

$C_6H_6^+$ or $C_6H_5D^+$, and that at 79 to $C_6H_5(2C^{13})^+$ or $C_6H_5(1C^{13})^+$ or $C_6H_5D^+$. The deuterium in the two deuterated samples of hydrocinnamic acid cited above is therefore present solely at the benzylic position.

Methylethylphenylbenzyl-7- C^{14} -phosphonium Iodide. To 25 ml of tetrahydrofuran, distilled from lithium aluminum hydride after first having been treated with sodium hydroxide pellets, was added 2.59 g of inactive methylethylphenylbenzylphosphonium iodide.¹⁶ A nitrogen atmosphere was maintained over the stirred mixture as 0.50 g of lithium aluminum hydride was added, and the new mixture was stirred and refluxed for 4 hr. Most of the tetrahydrofuran was removed by distillation, and then a solution of 1.53 g of benzyl-7- C^{14} iodide having a specific activity of 39.1 $m\mu$ curies/mg of C in 15 ml of ether was added. The solution was allowed to stand overnight in the refrigerator, and then 0.8516 g of crude methylethylphenylbenzyl-7- C^{14} -phosphonium iodide which had crystallized was collected by filtration. This salt was contaminated with methylethylphenylphosphine oxide which had resulted by partial air oxidation of methylethylphenylphosphine during the manipulations cited above, even though the mixture had been protected by a nitrogen atmosphere as much as possible during the various operations. Therefore, the crude salt was added to 8.8255 g of inactive methylethylphenylbenzylphosphonium iodide and recrystallized several times from acetone containing about 5% of methanol. The melting point of the completely purified salt was 170–171° (lit.¹⁶ mp 170–171°).

Anal. Found activity for $C_{16}H_{20}PI$: 1.38 $m\mu$ curies/mg of C.

Reaction of Methylethylphenylbenzylidene-7- C^{14} -phosphorane with Styrene Oxide. By the usual procedure, 7.0964 g of methylethylphenylbenzyl-7- C^{14} -phosphonium iodide was converted to the ylide and condensed with styrene oxide. Pyrolysis of the adduct in decalin and the work-up described previously afforded 1.16 g of crude, labeled benzylacetophenone. After several recrystallizations from ethanol, 0.4591 g of pure material, mp 71–72°, was obtained. This was diluted to 4.7700 g with inactive benzylacetophenone and recrystallized again from ethanol to give 3.1687 g of the ketone.

Anal. Calcd activity for $C_{15}H_{14}O$: 0.142 $m\mu$ curie/mg of C. Found: 0.145 $m\mu$ curie/mg of C.

Schmidt Reaction of the Active Benzylacetophenone. This was carried out as described previously, and, from 2.9490 g of the labeled ketone, there was obtained 0.2661 g of highly purified, active hydrocinnamanilide, mp 96–97°.

Anal. Calcd activity for $C_{15}H_{15}NO$: 0.142 $m\mu$ curie/mg of C. Found: 0.139 $m\mu$ curie/mg of C.

Hydrolysis and Degradation of Active Hydrocinnamanilide. This was carried out as described previously on the 0.2661 g of the active anilide, and there was obtained 0.18 g of crude, active hydrocinnamic acid. Several recrystallizations from hexane afforded 0.0321 g of pure acid, mp 47–48°. This was diluted to 4.3815 g with inactive hydrocinnamic acid and crystallized again from hexane.

A portion of the active hydrocinnamic acid was subjected to the Schmidt reaction, and the carbon dioxide which was collected was found to be inactive.

A 1,000-g portion of the active hydrocinnamic acid was added to 50 ml of 0.1 *M* sodium hydroxide solution containing 4.75 g of potassium permanganate, and the mixture was heated at a bath temperature of 130° for 4.5 hr until the purple color had faded. The mixture was acidified with sulfuric acid, 1 ml of ethanol was added, and the mixture heated on the steam bath for 2 hr. A small amount of sodium bisulfite was then added to complete the reduction of the manganese dioxide present. The clear solution, when cooled in an ice bath, gave 0.70 g of benzoic acid. This was recrystallized from distilled water to give pure, active acid of mp 121–122°. A portion of this acid was subjected to the Schmidt reaction and the carbon dioxide which was evolved was collected.

