603. *Oxidations of Organic Compounds with Quinquevalent Vanadium. Part II.[1] The Oxidation of Ketones.*

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The oxidations of cyclopentanone and cyclohexanone by quinquevalent vanadium in sulphuric and perchloric acid solutions are first-order reactions in respect to both V^V and the organic substrate. The dependence on acidity in perchloric acid solution can be attributed to oxidation by a yellow cation, probably $V(OH)_3^{++}$, and in sulphuric acid solution to a more active red sulphate complex. There is a large positive salt effect.

Oxygen retards the disappearance of V^V when cyclopentanone is being oxidised, but, though it is absorbed, it has no effect on this rate with cyclohexanone as substrate.

Reaction products have been examined, and it is concluded that oxidations of ketones by V^V involve consecutive one-electron abstraction steps.

IN Part I of this series [1] it was indicated that ketones are oxidised by acid solutions of quinquevalent vanadium with formation of transient organic free radicals. We have now studied kinetically the oxidations of cyclohexanone and cyclopentanone using both sulphuric and perchloric acid and have elucidated somewhat further the nature of the oxidising species. The investigation also sheds some light on the mechanism of the oxidation.

RESULTS

(1) *Dependence of Rate on Ketone Concentration.*—With both ketones the rate of consumption of V^V is a first-order process with respect to the ketone concentration. The rate is expressed as the pseudo-unimolecular rate constant k obtained from the slope of the graph of log $[V^V]$ against time (see Tables 1 and 2).

[1] Part I, Littler and Waters, *J.*, 1959, 1299.

(2) *Dependence of Rate on* V^V *Concentration.*—As in the experiments described in Part I, oxidations carried out in the presence of excess of the organic compound all gave good first-

TABLE 1. *Oxidation of cyclopentanone in aqueous sulphuric acid: reaction order with respect to ketone, at 40°.*

$[H_3O^+] = 5\cdot18M$, $[V^V] = 0\cdot0486N$.

[Ketone] (M)	0·121	0·090	0·060	0·030	0·012
10^4k (sec.$^{-1}$)	9·17	7·13	5·09	2·54	1·05
10^3k/[Ketone]	7·5	7·9	8·5	8·5	8·7

Mean value of k/[Ketone] = $(8\cdot22 \pm 0\cdot4) \times 10^{-3}$ sec.$^{-1}$ mole^{-1}.

TABLE 2. *Oxidation of cyclohexanone in aqueous sulphuric acid: reaction order with respect to ketone, at 35°.*

$[H_3O^+] = 1\cdot1M$, $[V^V] = 0\cdot0565N$, ionic strength = $1\cdot2M$.

[Ketone] (M)	0·1205	0·241	0·3615
10^4k	2·43	4·98	7·35
10^3k/[Ketone]	2·02	2·07	2·04

Mean value of k/[Ketone] = $(2\cdot04 \pm 0\cdot02) \times 10^{-3}$ sec.$^{-1}$ mole^{-1}.

TABLE 3. *Oxidation of cyclohexanone in perchloric acid: reaction order with respect to* $[V^V]$.

[Ketone] = 0·241M, ionic strength = 2·4M.

$[V^V]$ (N)	$[H_3O^+]$ (M)	10^4k (sec.$^{-1}$)	10^4k, corr., to $[H_3O^+] = 2\cdot00M$
0·113	2·005	11·3	11·28
0·0565	2·061	8·75	8·48
0·0226	2·095	6·05	5·77

order reaction plots with respect to $[V^V]$ for at least 50% of the reaction. With cyclohexanone in perchloric acid, however, the velocity constant increased with $[V^V]$ as Table 3 shows. This change of reaction velocity is not due to a salt effect since the ionic strength was kept at a constant high value by the use of perchloric acid–sodium perchlorate mixtures.

