

were isolated by passing the light through a monochromator (Ritsu, MC-10N). A He-Ne laser was used for the light of 633 nm.

Quantum yields were determined by measuring the rate of isomerization in the initial stage of the reaction at low concentration (absorbance at the measuring wavelength < 0.2) and the light intensity was measured with a ferrioxalate actinometer and a photometer (International Light, IL 700).

Absorption spectra were measured with a spectrophotometer (Shimadzu MPS-2000) and NMR measurements were carried out

with a 360-MHz NMR spectrometer (Brucker WN-360).

**Registry No.** 1 ( $R^1 = R^2 = CH_3$ ), 81667-52-9; **3b**, 112440-44-5; *trans*-**3b**, 112459-53-7; **3c**, 112440-45-6; **3d**, 112440-46-7; *trans*-**3d**, 112440-50-3; **4d**, 112440-51-4; **5**, 112440-47-8; **6**, 112440-48-9; furyl fulgide, 77515-04-9; 2,3,5-trimethyl-4-(chloromethyl)thiophene, 63826-43-7; 2,3,5-trimethyl-4-(cyanomethyl)thiophene, 112440-49-0; 2,4,6-trimethylacetophenone, 1667-01-2; 2,5-dimethyl-3-acetylthiophene, 2530-10-1; 2,5-dimethyl-3-acetylfuran, 10599-70-9; 2,3,5-trimethylthiophene, 1795-05-7.

## Oxidation of Cyclic Ketones Catalyzed by Polyethylene Glycol and Rhenium Carbonyl under Basic and Exceptionally Mild Conditions

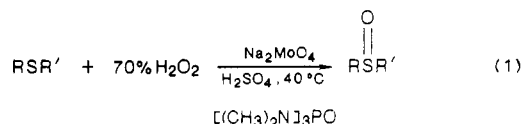
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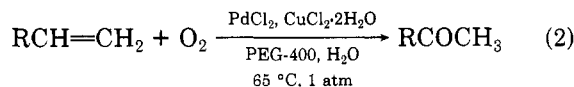
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Monocyclic ketones react with oxygen, potassium hydroxide, potassium carbonate, and catalytic amounts of rhenium carbonyl and polyethylene glycol (PEG-400 or  $R_4N^+X^-$  or TDA-1), at room temperature and 1 atm, to give diacids in fine yields. Bicyclic ketones afford keto diacids or hydroxyquinones, depending on the nature of the substrate.

Phase-transfer catalysis is of genuine use for promoting metal-catalyzed oxidation reactions. For example, trioctylmethylammonium tungstate complexed by appropriate, lipophilic, neutral or anionic ligands catalyzes the epoxidation of olefins by hydrogen peroxide.<sup>2</sup> The oxidation of sulfides to sulfoxides can also occur by using tungstates or molybdates as catalysts (eq 1).<sup>3</sup> Oxygen can



be employed as an oxidant under phase-transfer conditions. Palladium chloride catalyzed oxidation of terminal olefins to ketones (Wacker reaction) proceeds in good yields when a quaternary ammonium salt, containing at least one long-chain alkyl group, is used as the phase-transfer agent.<sup>4</sup> Both terminal and internal olefins can be oxidized by using either  $\beta$ -cyclodextrin<sup>5</sup> or polyethylene glycol of molecular weight 400 (eq 2).<sup>6</sup>



The conversion of cyclic ketones to diacids is another process of considerable industrial value.<sup>7</sup> It has been

reported that rhenium carbonyl can catalyze the oxidation of cyclohexanone, cyclopentanone, and cycloheptanone to diacids by means of molecular oxygen.<sup>8</sup> However, elevated temperatures (96–98 °C) and pressures (300–500 psi) are required, and product yields are not high. A second method of autoxidation of ketones involves the use of sodium or potassium hydroxide, or alkoxides, in hexamethylphosphoramide at 23.5 or 80 °C.<sup>9</sup> Only moderate yields of diacids resulted for cyclic systems larger than cyclohexanone. We now report that, by the use of catalytic quantities of polyethylene glycol and rhenium carbonyl in basic media, one can achieve the oxidation of cyclic ketones in fine yields, and under exceptionally mild conditions.

