those in Table I. [b] No reaction within 40 h. [c] The resulting epoxide 1b was successively converted into ethoxycyclohexanol by the vanadium catalyst.

Table III. Effect of Various Solvents on Cyclohexene Oxidation Catalyzed by VO(acac)₂-AIBN[a]

solvent	induction period, h	O₂ absorption rate, mL of O₂/ min·mol	% conversion	% yield	% selectivity[b]			
					1a	1b	1c	1d
acetonitrile	5.0	6.7	30	19	52	25	11	12
benzene	3.5	3.9	36	27	54	23	12	11
1,4-dioxane	0.5	6.8	30	21	43	31	10	16
1,2-dichloroethane	2.5	6.0	28	24	61	23	6	10
1,1,1-trichloroethane	2.0	6.0	40	26	55	23	12	10
1,1,2-trichloroethane	5.0	7.8	26	20	52	23	14	11
1,1,2-trichloroethane	5.0	7.8	48	30	65	17	5	13

[a] Reaction conditions: VO(acac)₂ (0.01 mmol), AIBN (0.1 mmol), solvent (2.0 mL), other conditions are the same as those in Table I. [b] Products are the same as those in Table I.

Table IV. Effect of Various Solvents on 1-Methylcyclohexene Oxidation Catalyzed by VO(acac)₂-AIBN[a]

solvent	induction period, h	O₂ absorption rate, mL of O₂/ min·mol	% conversion	% yield	% selectivity[b]					
					2a-1	2a-2	2a-3	2b	2c	2d
acetonitrile	0.5	23	40	24	15	36	23	14	7	5
1,2-dichloroethane	1.5	10	41	28	16	34	24	17	6	3
1,2-dichloroethane[c]	0.4	45	31	20	9	33	21	29	5	3
1,2-dichloroethane[d]	10	6.1	29	20	18	36	23	15	5	3
benzene	1.4	10	31	18	13	29	23	22	5	8
CCl₄	1.5	11	33	18	14	34	23	20	3	6
1,4-dioxane	0	12	28	17	15	34	22	20	4	5
n-hexane	0.3	7.0	40	20	14	32	22	26	2	4

[a] Reaction conditions are the same as those in Table III; GLC (PEG 20M). [b] Products: 2a-1, 1-methyl-2,3-epoxycyclohexanol; 2a-2, 3-methyl-2,3-epoxycyclohexanol; 2a-3, 2-methyl-2,3-epoxycyclohexanol; 2b, 1-methyl-1,2-epoxycyclohexane; 2c, 1-methylcyclohex-2-en-1-ol, 3-methylcyclohex-2-en-1-ol, and 2-methylcyclohex-2-en-1-ol; 2d, 3-methylcyclohex-2-en-1-one and 2-methylcyclohex-2-en-1-one. [c] 80 ± 1 °C. [d] 50 ± 1 °C.

during the induction period.[9] The oxidation did not occur even after 40 h in acetonitrile, aniline, or hexane solvent. Both *N,N*-dimethylformamide and ethanol solvents showed high oxidation rates with short induction periods but did not give 1a. Alcohols prevent the attack of the allylic alcohol on a oxo–vanadium intermediate species, which results in exclusive formation of 1b–d.

Next, the oxidation of 1 using the VO(acac)₂-AIBN catalyst system was performed in various solvents. Typical results are shown in Table III. The induction periods were shortened in all reactions. The use of 1,2-dichloroethane could increase the oxidation rate twofold and improve somewhat the selectivity for 1a. Figure 1 shows the product distribution in the course of the oxidation. Up to high conversions, about 60% selectivity for 1a could be maintained. It is notable that 1,2-dichloroethane gave high

selectivity for volatile oxidation products, and then the total yield of the four oxidation products 1a–d reached 26% at 30% conversion of the olefin 1. Furthermore, 1,1,2-trichloroethane gave 65% selectivity for 1a at 48% conversion. The best solvent for the epoxy alcohol formation seems to be chloro hydrocarbons. The function of these solvents in the oxygen-transfer process is not known. Probably the solvents promote the coordination of 1c to an oxo–vanadium species in agreement with the fact that the rate enhancement and directing control by the allylic hydroxyl are essential features of the vanadium-catalyzed epoxidation.