(3) *Dependence of Rate on Acidity.*—In Part I the oxidising power of V^V was investigated only in aqueous sulphuric acid. Evidence of oxidation both by a univalent cation, (VO_2^+), and by another species present in stronger acid was obtained. In contrast to that of pinacol, the rate of oxidation of ketones has no acid-independent component. When perchloric acid is used solutions of V^V remain yellow from 0·1M-acidity up to the strongest solutions (*ca.* 9·5M-HClO$_4$) that were made up. Table 4 shows that for the oxidation of cyclohexanone in solutions of constant high ionic strength the rate of oxidation is of first order with respect to hydrogen-ion concentration, $[H_3O^+]$, and does not depend on the Hammett acidity function H_0.

TABLE 4. *Oxidation of cyclohexanone in perchloric acid: dependence of rate on acidity, at 35°.*

$[V^V] = 0\cdot056N$, [Ketone] = 0·096M, ionic strength = 6M.

$[H_3O^+]$ (M)	1·06	1·95	2·84	3·74	4·63	5·53
10^4 (sec.$^{-1}$)	2·24	4·01	5·83	7·75	9·81	12·4
H_0 (ref. 2)	−1·47	−1·83	−2·10	−2·37	−2·64	−2·93
10^4k/$[H_3O^+]$	2·11	2·06	2·05	2·07	2·12	2·14

Mean value of k/$[H_3O^+]$ = $(2\cdot09 \pm 0\cdot03) \times 10^{-4}$ sec.$^{-1}$ mole^{-1}.

TABLE 5. *Oxidation of cyclopentanone in sulphuric acid: dependence of rate on acidity, at 40°.*

[Ketone] = 0·121M, $[V^V] = 0\cdot0971N$.

$[H_3O^+]$ (M)	1	2	2·87	3·81	4·75	5·18
H_0 (ref. 2)	−0·26	−0·84	−1·31	−1·77	−2·16	−2·36
$\alpha^{\pm}$ (ref. 3)	0·1316	0·2566	0·402	0·621	0·938	1·12
10^4k (sec.$^{-1}$)	0·49	1·33	2·54	4·53	7·3	9·8

In sulphuric acid solutions, however, the rates of oxidation of both cyclopentanone and cyclohexanone increase more rapidly as the acid concentration is increased (Tables 5 and 6).

² Paul and Long, *Chem. Rev.*, 1957, **57**, 1.
³ Stokes, *Trans. Faraday Soc.*, 1948, **44**, 295.

Even in M-acid oxidation occurs in sulphuric acid about 7 times as rapidly as in perchloric acid (Table 7).

TABLE 6.   *Oxidation of cyclohexanone in sulphuric acid: dependence of rate on acidity, at 25°.*

$[V^V] = 0.0565N$, [Ketone] $= 0.096M$, ionic strength $= 6M$.

$[H_3O^+]$ (M)	1·1	3·5	5·9
10^4k (sec.$^{-1}$)	3·21	10·9	40·6
$(10^4k)^{\frac{1}{2}}/[H_3O^+]$	1·63	0·94	1·08

TABLE 7.   *Comparison of oxidation rates for cyclohexanone in sulphuric and perchloric acids.*

$[V^V] = 0.0565N$, ionic strength $= 1.2M$.

Temp.	[Ketone]	Acid	10^4k (sec.$^{-1}$)	$10^3k/$[Ketone]
35°	0·1205	H_2SO_4, 1·1M	2·43	2·02
35	0·096	$HClO_4$, 1·06M	0·301	0·314
50	0·1205	H_2SO_4, 1·1M	10·5	87·2
50	0·1205	$HClO_4$, 1·06M	1·32	11·0

(4) *Salt Effects.*—Table 8 shows that addition of sodium perchlorate markedly increases the rate of oxidation of cyclohexanone. This observation shows the importance of maintaining constant ionic strength in the measurements listed in Table 4.

TABLE 8.   *Effect of sodium perchlorate on oxidation rate of cyclohexanone.*

(a) $[V^V] = 0.0565N$; acid is $HClO_4$, 1·06M; [Ketone] $= 0.1205M$. Ionic strength adjusted with $NaClO_4$. Temp. = 50°.
(b) $[V^V] = 0.0565N$; acid is H_2SO_4, 1·1M. Ionic strength adjusted with $NaClO_4$. Temp. = 25°.