Anal. Calcd activity for CO_2 : 0.0156 $m\mu$ curie/mg of C. Found: 0.0150 $m\mu$ curie/mg of C.

Acknowledgment. This work was supported in part by a grant from the Petroleum Research Fund administered by the American Chemical Society. Grateful acknowledgment is hereby made to the donors of the fund. It was also supported in part by the U. S. Atomic Energy Commission. The authors also wish to thank Dr. David R. Christman for the radioanalyses, Miss C. Redvanly for carrying out the Schmidt reactions of the radioactive carboxylic acids, and Dr. Irving S. Fagerson for help with the mass spectral analyses.

Mechanism of the Chromic Acid Oxidation of Ketones^{1,2}

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Abstract: The chromic acid oxidation of isobutyrophenone in acetic acid and of 2-chlorocyclohexanone in water undergoes, with increasing concentration of chromic acid, a change from first- to zero-order dependence in the oxidant. The limiting rate is close to the rate of enolization as determined by bromination measurements. This demonstrates that the oxidation of ketones proceeds through the enol intermediates. No direct oxidation of the keto form could be observed.

In a previous paper⁴ we offered proof that the main intermediate in the oxidation of cyclohexanone is 2-hydroxycyclohexanone. This study is concerned with the mechanism of its formation.

(1) This work was supported by the Petroleum Research Fund administered by the American Chemical Society by Grant No. 1524-A4. The support is gratefully acknowledged.

(2) Presented in part at the 150th National Meeting of the American Chemical Society, Atlantic City, N. J., Sept 1965. Preliminary communication: J. Roček and A. Riehl, *J. Am. Chem. Soc.*, **88**, 4749 (1966).

(3) Author to whom inquiries may be addressed, at the Department of Chemistry, University of Illinois, Chicago, Ill. 60680.

In an oxidation reaction a ketone can react with the oxidant either directly or in its enol form. Direct oxidations, demonstrated by an oxidation rate exceeding the rate of enolization, have been found for cobaltic^{5,6} and ceric^{6,7} salts and for manganic sulfate⁶ as oxidants. All of them undergo a one-electron reduction, and the reactions seem to have a free-radical mechanism.

(4) J. Roček and A. Riehl, *J. Org. Chem.*, **32**, 3569 (1967).

(5) D. G. Hoare and W. A. Waters, *J. Chem. Soc.*, 971 (1962).

(6) J. S. Littler, *ibid.*, 832 (1962).

(7) S. Venkatakrisnan and M. Santhappa, *Z. Physik. Chem. (Frankfurt)*, **16**, 73 (1958).

Examples of oxidations proceeding *via* an enol intermediate have been found for thallic, mercuric, and permanganate salts⁸ and for manganic pyrophosphate.⁹ In all these reactions the formation of the enol is rate limiting, and the reactions are therefore of zero order in the ketone with the rates of oxidations and enolizations being equal.

The only serious attempt to discuss the mechanism of the chromic acid oxidation of ketones has been made in two recent papers, both concerned with the oxidation of cyclohexanone, and both proposing a mechanism involving an enol intermediate.¹⁰ Umeda and Tarama¹² base their claim on certain similarities existing between the oxidation of cyclohexanone and cyclohexene, particularly on changes of the acidity of the system in the first minutes of the reaction.¹³ Best, Littler, and Waters¹⁴ found that the oxidation of cyclohexanone follows the rate law (1). Further, they observed a primary isotope

$$v = k[\text{ketone}][\text{HCrO}_4^-][\text{H}^+] \quad (1)$$

effect in the oxidation of cyclohexanone-2,2,6,6-*d*₄ ($k_{\text{H}}/k_{\text{D}} = 4.0:5.5$) and a rather large solvent isotope effect ($K_{\text{D}_2\text{O}}/k_{\text{H}_2\text{O}} = 3.7:5.2$); none of these observations can be readily interpreted to give a clear conclusion about the reaction mechanism.