Oxidation of 1-Methylcyclohexene. Direct epoxy alcohol synthesis from 1-methylcyclohexene (2) was tried under an oxygen atmosphere using the VO(acac)₂-AIBN catalyst system, which has good selectivity for the epoxy alcohol (1a) in the oxidation of 1. As expected, three epoxy alcohols, 2a-1, 2a-2, and 2a-3, were obtained (Table IV). The stereochemistry of the alcohols was assigned as the

(9) Budnik, R. A.; Kochi, J. K. *J. Org. Chem.* **1976,** *41,* 1384.

Table V. Ring Size Effect on Oxidation of Various Cyclic Olefins[a]

olefin	$\omega\text{-}C_1=C_2-$ C_3-C_4	induction period, h	O_2 absorption rate, mL of O_2/ min·mol	% conversion	% yield	n	% selectivity[b]			
							a	b	c	d
cyclohexene	15°	2.5	16.5	24	19	2	41	28	15	16
cycloheptene	58.5°	4	16.2	38	24	3	10	40	9	34
cyclooctene	83.0°, 90.8°	8	1.5	6	3	4	0	99	1	0
cyclododecene[c]	>110°	6	2.7	14	9	8	53	40		5

[a] Reaction conditions: olefin (20 mmol), VO(acac)$_2$ (0.01 mmol), AIBN (0.1 mmol), others are the same as those in Table I.

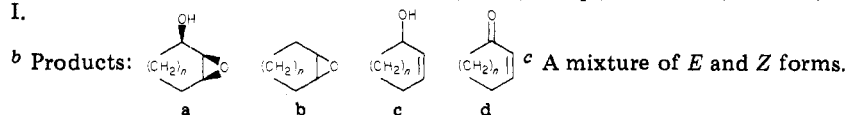[b] Products: (structures a, b, c, d) [c] A mixture of E and Z forms.
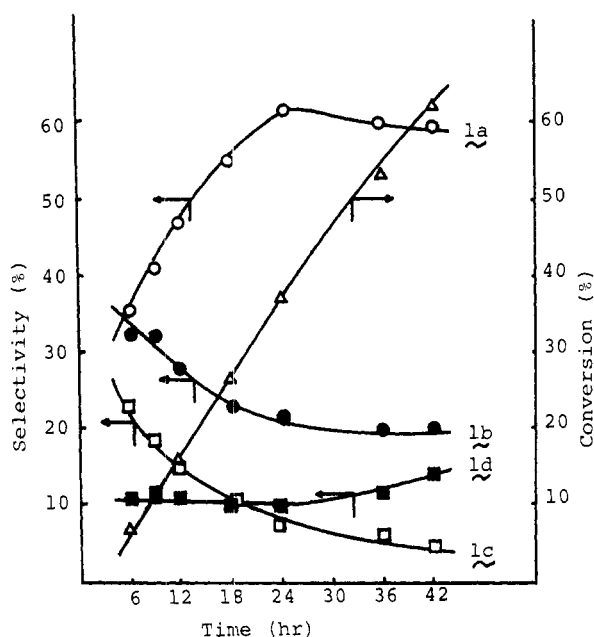
Figure 1. Product distribution and cyclohexene conversion using 1,2-dichloroethane: 1a, epoxy cyclohexanol; 1b, cyclohexene oxide; 1c, cyclohexenol; 1d, cyclohexenone.