Ionic strength (M)		10^4k	
(a) $\begin{cases} 1·2 \\ 3·6 \\ 5·0 \\ 6·0 \end{cases}$		1·32 4·98 11·1 17·3	

	[Ketone]		$10^4k/$[Ketone]
(b) $\begin{cases} 1·2 \\ 6·0 \end{cases}$	0·116 0·096	0·87 3·21	8·5 33·4

(5) *Kinetic Effects due to Transient Organic Free Radicals.*—Addition of vinyl cyanide leads to the production of insoluble polymers that contain ketonic end groups. With cyclopentanone this addition slightly increases the oxidation rate, but with cyclohexanone the oxidation rate is slightly decreased (Table 9).

TABLE 9.   *Effect of addition of vinyl cyanide on oxidation rate in nitrogen atmosphere.*

(a) $[V^V] = 0.0971N$; H_2SO_4, 1M; [cyclopentanone] $= 0.121M$. Temp. = 40°.
(b) $[V^V] = 0.0565N$; $HClO_4$, 1·06M; ionic strength $= 1.20M$. Temp. = 50°. Ketone is cyclohexanone.
(c) $[V^V] = 0.0565N$; H_2SO_4, 1·1M; ionic strength $= 1.20M$. Temp. = 35°. Ketone is cyclohexanone.

[Vinyl cyanide] (M)	[Ketone] (M)	10^4k (sec.$^{-1}$)	$10^3k/$[Ketone]
(a) $\begin{cases} 0 \\ 0·485 \end{cases}$	0·121 0·121	0·313 0·481	2·59 3·98
(b) $\begin{cases} 0 \\ 0·613 \end{cases}$	0·241 0·241	2·48 1·93	10·3 8·0
(c) $\begin{cases} 0 \\ 1·20 \end{cases}$	0·1205 0·1108	2·43 1·96	20·2 17·7

The infrared absorption of the polymer obtained during oxidation of cyclopentanone showed a band at 1733 cm.$^{-1}$. This indicates that the ketone was present in a five-membered ring,[4] and that the polymer end-group is as inset.

Oxygen was absorbed by oxidising solutions of both cyclopentanone and cyclohexanone. With the former, oxygen decreased the overall rate of consumption of V^V, but with the latter the effect was not so marked, indicating that the rate of destruction of the primary radical must be large compared with its rate of combination with oxygen (Table 10). V^{IV} was found to have no specific effect on the rate of oxidation of ketones.

[4] Bellamy, " The Infra-red Spectra of Complex Molecules," Methuen, London, 1954.

TABLE 10. *Effect of oxygen on the oxidation of ketones.*

(a) $[H_3O^+] = 1.0M$ (H_2SO_4); $[V^V] = 0.0971N$; cyclopentanone used.
(b) $[H_3O^+] = 1.1M$ (H_2SO_4); $[V^V] = 0.0565N$; ionic strength = $1.2M$; cyclohexanone used.

	Temp.	[Ketone] (M)	Gas	$10^4 k$ (sec.$^{-1}$)		Temp.	[Ketone] (M)	Gas	$10^4 k$ (sec.$^{-1}$)
	30°	0.121	Air	0.14		25°	0.116	N_2, air	0.87
(a)	30	0.121	N_2	0.12		25	0.116	O_2	0.96
	30	0.121	O_2	0.026		35	0.116	N_2	2.51
					(b)	35	0.116	O_2	2.75
						50	0.1205	N_2	10.4
						50	0.1205	O_2	9.8

(6) *Stoicheiometry of the Oxidations.*—Consecutive reactions occur in the oxidations of both ketones. With cyclopentanone and excess of V^V eventual totals of 10·3 and 10·1 equivalents of oxidant were consumed in replicate experiments. Carbon dioxide was not evolved but a test with chromotropic acid [5] indicated the production of formic acid. The conversion of cyclopentanone into an equimolar mixture of succinic and formic acids would require 10·0 equivalents of an oxidant.

Cyclohexanone, however, reduced only 6·68 and 6·14 equivalents of V^V in similar experiments, and from the reaction product adipic acid (m. p. 149°, crude; after crystallisation m. p. and mixed m. p. 152°) was isolated in 95% yield. A small amount of a brown insoluble material, not containing vanadium, was deposited as the oxidation proceeded.