We felt, therefore, that the mechanism of the formation of the α -hydroxy ketone in the chromic acid oxidation of ketones has not been established and that the problem should be reinvestigated. Since the direct ketone oxidation and the oxidation by way of an enol intermediate cannot be kinetically distinguished as long as the oxidation is low compared to enolization, our efforts were directed toward finding a system where the oxidation and enolization would be of a comparable rate.

Experimental Section

Materials. Glacial acetic acid (Fisher reagent) was analyzed for its water content by the Karl Fischer method;¹⁵ water was added to prepare a 99.0% w/w solution. The solution was tested for its stability toward chromic acid under standard reaction conditions and it was found to react with chromic acid at a rate too slow to affect any of the kinetic measurements. Cyclohexyl phenyl ketone was obtained from Aceto Chemical Co., mp 54–55°. The ketones listed below were tested for purity by glpc; where more than a single peak was obtained, the compound was further purified by glpc. Isobutyrophenone, propiophenone, 3-methylcyclohexanone, and 3-methyl-2-butanone were all Eastman products. 2-Methylcyclohexanone, 2-cyclohexen-1-one, and 2-chlorocyclohexanone (stabilized with 1% MgO–CaCO₃) were products of the Aldrich Chemical Co. The last ketone was distilled under reduced pressure before use; a constant boiling fraction (54–55° (7.5 mm)) was used in the kinetic studies. Other materials were the same as used in the preceding paper.⁴

(8) J. S. Littler, *J. Chem. Soc.*, 827 (1962).

(9) A. Y. Drummond and W. A. Waters, *ibid.*, 497 (1955).

(10) Prior to that, Wenkert and Jackson¹¹ assumed intuitively that the chromic acid oxidation of a ketone proceeds by way of an enol intermediate without, however, offering any experimental support for their assumption.

(11) E. Wenkert and B. G. Jackson, *J. Am. Chem. Soc.*, 80, 211 (1958).

(12) K. Umeda and K. Tarama, *Nippon Kagaku Zasshi*, 83, 1216 (1962).

(13) As the oxidations were carried out in rather strongly acid solutions (0.4 M HCl), these changes in themselves are surprising. The reason for the observed changes in the glass electrode potentials is not clear.

(14) P. A. Best, J. S. Littler, and W. A. Waters, *J. Chem. Soc.*, 822 (1962).

(15) J. A. Riddick and E. E. Toops, Jr., in "Techniques of Organic Chemistry," Vol. III, A. Weissberger, Ed., 2nd ed, Interscience Publishers Inc., New York, N. Y., 1956, Chapter 5.

Kinetic Measurements. Reaction rates were measured spectrophotometrically in a thermostated cell holder of a Carl Zeiss PMQ II spectrophotometer at 350 m μ for chromic acid oxidations and at 398 or 450 m μ for bromination experiments; the latter wavelength was used in 99% acetic acid and represents the isobestic point for bromine-tribromide ion.¹⁶ Quartz inserts were used for measurements at high concentrations. Calibration curves were used to correct for deviations from the Lambert–Beer law.

Rate constants were determined graphically as zero- or first-order rate constants extrapolated to zero time in cases of nonlinear plots. First-order dependence on ketone concentration was assumed for all reactions and was verified experimentally in several cases.

Determination of the Products Formed in the Oxidation of 2-Chlorocyclohexanone. According to glpc analysis,⁴ the oxidation products of 2-chlorocyclohexanone are 77% adipic, 14% α -chloroadipic, 5% glutaric, and 4% succinic acids. α -Chloroadipic acid (as dimethyl ester) was observed as a new peak of longer retention time (compared with the oxidation products of cyclohexanone⁴) and identified by infrared (spectrum closely related to that of dimethyl adipate) and by chlorine analysis (calcd: 17%; found: very approximately 20%, the analytical result is very crude because only a minute amount of the compound (0.679 mg) was available).