cis configuration. The product ratio of these three alcohols is explained reasonably by the distribution of intermediate hydroperoxides (Scheme II); in a previous paper,[3b] we reported that a mixture of three hydroperoxides (2e-1, 2e-2, and 2e-3) was isolated in the ratio of 15:51:34 from the autoxidation of 2 using AIBN at 50 °C. The yield of 2a-1 plus 2a-2 derived from allylic radical (I) is larger than that of 2a-3 from II. This might be explained in terms of Bolland's rule.[10] The same tendency was also observed in the oxidation of 2 using the Wilkinson complex, RhCl(PPh$_3$)$_3$;[11] hydrogens at C-3 are favorably abstracted over those at C-6 in the ratio of 3:1 with this complex, while the ratio is 2:1 with the VO(acac)$_2$-AIBN catalyst. Attack by molecular oxygen at the less hindered site of allylic radical (I) gives preferentially the hydroperoxide (2e-2) rather than 2e-1, which results in the selective formation of 2a-2.

Increasing the reaction temperature decreased the selectivity for the epoxy alcohols 2a, while the selectivity for

Scheme II
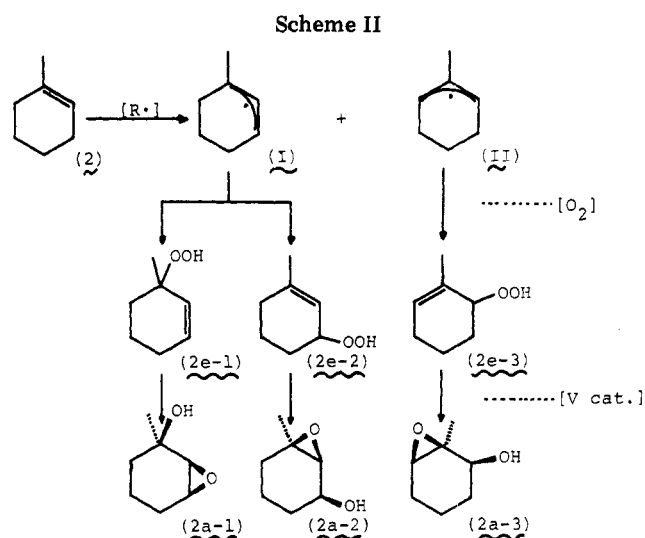
methylcyclohexene oxide (2b) was increased. Since the directing control exerted by the allylic hydroxyl is lost at high temperature, the reaction for selective epoxy alcohol formation should operate below 60 °C. The variation of solvents did not strongly influence the distribution of the three epoxy alcohols. On the other hand, the oxidation rates increase with increasing dielectric constant of the solvent.[12] Oxidation of 2 yielded the epoxy alcohols with high selectivity in various solvents. It is notable that the sum of the three epoxy alcohols 2a and the epoxide 2b reached about 90% selectivity.

Effect of Ring Size on Cyclic Olefin Oxidation. The results of oxidation of cyclic olefins (1, 3-5) with the VO(acac)$_2$-AIBN system are summarized in Table V. In the case of cycloheptene (3), cycloheptene oxide (3b) and cycloheptenone (3d) were major products. Cyclododecene (5) gave two epoxidation products, the epoxy alcohol 5a and epoxide 5b. Cyclooctene (4) did not yield the corresponding epoxy alcohol; cyclooctene oxide (4b) was formed exclusively. Furthermore, using only AIBN, 4 gave 4b selectively. The selectivities for epoxy alcohols decrease along the order $C_{12} \simeq C_6 > C_7 \gg C_8 = 0$. The oxidation rates obey the order $C_6 > C_7 \gg C_{12} > C_8$, which can be explained reasonably by considering the geometry about the olefinic carbons. The allylic hydrogens of 1 and 5 are abstracted easily, because the removal of hydrogens allows

(10) Bolland, J. L. *Trans. Faraday Soc.* **1950**, *46*, 358.