Treatment of cyclohexanone with oxygen, potassium hydroxide, potassium carbonate, and catalytic quantities of rhenium carbonyl and PEG-400, in 1,2-dimethoxyethane (DME) for 24 h at room temperature and 1 atm, afforded pure adipic acid in 74% yield. The ratio of cyclohexanone to  $\text{Re}_2(\text{CO})_{10}$  was 100:1. As the results in Table I indicate, low product yields are attained in the absence of either the phase-transfer agent, the metal catalyst, and one or both potassium bases. Sodium carbonate and sodium hydroxide are inferior to their potassium analogues as is the use of hexane or methylene chloride as the organic solvent. Note that tris[2-(2-methoxyethoxy)ethyl]amine (TDA-1)<sup>10</sup> and quaternary ammonium salts (e.g., benzyltriethylammonium chloride) are also useful phase-transfer agents for the oxidation reaction. Rhenium trichloride is ineffective as a catalyst for the oxidation reaction.

A series of monocyclic ketones (eq 3) were subjected to rhenium carbonyl catalyzed oxidation in the presence of

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Table I. Phase Transfer Catalyzed Oxidation of Cyclohexanone to Adipic Acid<sup>a</sup>

phase-transfer agent	organic phase	K <sub>2</sub> CO <sub>3</sub>	KOH	Re cat.	yield of adipic acid, <sup>b</sup> %
PEG-400	DME	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	74
PEG-400	DME	yes	yes		12
	DME	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	24
PEG-400	DME			Re <sub>2</sub> (CO) <sub>10</sub>	11
PEG-400	DME		yes	Re <sub>2</sub> (CO) <sub>10</sub>	36
PEG-400	DME	yes		Re <sub>2</sub> (CO) <sub>10</sub>	6
PEG-400	DME	Na <sub>2</sub> CO <sub>3</sub>	NaOH	Re <sub>2</sub> (CO) <sub>10</sub>	41
TDA-1	DME	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	71
(C <sub>4</sub> H <sub>9</sub> ) <sub>4</sub> N <sup>+</sup> Br <sup>-</sup>	DME	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	68
PhCH <sub>2</sub> N(C <sub>2</sub> H <sub>5</sub> ) <sub>3</sub> <sup>+</sup> Cl <sup>-</sup>	DME	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	73
PEG-400	C <sub>6</sub> H <sub>14</sub>	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	20
PEG-400	CH <sub>2</sub> Cl <sub>2</sub>	yes	yes	Re <sub>2</sub> (CO) <sub>10</sub>	29
PEG-400	DME	yes	yes	ReCl <sub>3</sub>	20

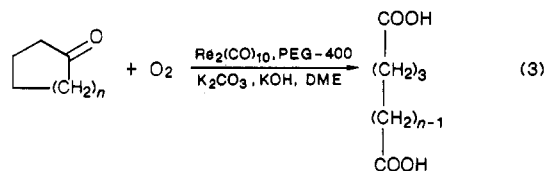
<sup>a</sup>Ten millimoles of cyclohexanone; 0.1 mmol of Re<sub>2</sub>(CO)<sub>10</sub>; 40 mmol each of K<sub>2</sub>CO<sub>3</sub> and KOH; 20 mL of organic phase; amount of phase-transfer agent was 3 drops (PEG), 1.0 mmol (TDA-1), or 0.3 mmol (R<sub>4</sub>N<sup>+</sup>Br<sup>-</sup>); 24 h; room temperature, 1 atm. <sup>b</sup>Yields are of pure products.