Results

Effects of Solvent Composition. Best, Littler, and Waters¹⁴ have studied the effect of chromic acid concentration on the rate of the oxidation of cyclohexanone in an aqueous solution. Their data show the reaction rate to increase with increasing chromic acid concentration throughout the whole range which they investigated (0.005 to 0.05 M CrO₃). The reaction is less than first order in chromic acid, a finding which Waters and co-workers rationalized by assuming that only the monomeric chromium species can participate in the oxidation reaction.¹⁷ On the other hand, the relatively slow increase of reaction rate with increasing chromic acid concentration could also indicate a gradual change from a first-order to a zero-order dependence in chromic acid as would be required by an oxidation mechanism proceeding through enolization. However, no decision can be reached on the basis of Waters' data: even the highest oxidation rate which he could measure was still about ten times slower than the rate of enolization under the same reaction conditions.

This situation is not changed significantly when the solvent is changed from water to acetic acid (Table I) in

Table I. Chromic Acid Oxidation of Cyclohexanone in 90% Acetic Acid at 30.0°; 0.50 M HClO₄

Cyclohexanone, M	CrO ₃ , M	k_2 , M ⁻¹ min ⁻¹	$v_{\text{oxidn}}/v_{\text{enolizn}}^a$
0.0030	0.00050	0.607	0.0064
0.0755	0.00094	0.564	0.011
0.0791	0.0019	0.436	0.017
0.0755	0.0056	0.251	0.028
0.0765	0.0098	0.214	0.049
0.0760	0.020	0.180	0.075
0.156	0.039	0.167	0.14
0.171	0.079	0.116	0.19

^a The first-order rate constant for bromination of cyclohexanone under these reaction conditions is $7.1 \times 10^{-2} \text{ min}^{-1}$.

(16) R. F. Ciecuch, Ph.D. Thesis, Harvard University, 1960.

(17) This interpretation is similar to that invoked earlier by Westheimer and co-workers¹⁸ in the case of the chromic acid oxidation of alcohols.

(18) F. H. Westheimer and A. Novick, *J. Chem. Phys.*, 11, 506 (1943).

spite of the frequent observations that acetic acid solutions specifically accelerate chromic acid oxidations.¹⁹⁻²¹

Further, the oxidation rates of cyclohexanone do not increase with increasing concentration of acetic acid significantly more than does the H_0 acidity (Table II).

Table II. Effect of Solvent Composition on the Rate of Oxidation and Bromination of Cyclohexanone at 30°




Solvent	HClO ₄	H ₀	Oxidation $k, M^{-1} \text{ min}^{-1}$	Bromination $10^3 k, \text{ min}^{-1}$	H ₀ + log k_{oxdtn}
H ₂ O	1.0	-0.22 ^a	0.151	1.37	-1.0
90% AcOH	0.50	-0.9 ^b	0.61	7.1	-1.1
99% AcOH	0.10	-1.6 ^c	3.06	14.6	-1.1

^a From M. A. Long and F. A. Paul, *Chem. Rev.*, **57**, 1 (1957).
^b (H_0)₁ for 2-nitraniline as reference indicator [J. Roček, *Collection Czech. Chem. Commun.*, **22**, 1 (1957)]. ^c Estimated from the value of -1.44 given by Ciecuch¹⁶ for 98% acetic acid.

In this respect cyclohexanone resembles aldehydes.²² The rate of bromination changed in the same direction as the rate of oxidation even though the total increase in the rate of bromination from an aqueous solution to 99% acetic acid was only about half as large as the increase in the oxidation rate.

Effect of Structure on the Rates of Oxidation and Enolization of Ketones. Tables III and IV summarize

Table III. Rates of Bromination and Chromic Acid Oxidation for Several Ketones in Aqueous 1.0 M HClO₄ at 30°

Ketone	Enolization		Oxidation		$v_{\text{oxdtn}}/v_{\text{enoliztn}}$
	$10^3 k, \text{ min}^{-1}$	CrO ₃ , $10^3 M$	$k_2, M^{-1} \text{ min}^{-1}$	$v_{\text{oxdtn}}/v_{\text{enoliztn}}$	
	1.37	0.54	0.151	0.0064	
	1.26	0.54	0.496	0.021	
	0.0443	0.50	0.39	0.43	
CH ₃ COCH(CH ₃) ₂	0.162	0.54	0.238	0.080	

the oxidation and bromination rates of several ketones in aqueous and 99% acetic acid solution, respectively. The use of water as solvent is severely limited by the low solubility of ketones of high molecular weight; therefore, a considerably larger number of ketones was investigated in acetic acid.