2-Hydroxycyclohexanone, which was shown to be the first oxidation product when Mn^{III} was the oxidant,[6] oxidises about 200 times as fast as cyclohexanone itself, as Table 11 shows.

TABLE 11. *Comparison of oxidation rates of cyclohexanone and 2-hydroxycyclohexanone.*

$[V^V] = 0.0226N$, $[H_3O^+] = 0.44M$ (H_2SO_4), ionic strength = $0.48M$, temp. = 50°.

[Substrate]	$10^4 k$ (sec.$^{-1}$)	$10^3 k/$[Substrate]
Cyclohexanone, 0·0125M	0·119	0·95
2-Hydroxycyclohexanone, 0·0158M	33·0	209

DISCUSSION

(1) *Nature of the Reactive Species.*—The very extensive oxidation of ketones by acid V^V is closely similar to the oxidations that can be effected by ceric and manganic salts, which also are one-electron-abstracting agents. For oxidation of cyclohexanone by manganic pyrophosphate Drummond and Waters [6] found that the limiting rate was that of the acid-catalysed enolisation of the ketone. This, at pH = 0·5 ($[H^+] = 0.32M$, activity coefficient being assumed to be unity and sulphuric acid regarded as monobasic in this range), was 8.5×10^{-3} mole l.$^{-1}$ hr.$^{-1}$ at 25°. Now extrapolation of Table 6 gives 5.3×10^{-3} equiv. l.$^{-1}$ hr.$^{-1}$ for the rate of V^V oxidation of cyclohexanone at this acidity, though at a much greater ionic strength. Even at high V^V concentration no trend towards oxidation at zero-order rate in V^V has been detected (cf. Table 3). Thus in the present series of experiments it is again possible for ketone oxidation to occur subsequent to enolisation.

Under these conditions of fast enolisation and slow oxidation the acid-catalysis of the reaction must be related to the structure of the oxidant and not of the organic substrate. Now, quinquevalent vanadium is completely converted into a univalent cation, VO_2^+, even in 0·1M-mineral acid, but the oxidations of the two ketones are wholly acid-dependent (Tables 4, 5, 6) so that, in contrast to the case of pinacol, the cation VO_2^+ cannot be an active oxidant. The occurrence at higher acidities of the rapid equilibrium $H_3O^+ + VO_2^+ \rightleftharpoons V(OH)_3^{2+}$ can be postulated,[7] and if $V(OH)_3^{2+}$ is presumed to be an active oxidant this equilibrium would account for the observations made in perchloric acid, where the acid-dependence is on $[H_3O^+]$ and not on Hammett's h_0, as would probably be the case with a cation $VO \cdot OH^{2+}$ that did not incorporate a water molecule.

The marked positive salt effect again indicates that the rate-determining reaction involves a charged ion, whilst colorimetric measurements fail to yield confirmatory evidence

[5] Feigl, " Spot Tests," Elsevier, Amsterdam, 1947.
[6] Drummond and Waters, *J.*, 1955, 497.
[7] Ramsey, Colichman, and Pack, *J. Amer. Chem. Soc.*, 1946, **68**, 1695; Boyer and Ramsey, *ibid.*, 1953, **75**, 3802.

of the presence of two different ions, VO_2^+ and $V(OH)_3^{2+}$, in perchloric acid solutions of V^V. The noticeable colour change from yellow to red in sulphuric acid solutions, together with the kinetic measurements of Tables 4—7, establishes without doubt the existence of a charged sulphate complex, such as $V(O\cdot SO_3H)_3^{2+}$ or $VO(O\cdot SO_3H)^{2+}$ or $V(OH)_3HSO_4^+$ of enhanced oxidising power. The last would give second-order dependence on sulphuric acid as approximately indicated by Table 6. Complex formation of this type accords, too, with the fact (Table 8) that the salt effect is somewhat less in sulphuric than in perchloric acid. Again, the solubility of V^V in sulphuric acid is much greater than in perchloric acid; $0\cdot4\text{N}$-solutions of V^V in 4M-sulphuric acid are quite stable and vanadium pentoxide dissolves easily in concentrated sulphuric acid, while $0\cdot2\text{N}$-solutions of V^V in $4\cdot4\text{M}$-perchloric acid precipitate vanadium pentoxide when warmed above $60°$, and only $0\cdot02\text{N}$-solutions of V^V can be prepared at room temperature in 60% perchloric acid by direct dissolution of vanadium pentoxide in the acid. Light absorption of V^V solutions in sulphuric acid is noticeably shifted towards longer wavelengths than that of solutions in perchloric acid but, since in both solvents the absorption maximum occurred below $2000\,\text{Å}$, spectrophotometric measurements could not be used to investigate the extent of sulphuric acid complex formation.

