Kinetics and mechanism of the oxidation of alcohols by tetrapropylammonium perruthenate[1]

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Abstract: 2-Propanol is oxidized by tetrapropylammonium perruthenate (TPAP) in a reaction that is second order in TPAP and first order in 2-propanol. One of the products, believed to be ruthenium dioxide, is an effective catalyst for the reaction, making it an autocatalytic process. The rate of oxidation is relatively insensitive to the presence of substituents. Primary kinetic deuterium isotope effects are observed when either the hydroxyl or the α hydrogen is replaced by deuterium. The only product obtained from the oxidation of cyclobutanol is cyclobutanone, indicating that the reaction is a two-electron process. Tetrahydrofuran is oxidized at a rate that is several orders of magnitude slower than that observed for 2-propanol, suggesting that the reaction of TPAP with alcohols may be initiated by formation of perruthenate esters. A tentative mechanism consistent with these observations is proposed.

Key words: oxidation, alcohols, tetrapropylammonium perruthenate, reaction mechanism, autocatalysis.

Résumé : La réaction du propan-2-ol par le perruthénate de tétrapropylammonium (PTPA) est du deuxième ordre en PTPA et du premier ordre en propan-2-ol. Un des produits, qu'on suppose être le dioxyde de ruthénium, est un catalyseur efficace de la réaction qui la transforme en processus autocatalytique. La vitesse d'oxydation est pratiquement insensible à la présence de substituants. On observe des effets isotopiques cinétique du deutérium lorsqu'on remplace l'hydrogène de l'hydroxyle ou l'hydrogène en α par du deutérium. Le seul produit obtenu lors de l'oxydation du cyclobutanol est la cyclobutanone, ce qui indique que la réaction se produit par un processus à deux électrons. Le tétrahydrofurane est oxydé à une vitesse qui est de plusieurs ordres de grandeur plus faible que celui observé pour le propan-2-ol, ce qui suggère que la réaction du PTPA avec les alcools est peut-être initiée par la formation d'esters de l'acide perrhuténique. On propose un mécanisme qui est en accord avec les observations.

Mots clés : oxydation, alcools, perrhuténate de tétrapropylammonium, mécanisme de réaction, autocatalyse.

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Introduction

The historical chemistry of tetrapropylammonium perruthenate (TPAP) has been reviewed (1–3). It is an excellent oxidant for the conversion of primary alcohols to aldehydes and secondary alcohols to ketones in nonaqueous solvents. The reaction is particularly fast, and good yields are usually obtained. Primary alcohols can be oxidized selectively in the presence of secondary alcohols (4) and 1,4- and 1,5-diols are converted to the corresponding five- and six-membered lactones (4, 5).

TPAP has also been used for the oxidation of sulfides to sulfones (6), secondary nitro compounds to ketones (7), and alkylboranes to the corresponding carbonyl compounds (8).

In addition to its use in solvents such as methylene chloride and acetonitrile, TPAP can be used effectively in ionic liquids (9).

Recent applications include the selective oxidation of a secondary alcohol that is part of a molecule that also contains a reactive ether functionality (10), the conversion of a primary alcohol to an aldehyde as a part of the asymmetric total synthesis of pironetin (11), the oxidation of 3-, 11-, 15-, 17-, and 20-hydroxy steroids to the corresponding ketones (12), and the preparation of a pyrrole from the corresponding α-aziridinyl alcohol (13).

TPAP can be used as a stoichiometric oxidant (14–18) or as a catalytic reagent in conjunction with a cooxidant such as N-methylmorpholine N-oxide (4–14).

Other than our previously published observation that its reactions with alcohols are autocatalytic (19), little is known about the mechanisms of TPAP oxidations. In an attempt to obtain a better understanding of the mechanism, a kinetic study of its reactions with aliphatic alcohols has been undertaken. Although autocatalytic reactions are not easily amenable to kinetic studies, sufficient experimental evidence has been obtained to propose a tentative reaction mechanism.

Experimental

Materials

Methylene chloride, used as the solvent in kinetic experiments, was purified by successive distillations from calcium hydride and tetrabutylammonium permanganate. The purified solvent was stored over molecular sieves.

2-Propanol and the substituted 2-propanols were obtained commercially. They were distilled over calcium oxide and a middle fraction was collected and analyzed using gas chromatography. Purities of 99.9% or greater were obtained by this method. The observed boiling points were in agreement with published values (20). 2-Propanol-2-*d* and 2-propanol-O-*d* were prepared and purified as previously described (21).

Tetrahydrofuran, obtained from Aldrich, was purified by passage through a column of alumina to remove peroxide and fractionally distilled. A freshly purified sample with a boiling point of 64.0–64.2 °C was used in each experiment (22).

Tetrapropylammonium perruthenate, obtained from Aldrich, was dissolved in freshly purified methylene chloride, placed in a 10 mL brown bottle and used immediately in kinetic experiments. The concentration was determined spectrophotometrically from measurement of absorbances at 384 or 270 nm as described in the following.

Spectral studies

The UV–vis spectra of TPAP and its reduction product (RuO_2) have been reproduced in Fig. 1. It is apparent from these spectra that the greatest change in absorbance occurs at about 270 nm when TPAP is reduced by 2-propanol. Therefore, this wavelength is the most logical one to use for kinetic studies. However, before proceeding on that assumption, it was confirmed that the absorbances of both the reactant and the product are proportional to their concentrations at this wavelength. This was done by preparing the corresponding plots of absorbance vs. concentration, as in Figs. 2 and 3. From these plots it is apparent that both TPAP and RuO_2 obey Beer's Law at 270 nm.