The results given in the two tables show that although the introduction of methyl groups into the cyclohexanone molecule generally leads to a decrease in enolization rates, α -methylcyclohexanones are oxidized faster than the parent compound. The introduction of a chlorine atom next to the carbonyl has a definite rate-retarding effect for both enolization and oxidation in acetic acid, the effect on the former being, however,








(19) M. Cohen and F. H. Westheimer, *J. Am. Chem. Soc.*, **74**, 4387 (1952).

(20) J. Roček and F. H. Westheimer, *ibid.*, **84**, 2241 (1962).

(21) J. Roček, *Collection Czech. Chem. Commun.*, **22**, 1509 (1957).

(22) The reason for the different behavior of aldehydes has recently been discussed in detail: J. Roček in "The Chemistry of the Carbonyl Group," S. Patai, Ed., Interscience Publishers Ltd., London, 1966, p 474.

Table IV. Oxidation and Bromination Rates of Ketones in 0.10 M HClO₄ in 99% Acetic Acid at 30°^a

Ketone	Bromination $10^3 k, \text{ min}^{-1}$	Oxidation $k_2, M^{-1} \text{ min}^{-1}$	$v_{\text{oxdtn}}/v_{\text{enoliztn}}$
	14.6	2.38	0.098
	9.34	8.54	0.55
	8.99	1.24	0.083
	4.50	3.29	0.44
	0.536	0.84	0.92
CH ₃ COCH(CH ₃) ₂	1.55	0.50	0.19
	0.49	0.085 ^b	0.020
	0.038	0.049	0.78

^a Concentrations: ketone 0.01 to 0.07 M, chromium trioxide 0.006 M, and bromine 0.005 M. ^b CrO₃ = 1.2×10^{-3} M.

much stronger. In aqueous solution chlorocyclohexanone is oxidized faster than cyclohexanone. The least reactive compound of those investigated is clearly isobutyrophenone. Its oxidation rate is about 50 times lower than that of cyclohexanone; however, the rate of enolization is depressed by a factor of almost 500.

In the oxidation of a ketone to a hydroxy ketone three molecules of a ketone undergo oxidation for every two molecules of chromic acid being reduced. Hence, the rate of oxidation which is customarily expressed in terms of changes in the concentration of chromic acid will be 1.5 times lower than the rate of enolization expressed in terms of ketone concentration. In the oxidation of a ketone which does not proceed beyond the hydroxy ketone, the relative rate of chromic acid oxidation to enolization (*i.e.*, bromination)²³ should reach a limiting value of 0.67. On the other hand, if the oxidation proceeds further, a higher value of the relative rates has to be expected. For example, the oxidation of cyclohexanone⁴ leads to a mixture of products among which adipic and glutaric acid predominate; an average of four molecules of oxygen is being used for each molecule of cyclohexanone. The limiting value in this case then should be about four times as high or approximately 2.7. Therefore, one cannot expect a simple integer relative rate. On the other hand, it is clear that the highest possible relative rate of oxidation with respect to enolization is desirable. Table IV clearly shows isobutyrophenone to be the most promising ketone of this group.

The Oxidation of Isobutyrophenone. The results of a study of the dependence of oxidation rates of isobutyrophenone on the initial concentration of chromic acid are given in Table V. While the second-

(23) Green, Kemp, Littler, and Waters²⁴ have recently shown that only the monobromo compound is formed in the bromination of cyclohexanone under kinetic conditions in aqueous solutions. It is not known whether the same is true for the other ketones in acetic acid, but it is reasonable to assume it. The bromination rates then measure directly the rate of the enolization of the ketone.

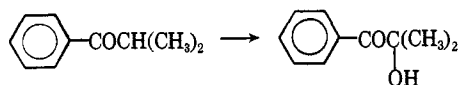
(24) A. J. Green, T. J. Kemp, J. S. Littler, and W. A. Waters, *J. Chem. Soc.*, 2722 (1964).