(2) *Mechanism of Ketone Oxidation.*—The effects of adding vinyl cyanide and oxygen to both reacting ketones show conclusively that free organic radicals must be formed,[1] and thus V^V cannot be reduced below the valency level V^{IV}. The strict first-order dependence of the oxidation rate on ketone concentration indicates that complex formation does not occur noticeably before the oxidation step (compare oxidations of 1,2-diols and of pyruvic acid by manganic pyrophosphate[6,8]). Comparison with the conclusions of Drummond and Waters concerning cyclohexanone oxidation by manganic pyrophosphate is of interest: $V(OH)_3^{2+}$ is the slower oxidant of cyclohexanone but it is a much faster oxidant of 2-hydroxycyclohexanone. The ultimate degradation of the ketones, however, does not differ significantly from that found with any other one-electron-abstracting agents.

<div align="center">EXPERIMENTAL</div>

Materials.—V^V *Solutions.* " AnalaR " ammonium metavanadate was dissolved or suspended in distilled water, and the calculated quantity of acid added. When solutions in perchloric acid (B.D.H.) were required it was essential that all the vanadate should be in solution, to minimise or eliminate precipitation of vanadium pentoxide. The acidity was determined and the ionic strength adjusted before the acid was added to the ammonium vandate solution, as addition of ammonium vanadate does not affect the ionic strength of the acid solution used:

$$2H^+ + NH_4VO_3 \rightleftharpoons VO_2^+ + NH_4^+ + H_2O$$

The $[V^V]$ was then found by titration, and a corrected acidity value was calculated from the above equation. The ionic strength was adjusted by using sodium perchlorate (Hopkin and Williams's " recrystallised " grade) which was shown not to contain sufficient chlorate to interfere with the titration of Fe^{2+} by V^V. Solutions of this were standardised by weighing the sodium perchlorate remaining after evaporation to dryness and ignition to $160°$, at which temperature the anhydrous salt is stable.[9]

Cyclopentanone was purified *via* its bisulphite compound, which was decomposed with acid, and the ketone extracted with ether. The ether was distilled off, and the fraction, b. p. 128—130°, was collected and refractionated. The purity was checked by the infrared spectrum.[10]

Cyclohexanone was purified by the bisulphite compound, which was decomposed with sodium carbonate,[11] the ketone steam-distilled off, and the dry, washed, ethereal extract was carefully fractionated under nitrogen.

[8] Drummond and Waters, *J.*, 1953, 3119.
[9] Duval, *Analyt. Chim. Acta*, 1947, **1**, 341.
[10] Randall, Fowler, Fuson, and Dangl, " Infrared Determination of Organic Structures," D. Van Nostrand Co. Inc., 1949.
[11] Garland and Reid, *J. Amer. Chem. Soc.*, 1925, **47**, 2333.

Pure 2-hydroxycyclohexanone was kindly given by Dr. M. L. Tomlinson.

Kinetic Measurements.—These were carried out as in Part I, except that for the work at 50° a totally enclosed reaction vessel, having two bulbs in which the unmixed reactants could be allowed to reach the temperature of the thermostat, was used. At zero time one bulb was rotated at a ground-glass joint, and the liquids were mixed by manual shaking. The whole vessel, except for a stoppered neck through which samples could be withdrawn, was immersed below the surface of the thermostat liquid.

It has been found that, in the absence of daylight, accurate titrations, by the procedure described in Part I, can be carried out in diffused light from a mercury lamp, filtered through glass.