Table II. Oxidation of Ketones by O<sub>2</sub>/Re<sub>2</sub>(CO)<sub>10</sub>/PEG-400/K<sub>2</sub>CO<sub>3</sub>/KOH<sup>a</sup>

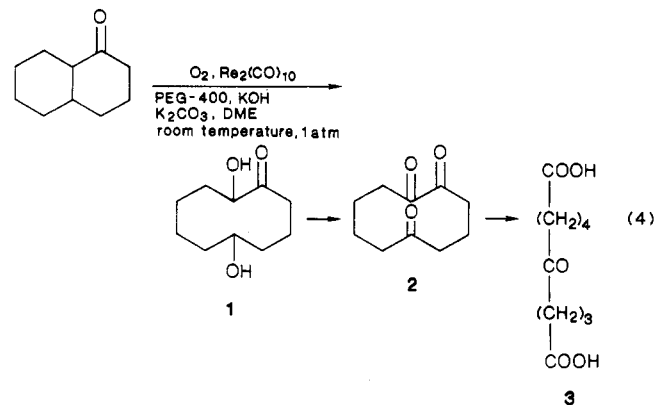
reactant	rcn time, h	product	yield, <sup>b</sup> %
cyclohexanone	24	adipic acid	74
cycloheptanone	24	HOOC(CH <sub>2</sub> ) <sub>5</sub> COOH	80
cyclooctanone	48	HOOC(CH <sub>2</sub> ) <sub>6</sub> COOH	82
cyclononanone	48	HOOC(CH <sub>2</sub> ) <sub>7</sub> COOH	89
cyclododecanone	96 <sup>c</sup>	HOOC(CH <sub>2</sub> ) <sub>10</sub> COOH	86
4- <i>tert</i> -butylcyclohexanone	24	HOOC(CH <sub>2</sub> ) <sub>2</sub> CH[C(CH <sub>3</sub> ) <sub>3</sub> ]CH <sub>2</sub> COOH	36
1-decalone	21	HOOC(CH <sub>2</sub> ) <sub>4</sub> CO(CH <sub>2</sub> ) <sub>5</sub> COOH	85
1-tetralone	6	2-hydroxy-1,4-naphthoquinone	93
2-tetralone	8	2-hydroxy-1,4-naphthoquinone	63
1,3-diphenyl-2-propanone	6	benzoic acid	72
1-phenyl-2-butanone	24	benzoic acid	74

<sup>a</sup>Substrate, 10.0 mmol; 0.1 mmol of Re<sub>2</sub>(CO)<sub>10</sub>; 40 mmol each of K<sub>2</sub>CO<sub>3</sub> and KOH; 3 drops of PEG-400, 20 mL of DME, room temperature; 1 atm. <sup>b</sup>Yields are of pure materials. <sup>c</sup>Temperature 50 °C.

base with PEG-400 as the solid-liquid phase transfer agent. The yields of pure dicarboxylic acids were usually excellent.



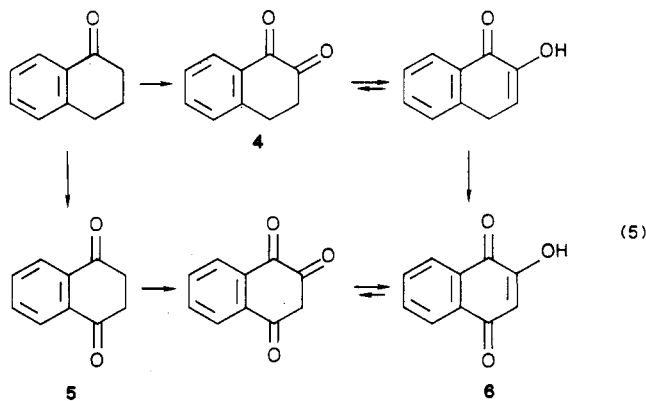
Some interesting results were obtained in the case of bicyclic ketones. Oxidation of 1-decalone afforded 5-ketodecane-1,10-dioic acid (3), characterized on the basis of analytical and spectral data (see Experimental Section).



It is conceivable that key intermediates in this reaction include the hydroxylated ketone 1 and the triketone 2. Reactions analogous to those giving 1 and 2 have been reported in the literature. For instance, lead tetraacetate oxidation of decalin-9,10-diol in benzene gave 1,6-cyclodecanedione in 59% yield.<sup>11</sup> It is also known that ben-

zyltriethylammonium permanganate can convert decalin to the 9-hydroxy analogue.<sup>12</sup> That rhenium carbonyl is able to catalyze the oxidation of C-H bonds at the ring junction was demonstrated by the conversion of a mixture of *cis*- and *trans*-decalin to 5-ketodecane-1,10-dioic acid (3) in 73% yield.