Table V. Effect of Chromic Acid Concentration on the Rate of the Oxidation of Isobutyrophenone in 99% Acetic Acid at 30°; $\text{HClO}_4 = 0.50 M$

Ketone, <i>M</i>	$[\text{CrO}_3]_0,^a$ $10^3 M$	$k_2,^b$ $M^{-1} \text{ min}^{-1}$	$10^3 k_1,^c$ min^{-1}	$v_{\text{oxdtn}}/$ v_{enolzttn}^d
0.0532	2.16	0.72	1.05	0.43
0.0551	4.32	0.40	1.42	0.62
0.0532	8.62	0.19	1.54	0.67
0.0531	12.9	0.13	1.46	0.63
0.0563	17.2	0.09	1.51	0.66
0.0808	21.6	0.08	1.51	0.66
0.133	33.6	0.06	1.49	0.65

^a Total concentration of chromium(VI) at zero time. ^b $-(1/[\text{ketone}])(d[\log [\text{CrO}_3]/dt])$ at zero time. ^c $-(1/[\text{ketone}])(d[\text{CrO}_3]/dt)$ at zero time. ^d k_1/k_{bromntn} ; $k_{\text{bromntn}} = 2.30 \times 10^{-3} \text{ min}^{-1}$.

order rate constants (column 3) decrease by a factor of more than ten over an about 15-fold concentration range of chromic acid, the first-order rate constants (first order in the ketone, zero order in chromic acid) (column 4) reach a practically constant value for concentrations of chromic acid from about 0.002 *M* upward. The limiting ratio of oxidation to bromination rate is 0.67 as predicted for an oxidation in which only one oxygen atom is used for each ketone molecule. Although we have not isolated the oxidation product in this case, we assume from this rate ratio that the main oxidation product is the corresponding α -hydroxy ketone.



Oxidation of 2-Chlorocyclohexanone. 2-Chlorocyclohexanone is sufficiently water soluble to permit an investigation of its oxidation in an aqueous solution. The results of a series of rate measurements in which the initial chromic acid concentration was changed over more than two orders of magnitude are given in Table VI. The second-order rate constants decrease

Table VI. Effect of Chromic Acid Concentration on the Rate of the Oxidation of 2-Chlorocyclohexanone in Aqueous 1.0 *M* Perchloric Acid at 30°

$[\text{CrO}_3]_0,^a$ $10^3 M$	Ketone, $10^3 M$	$10^4 k_1,^b$ min^{-1}	$k_2,^c$ $M^{-1} \text{ min}^{-1}$	$v_{\text{oxdtn}}/$ v_{enolzttn}^d
0.522	1.66	1.81	0.347	0.41
1.07	6.51	2.69	0.252	0.61
2.92	7.14	5.15	0.176	1.16
5.65	7.09	6.15	0.109	1.39
12.1	7.18	8.09	0.067	1.84
24.5	7.74	9.42	0.038	2.12
35.5	6.98	9.80	0.028	2.21
45.1	23.6	10.0	0.022	2.26

^a Total concentration of chromium(VI) at zero time. ^b $-(1/[\text{ketone}])(d[\text{CrO}_3]/dt)$ at zero time. ^c $k_2 = k_1/[\text{CrO}_3]_0$. ^d k_1/k_{bromntn} ; $k_{\text{bromntn}} = 4.43 \times 10^{-4} \text{ min}^{-1}$.

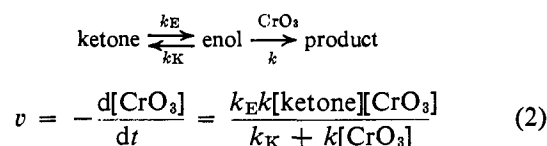
sharply with increasing chromic acid concentration. By interpolation it can be estimated that a change in chromic acid concentration from 0.005 to 0.05 will cause a decrease in k_2 by a factor of more than five. Best, Littler, and Waters investigated the oxidation of cyclohexanone under comparable conditions and found the rate constant to decrease by about 20% for the same change in the chromic acid concentration. The first-

order rate constants, though not as invariable as in the previously discussed example of the oxidation of isobutyrophenone, increase by a factor of less than two over the same concentration range of chromic acid.