(11) Kaneda, K.; Itoh, T.; Fujiwara, Y.; Teranishi, S. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 3810.

(12) (a) Russell, G. A.; Williamson, R. C. *J. Am. Chem. Soc.* **1964**, *86*, 2357. (b) Hendry, D. G.; Russell, G. A. *Ibid.* **1964**, *86*, 2368.

an allylic radical system which has the geometry suitable for maximum overlap of n and π molecular orbitals. On the other hand, it is not so easy that the allylic radical from **4** can attain maximum overlap because of the conformational constraint of the ring system. Therefore both **1** and **3** are oxidized faster than **4**. The lower rate of **5** may be due to the entropy effect of the larger molecule. Mayo has discussed the origin of oxidation products of olefins in terms of the addition and hydrogen-abstraction mechanisms.[13] Olefins **1**, **3**, and **5** are oxidized mainly by the hydrogen-abstraction mechanism, producing allylic hydroperoxides, while in **4** the addition mechanism predominates. Considering the epoxy alcohol formation reaction proceeds via the oxygen transfer of hydroperoxide to allylic alcohol, the order for the epoxy alcohol selectivities can be well-explained. It seems that the hydroperoxy radical derived from the initiator may be the source of the epoxide **4b**.

Transannular Epoxidation of 1,4-Cyclooctadiene. Recently we synthesized bridged oxabicyclic compounds from the epoxidation of cyclic 2,4-dienols with t-BuOOH/VO(acac)$_2$.[14] On the basis of this knowledge, we schemed that the oxabicyclic compounds may be produced by a direct oxidation of dienes with molecular oxygen. First we attempted the preparation of cycloocta-2,4-dienyl hydroperoxide (**6e**) by the autoxidation of either 1,3-cyclooctadiene (**6**) or 1,4-cyclooctadiene (**7**). The conjugated diene (**6**) gave a mixture containing co-oligomers of O$_2$ and **6**, and **6e**. But the latter compound could not be isolated in spite of elaborate efforts. The nonconjugated diene (**7**) was oxidized easily because of its biallyl system.[15] The hydroperoxide **6e** was formed in 88% selectivity at 28% olefin conversion and could be isolated easily in 95% purity. The structure of **6e** was determined by its reduction to cycloocta-2,4-dien-1-ol (**6c**) with Na$_2$SO$_3$. The GLC analysis of the reduction solution showed **6c** (98.3%) and cycloocta-2,7-dien-1-ol (**7c**, 1.7%).
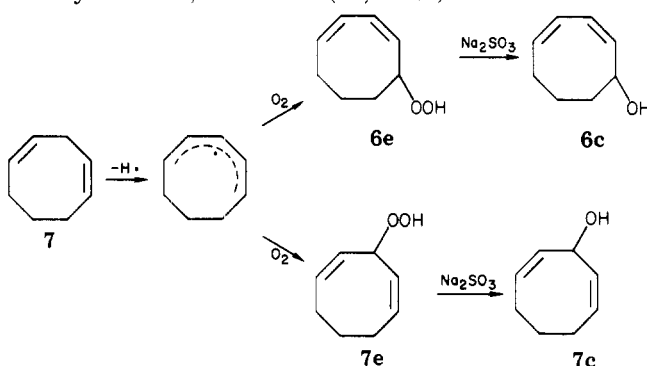
Treatment of **6e** with VO(acac)$_2$ gave 9-oxabicyclo-[3.3.1]non-3-en-2-ol (**6a**, 42%) as an expected product, accompanied by the 2,4-dienol **6c** (27%), the 2,4-dienone **6d** (15%), and trans-2,3-epoxycyclooct-4-en-1-ol (**7a**, 4%). **6d** and **7a** are unfavorable compounds for the selective formation of the oxabicycloenol **6a**.