If one of the rings in the bicyclic substrate is aromatic, then hydroxyquinone formation occurs in good yield. The same product, 2-hydroxy-1,4-naphthoquinone (6), was obtained by using either 1- or 2-tetralone as the reactant. Tetralin-1,2-dione (4), and the 1,4-dione isomer 5 are possible intermediates in the reaction of 1-tetralone (eq 5). The enol tautomer 6 is favored over its triketo tau-



tomer due to intramolecular hydrogen bonding (and resonance).

Acyclic benzyl ketones such as 1-phenyl-2-butanone or 1,3-diphenyl-2-butanone are converted to benzoic acid under the usual reaction conditions. Unactivated ketones such as 5-nonanone are inert to rhenium-catalyzed oxidation.

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The role of potassium hydroxide in the reaction is believed to be the deprotonation of the substrate, while potassium carbonate may serve as a dehydrating agent. The solubilization of both potassium salts may be promoted by PEG-400. In the previously described rhenium carbonyl catalyzed homogeneous oxidation of cyclic ketones, it was proposed that the metal complex is involved in hydroperoxide decomposition by a homolytic process. Under the basic phase-transfer conditions utilized in this investigation, rhenium carbonyl may alternatively promote the reaction of the carbanion with oxygen or the cleavage of the hydroperoxide anion. Irrespective of the mechanistic details, the oxidation of monocyclic ketones to diacids and of bicyclic ketones to keto diacids or hydroxyquinones occurs in high yield, and under remarkably mild conditions (room temperature, 1 atm) using rhenium carbonyl and PEG-400.

### Experimental Section

Melting point determinations were made by using a Fisher-Johns apparatus. Proton magnetic resonance spectra were recorded on a Varian XL-300 spectrometer, while an FT-80 instrument was used for carbon-13 spectral determinations. Infrared spectra were recorded on a Perkin-Elmer 783 spectrometer, and a VG-7070E spectrometer was used for mass spectral determinations. Elemental analyses were done by M-H-W Laboratories, Phoenix, AZ. Gas chromatographic determinations were made on a Varian Vista 6000 gas chromatograph (FID detector) equipped with a 2-m 5% Carbowax 20M (or OV-17) on Chromosorb W column.

All of the necessary chemicals were purchased from commercial sources. Solvents were purified by standard methods.

**General Procedure for the  $\text{Re}_2(\text{CO})_{10}$ -Catalyzed Oxidation of Ketones Using PEG-400, KOH, and  $\text{K}_2\text{CO}_3$ .** The ketone (10 mmol) was added to a stirred mixture of ground potassium hydroxide (40 mmol), ground potassium carbonate (40 mmol), rhenium carbonyl (0.1 mmol), and PEG-400 (3 drops) in 1,2-dimethoxyethane (20 mL). Oxygen was bubbled through the stirred reaction mixture until the ketone was consumed (see Tables

I and II for reaction times). The progress of the reaction was monitored by gas chromatography. The reaction mixture was acidified (ice bath) to pH 4 by using 10 N hydrochloric acid and then extracted with ether. The ether extract was dried ( $\text{MgSO}_4$ ) and concentrated by rotary evaporation to give the product. Further purification, when necessary, was effected by recrystallization or by silica gel column chromatography.

The same procedure was used with other phase-transfer agents, with the following quantities used: TDA-1, 1.0 mmol;  $\text{PhCH}_2\text{N}(\text{C}_2\text{H}_5)_3^+\text{Cl}^-$  or  $(\text{C}_4\text{H}_9)_4\text{N}^+\text{Br}^-$ , 0.3 mmol.