2-Chlorocyclohexanone is oxidized to a mixture of adipic acid (77%), 2-chloroadipic acid (14%), glutaric acid (5%), and succinic acid (4%). To form this product composition requires an average of 2.5 molecules of oxygen or 1.7 molecules of chromic acid to be consumed for each molecule of chloro ketone. The limiting value of $v_{\text{oxdtn}}/v_{\text{enolzttn}}$ should therefore be 1.7. The fact that this value is somewhat exceeded may indicate that further degradative processes beyond the dicarboxylic acid stage are taking place and consuming additional amounts of chromic acid.

Discussion

The Enol Intermediate. The rate equation for the oxidation of a ketone through an enol intermediate is eq 2.



The experimentally determined rate constants k_1 and k_2 are defined by eq 3 and are related to the rate constants of enolization (k_E), ketonization (k_K), and oxidation of the enol (k) through eq 4 and 5.

$$v = -\frac{d[\text{CrO}_3]}{dt} = k_1 [\text{ketone}] = k_2 [\text{CrO}_3] [\text{ketone}] \quad (3)$$

$$k_1 = k_E k [\text{CrO}_3] / (k_K + k [\text{CrO}_3]) \quad (4)$$

$$k_2 = k_E k / (k_K + k [\text{CrO}_3]) \quad (5)$$

or

$$\frac{1}{k_2} = \frac{k_K}{k_E k} + \frac{[\text{CrO}_3]}{k_E}$$

Kinetically, the above rate equation can be tested only if k_K and $k[\text{CrO}_3]$ are of a comparable magnitude. Then, at low chromic acid concentration the oxidation of the enol will be the rate-limiting step and the reaction will be first order in both the ketone and chromic acid; (5) will simplify to (6). At high chromic acid concen-

$$k_2 = (k k_E / k_K) \quad (6)$$

trations (for $k[\text{CrO}_3] \gg k_K$), enolization will become rate limiting and the reaction will be of zero order in chromic acid. Equation 4 will simplify to (7).

$$k_1 = k_E \quad (7)$$

For the enolization mechanism it is therefore required that (i) individual runs at high chromic acid concentration give a linear plot of concentration of chromic acid vs. time, (ii) a plot of k_1 vs. $[\text{CrO}_3]$ gives a curve approaching a constant value for $k_1 (=k_E)$ at high chromic acid concentrations, and (iii) a plot of $1/k_2$ vs. $[\text{CrO}_3]$ gives a straight line. Figures 1, 2, and 3 show that all these requirements are indeed fulfilled and we therefore conclude that both the isobutyrophenone in acetic acid

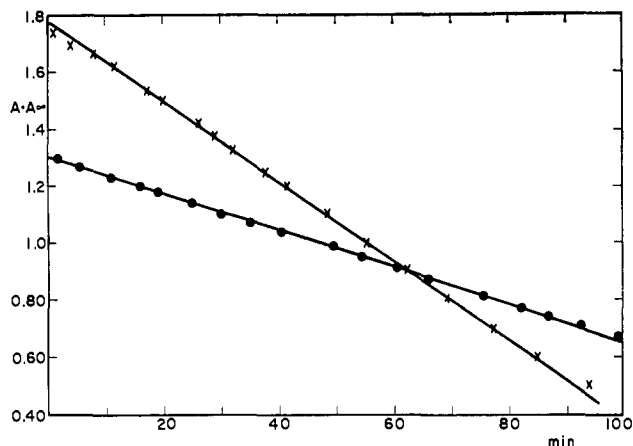


Figure 1. Zero-order plots of absorbancy vs. time for the oxidation of ketones by chromic acid at 30°: ●, isobutyrophenone in 0.50 M perchloric acid in 99% acetic acid; ×, 2-chlorocyclohexanone in 1.0 M aqueous perchloric acid.

and chlorocyclohexanone in aqueous solution are oxidized in their respective enol forms.²⁵

Oxidation of Cyclohexanone and Other Ketones.