In addition, the reaction of 3-deuterio-1,4-cyclooctadiene (**8**) afforded the oxabicycloenol deuterated on carbon-3. The ratio of deuterium to proton on carbon-3, 79:21, reflects the primary deuterium isotope effect of biallylic hydrogen abstraction (k_{C-H}/k_{C-D} = 3.8).[16] The one-pot
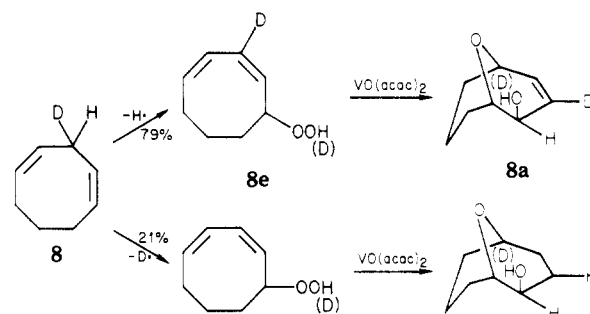
oxidation of **7** gave 43% selectivity for **6a** in the volatile products.

In conclusion, the VO(acac)$_2$–AIBN system is a convenient catalyst for one-pot epoxy alcohol synthesis from the reaction of olefins with molecular oxygen. In the case of olefins where the hydrogen abstraction mechanism predominates, the selective formation of epoxy alcohols can be attained.

Experimental Section

General. Infrared spectra were recorded on a JASCO-IR-E spectrophotometer. NMR spectra were obtained on JEO-JNM 4H-100 and Hitachi R-600S spectrometers, using tetramethylsilane (Me$_4$Si) as an internal standard. Mass spectra were recorded on a Hitachi RSM-4 mass spectrometer. Gas chromatography was performed on a Yanaco-G8 instrument, using a 3 m × 2.6 mm column packed with 3% silicone OV-17 on 60–80 mesh Celite, 20% poly(ethylene glycol) (PEG) 6000 on 60–80 mesh Celite, or 20% PEG 20M on 60–80 mesh Celite. Melting and boiling points are uncorrected.

Materials. Oxygen was passed through a calcium chloride drying tube before admission to the vacuum system. All solvents were dried and distilled under a nitrogen stream. Metal halides, metal acetylacetonato, metal carbonyl, metal oxide, and CpV(CO)$_4$ were commercial grade. AIBN was used without further purification. All olefins except 1,4-cyclooctadiene (**7**) and 3-deuterio-1,4-cyclooctadiene (**8**) were commercially available, distilled under a nitrogen stream, and purified by passing over activated alumina before use. These dienes (**7** and **8**) were prepared by the methods described in the literature.[17,18]

General Method of Olefin Oxidation with Metal Catalysts. The reaction vessel was a 50-mL flask with a side arm packed with silicon rubber. Metal catalyst was weighed into the vessel, which was attached to a reaction system consisting of a Hg manometer, a gas buret for measurement of O$_2$ absorption, and a vent for the vacuum line. Then it was set into an oil bath on a magnetic stirrer which was maintained at a constant temperature. The system was evacuated and flushed three times with dried oxygen. When a solvent was used, it was added to the vessel, and stirring was continued for 10 min. Stirring was then stopped and an olefin was introduced through the side arm. Oxidation was started with stirring the mixture anew. Samples were withdrawn from the reaction solution at appropriate times and analyzed by GLC. The oxidation products were collected by preparative GLC and/or identified by comparisons with authentic samples (retention time in GLC, IR, and NMR).

Epoxy alcohols **1a–6a** and allylic alcohols **1c–6c** were synthesized by the methods of our previous papers[3b,8,14] and references cited therein. Epoxides **1b–7b** were prepared by the reaction of olefins **1–7** with m-chloroperbenzoic acid. Cyclopent-2-en-1-one (**3d**) and cycloocta-2,4-dien-1-one (**6d**) were prepared by Jones oxidation of **3c** and **6c**, respectively.