Except for 5-ketodecane-1,10-dioic acid, all of the products are known compounds and were identified by comparison of melting points and spectral data with literature results and with authentic samples in most instances. Spectral data for 3 ( $\text{HOOCCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{COCH}_2\text{CH}_2\text{CH}_2\text{COOH}$ ):  $^1\text{H}$  NMR ( $\text{DMSO}-d_6$ )  $\delta$  1.40 (m, 4 H, protons on C-7, C-8), 1.62 (quintet, 2 H, protons on C-3), 2.14 (2 overlapping triplets, 4 H, protons on C-4, C-6), 2.33-2.43 (2 overlapping triplets, 4 H, protons on C-2, C-9);  $^{13}\text{C}$  NMR ( $\text{DMSO}-d_6$ )  $\delta$  18.7, 22.7, 24.0, 32.8, 33.5, 40.9, 41.5 (methylene carbons), 174.1, 174.3 (acid carbonyls), 209.9 (ketone carbon); assignments for both  $^1\text{H}$  and  $^{13}\text{C}$  NMR were confirmed by appropriate decoupling experiments; chemical-ionization mass spectrum,  $m/e$  217 ( $\text{M} + 1$ ), 199 ( $\text{M} + 1 - \text{H}_2\text{O}$ ), 181 ( $\text{M} + 1 - 2\text{H}_2\text{O}$ ); mp 108-110 °C.

Anal. Calcd for  $\text{C}_{10}\text{H}_{16}\text{O}_5$ : C, 55.54; H, 7.46. Found: C, 55.71; H, 7.71.

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**Registry No.** Cyclohexanone, 108-94-1; cycloheptanone, 502-42-1; cyclooctanone, 502-49-8; cyclononanone, 3350-30-9; cyclododecanone, 830-13-7; 4-*tert*-butylcyclohexanone, 98-53-3; 1-decalone, 4832-16-0; 1-tetralone, 529-34-0; 2-tetralone, 530-93-8; 1,3-diphenyl-2-propanone, 102-04-5; 1-phenyl-2-butanone, 1007-32-5; adipic acid, 124-04-9; heptanedioic acid, 111-16-0; octanedioic acid, 505-48-6; nonanedioic acid, 123-99-9; dodecanedioic acid, 693-23-2; 3-(1,1-dimethylethyl)hexanedioic acid, 10347-88-3; 5-oxodecanedioic acid, 1468-33-3; 2-hydroxy-1,4-naphthoquinone, 83-72-7; benzoic acid, 65-85-0.

## Intramolecular Hetero-Diels-Alder Reaction of Alkylidene- and Benzylidenepyrazolones and Benzylideneisoxazolones. Investigations toward the Conformation of the Transition State<sup>1</sup>

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Stereochemical aspects of the intramolecular hetero-Diels-Alder reaction of hetero dienes are studied. Knoevenagel condensation of aromatic aldehydes 1, 12, 15, and 21 with pyrazolones 8a-h and isoxazolone 17 gave the corresponding hetero dienes, e.g., 9a-h, which cyclized to the adducts 10a-h, 11a-h, 13, 14, 16, 19, 20, 23a-d, and 24a-d, respectively. Both *E* and *Z* hetero dienes gave mixtures of *cis*- and *trans*-annulated cycloadducts, with the *cis*-annulated compounds formed preferentially. This suggests an *E/Z* isomerization preceding the cycloaddition, which has been proved by UV-vis spectroscopy and HPLC. The tandem-Knoevenagel-Diels-Alder reaction of 1 and 8a and 8b was carried out with and without irradiation, yielding the same ratio of *cis* and *trans* adducts 10a,b and 11a,b. Since it has been shown that the ratio of *E* and *Z* hetero dienes is different in the two sets of experiments, it can be assumed that the cycloadducts are formed only via the *E* hetero diene. Reaction of the aliphatic aldehyde 25 with pyrazolones 8a-d gave the cycloadducts 28-30 with preferential formation of *cis*-annulated compounds 28a-d and 29a-d, whereas the reaction of 31 and 32 yielded the *trans* adduct 36 as main product.

The intermolecular Diels-Alder reaction<sup>2</sup> of  $\alpha,\beta$ -unsaturated carbonyls with electron-donor-substituted alkenes such as enol ethers or ketene acetals is a well-established method for the synthesis of dihydropyrans,<sup>2g</sup> whereas al-

ky-substituted alkenes do not act as dienophiles. Contrary to this observation, the intramolecular reaction of hetero

<sup>†</sup> Part of T.B.'s Ph.D. Thesis, Göttingen, 1987.

(1) Intra- and Intermolecular Hetero-Diels-Alder Reactions. 17. Part 16, see ref 12.