No rigorous evidence can be adduced from the present study to other ketones. However, the similarity between cyclohexanone and chlorocyclohexanone, in chemical structure, in the oxidation products, and in the response to changes in solvent composition, leads us to believe that the enolization mechanism holds also for the unsubstituted cyclohexanone. Further, the failure to find any ketones which under any conditions would undergo oxidation faster than enolization, and the fact that the enolization mechanism has been demonstrated for two ketones very different in nature and in two different solvents, seems to speak for its broad validity.

Reactivity of the Enol. For the ketones which are oxidized only slowly relatively to their rate of enolization and for low chromic acid concentrations in general, eq 5 will be reduced to

$$k_2 = kk_E/k_K = kK_E \quad (6)$$

where K_E is the equilibrium constant of enolization. If K_E is known, the rate constant measuring the reactivity of the enol can be determined. Unfortunately, very few reliable data are available for simple ketones.

The enol content in cyclohexanone has been determined by Schwarzenbach and Wittwer²⁶ and, more recently, by Bell and Smith.²⁷ The value of $K_E = 4.1 \times 10^{-6}$ as determined by Bell and Smith leads to the value of $k = 3.7 \times 10^4 M^{-1} \text{min.}^{-1}$ for the oxidation of the enol of cyclohexanone.²⁸

(25) If some direct oxidation of the ketone would take place besides the oxidation *via* enol, then the curves in Figure 2 would approach straight lines with definite positive slopes. The observation that the slopes in both cases approach a slope of zero indicates then that no or only very little direct oxidation of the ketone takes place even at high chromic acid concentrations.

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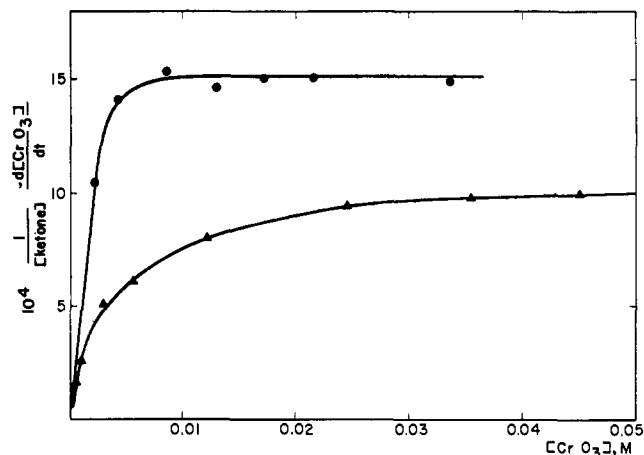


Figure 2. Effect of the initial concentration of chromic acid on the rate of oxidation at 30°: ●, isobutyrophenone in 0.50 M perchloric acid in 99% acetic acid; ▲, 2-chlorocyclohexanone in 1.0 M aqueous perchloric acid.

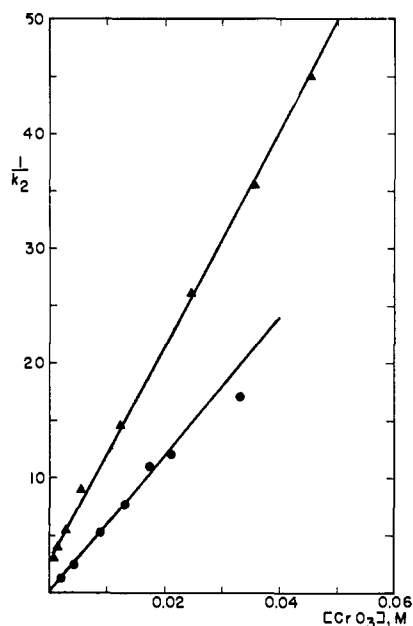


Figure 3. Dependence of reciprocal second-order rate constants on the initial chromium(VI) concentration for the oxidation of ketones by chromic acid at 30°: ●, isobutyrophenone in 0.50 M perchloric acid in 99% acetic acid; ▲, 2-chlorocyclohexanone in 1.0 M aqueous perchloric acid.

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(28) This enol is then about 18 times more reactive than the mono-enol of 1,2-cyclohexanedione, the oxidation rate of which we could measure directly.⁴ The rate-retarding effect of the keto group is in keeping with the generally observed effect of electronegative groups on the chromic acid oxidation of organic compounds.²⁹⁻³²

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