In the case of cyclododecene (**5**) oxidation, reactant **5** was a mixture of E and Z isomers (7:3). GLC analysis showed that the corresponding epoxide (**5b**) was a mixture of E and Z isomers with the same isomer ratio as that of starting olefin. The stereochemistry of epoxy alcohols **5a** was not determined precisely, because our GLC conditions could not separate the four isomer

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peaks of *E* and *Z* epoxy alcohols. But it was estimated that, by comparison of the NMR spectra with those of *E* epoxy alcohols, *E* isomers were the main products.

AIBN Autoxidation of 1,3-Cyclooctadiene (6) and 1,4-Cyclooctadiene (7) and Na₂SO₃ Reduction. Dried oxygen was slowly bubbled into a mixture of **6** (54 g, 500 mmol) and AIBN (0.11 g, 0.67 mmol) with stirring at 60 °C. After 7 h, absorption of oxygen reached 15% based on the olefin used, and then unreacted olefin was removed under reduced pressure to give an oily residue (13.5 g, 60% active oxygen). The methanol solution of aliquots (1 g) was reduced by Na₂SO₃ aqueous solution at 0 °C. The resulting solution was extracted with ether, and distillation gave 2,4-cyclooctadienol (**6c**, 0.38 g). Other aliquots (1 g) were treated with LiAlH₄/ether under reflux. The GLC analysis showed four isomers of enediols, cyclooct-2-ene-*cis*-1,4-diol (15%), cyclooct-2-ene-*trans*-1,4-diol (5%), cyclooct-3-ene-*cis*-1,2-diol (8%), cyclooct-3-ene-*trans*-1,2-diol (7%), which were assigned by comparison of GLC retention time with authentic samples.[19]

1,4-Cyclooctadiene (**7**) (10.8 g, 100 mmol) was oxidized by the same procedure as **6**. After 40 min, absorption of oxygen reached 28% on the basis of olefin used, and unreacted olefin was removed. The oily residue was extracted twice with 100 mL of *n*-hexane. The hexane solution was evaporated at 60 °C (0.1 mmHg) to give colorless cycloocta-2,4-dienyl hydroperoxide (**6e**, 2.1 g): NMR (CDCl₃) τ 1.85 (br s, 1 H, OOH), 4.1–4.4 (m, 4 H, CH=CH), 5.43 (m, 1 H, CH–O), 7.6–8.7 (m, 6 H, CH₂); IR (film) cm⁻¹ 3360, 3040, 1627, 1064, 1027, 950, 860, 807, 780, 677. Anal. Calcd for C₈H₁₂O₂: C, 68.55; H, 8.63. Found: C, 68.62; H, 8.67.

The hydroperoxide (**6e**, 0.6 g) was treated with Na₂SO₃, and the GLC analysis showed 2,4-cyclooctadienol (**6c**, 98.3%) and 2,7-cyclooctadienol (**7c**, 1.7%): IR (film) cm⁻¹ 3380, 3040, 1057 813, 795.

Reaction of Cycloocta-2,4-dienyl Hydroperoxide (6e) with VO(acac)₂ Catalyst. The reactant peroxide **6e** (1.40 g, 10 mmol) was added to 5 mL of a benzene solution of VO(acac)₂ (26.5 mg, 0.1 mmol). The mixture was stirred at 40 °C for 4 h under a nitrogen atmosphere. GLC analysis showed a mixture of 9-oxabicyclo[3.3.1]non-3-en-*exo*-2-ol (**6a**, 42%), cycloocta-2,4-dien-1-ol (**6c**, 27%), cycloocta-2,4-dien-1-one (**6d**, 15%), and *trans*-2,3-epoxycyclooct-4-en-1-ol (**7a**, 4%).[8b]

Oxidation of 3-Deuterio-1,4-cyclooctadiene (8) with VO-(acac)₂ Catalyst. 3-Deuterio-1,4-cyclooctadiene (**8**) (1.7 g, 15.6

mmol) was oxidized by the same procedure as **6**. The reaction rate, compared with that of **7**, was slow and absorption of oxygen reached 35%, on the basis of olefin consumed, after 7.5 h. Unreacted **8** was evaporated under reduced pressure. To the oily residue was added a benzene solution of VO(acac)₂ (4.5 mg, 0.017 mmol). The mixture was stirred at room temperature for 24 h. 3-Deuterio-9-oxabicyclo[3.3.1]non-3-en-*exo*-2-ol (**8a**) was isolated by preparative GLC: NMR (CDCl₃) τ 3.82 (d of d, 0.21 H), 4.08 (d, *J* = 3.8 Hz, and with further fine structures, 1 H), 5.66 (m, 1 H), 5.85 (d, *J* = 4.0 Hz, and with further fine structures, 1 H), 6.26 (br s, 1 H), 7.65 (br s, 0.79 H), 8.0–8.7 (m, 6 H); IR (film) cm⁻¹ 3300, 2215 (=CD), 1200, 1075–1057 (doublet), 1033–1020–1009 (triplet), 990–974 (doublet), 912, 878, 840, 800; mass spectrum *m/e* 140, 141 (M⁺·).

From these spectral data, it was confirmed that this epoxy alcohol (**8a**) was a mixture of 3-deuterio and 3-protio derivatives (79:21).

One-Pot Synthesis of Oxabicycloenol 6a from the Reaction of 1,4-Cyclooctadiene (7) and Molecular Oxygen. The oxidation of **7** (2.8 g, 26 mmol) with the VO(acac)₂ (3.5 mg, 0.013 mmol) and AIBN (10.7 mg, 0.065 mmol) catalyst system in 1,2-dichloroethane (6 mL) was performed under an oxygen atmosphere at 50 °C. After 10 h, an equimolar amount of oxygen was absorbed. Then the GLC analysis showed that **7** gave **6a** (43%), **7a** (10%), **7b** (23%), **6c** (15%), and **6d** (9%) among volatile products. 1,2-Dichloroethane was removed from the reaction solution under reduced pressure and the residue was chromatographed on a Florisil column. The eluate from petroleum ether–ether (1:1) was concentrated and evaporated. The residue was sublimed at 100 °C (0.2 mmHg). Crystallized **6a** was obtained (655 mg, isolated yield 18%).

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Acylanthranils. 9. Influence of Hydrogen Bonding on the Reaction of Acetylanthranil with Ammonia[1]

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It was shown that hydrogen bonding has a marked influence on the reaction of acetylanthranil (**1**) with ammonia. The product of the reaction in anhydrous benzene is 2-methylquinazolin-4-one (**5**, R = H) which is formed via pathway A as shown in Scheme I, but the rate of formation is unusually slow. The rate of this conversion is about 6 times faster in pyridine than in benzene. If water is added to the benzene system, the rate of reaction is increased by orders of magnitude, but the product is *o*-acetamidobenzamide (**4**, R = H) and not **5**. In contrast to this result, the addition of water to the pyridine system causes a small decrease in rate and only a slight change in selectivity. These results are consistent with postulated mechanisms whereby **1** reacts with molecular clusters of ammonia, i.e., with (NH₃)ₙ in benzene, with N(H·S)₃ in strong proton acceptor solvents S, and with (NH₃)ₙ·H₂O in benzene plus added water. It was verified that cyclodehydration of **4** to give **5** occurs at an appreciable rate in aqueous solution at elevated temperatures and that this rate is accelerated considerably by the presence of strong base even at room temperature. It was also observed that *o*-acetamidobenzamide exists in at least two crystalline forms, α and β, which have different physical properties.

We have shown[2] that primary amines react with acetylanthranil (**1**) via alternate pathways, A and B, as outlined in Scheme I. Reactions with small amines are complete within minutes to give the corresponding acet-