Kinetic methods

Determination of reaction rates was achieved by monitoring the increase in absorbance at 270 nm as the reaction progressed. Absorbance measurements were made using a Hewlett Packard 8450A spectrophotometer equipped with a thermostatted cell holder. Each experiment was repeated a minimum of five times and the average reported. The uncertainties noted are standard deviations.

The starting concentrations of the oxidant (TPAP) were between 1.57×10^{-4} and 4.11×10^{-4} mol/L. The concentration of the reductant (2-propanol) was at least 25 times greater in all experiments to ensure that pseudo-order conditions would pertain.

In a typical experiment, 10 mL of a freshly prepared solution of TPAP in methylene chloride was thermostatted at the required temperature in a water bath. An aliquot (2.00 mL) of this solution was then transferred to a cuvette and placed in the cell holder of the HP 8450A spectrophotometer, thermostatted at the same temperature. An excess of alcohol was added using a microliter syringe and the reaction rate was determined by monitoring absorbance changes at 270 nm. Usually, 99 absorbance readings were collected for each kinetic measurement.

A typical plot of absorbance against time is presented in Fig. 4. A sigmoidal plot of this type is typical of autocatalytic reactions. The rate, slow initially, increases dramatically as the product (catalyst) is formed, and then slows down again as the concentrations of reactants are dimin-

Fig. 1. UV–vis spectrum of tetrapropylammonium perruthenate (TPAP) and its reduction product (RuO_2).
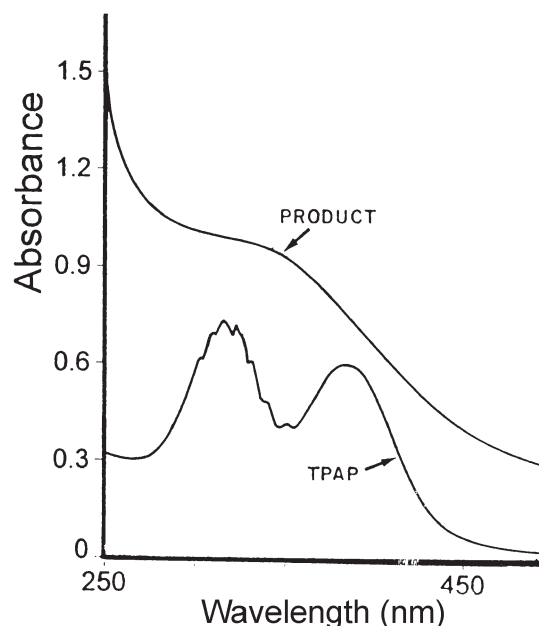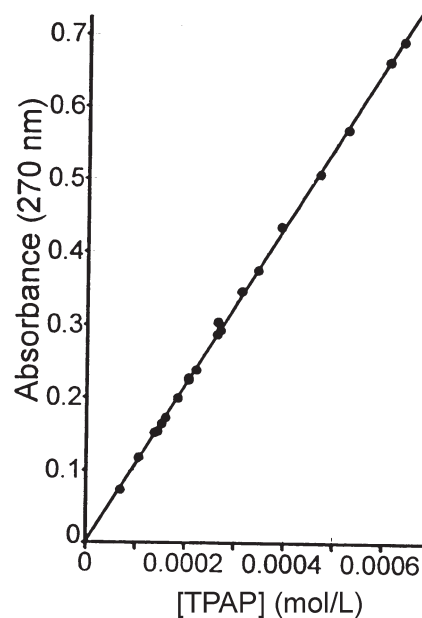

Fig. 2. Beer's Law plot for TPAP at 270 nm. Slope = 1084. Intercept = 0.0013. r^2 = 0.999.

ished. The autocatalytic nature of the reaction can also be illustrated by plotting the rate (dA/dt) against time as in Fig. 5. It can be seen that the reaction rate passes through a maximum, giving a "bell-shaped" curve that is diagnostic for autocatalytic reactions (23).

Stability of the oxidant

Tetrapropylammonium perruthenate is slowly reduced by the solvent under the experimental conditions used in this study. The pseudo-first-order reaction rate (Fig. 6) is insignificant when compared to the rate at which TPAP is reduced by 2-propanol and shows no evidence of auto-

Fig. 3. Beer's Law plot for the product (RuO$_2$) formed when TPAP is reduced by 2-propanol. Slope = 3858. Intercept = 0.0071. r^2 = 0.997.

Fig. 5. Plot of the reaction rate for the reduction of TPAP by 2-propanol vs. time.
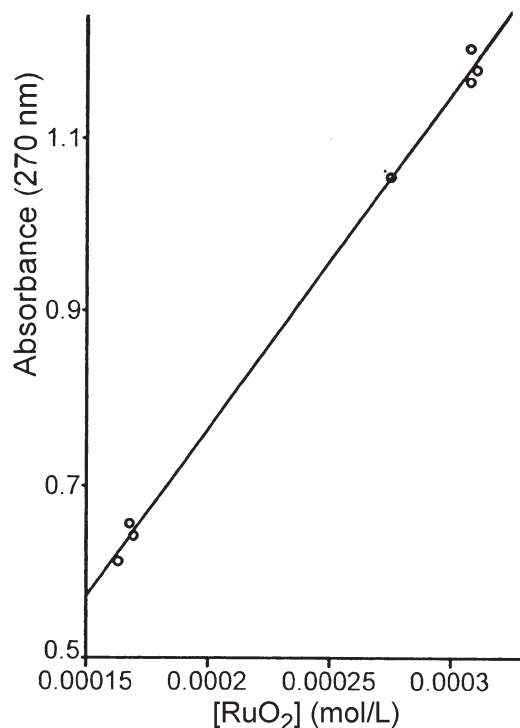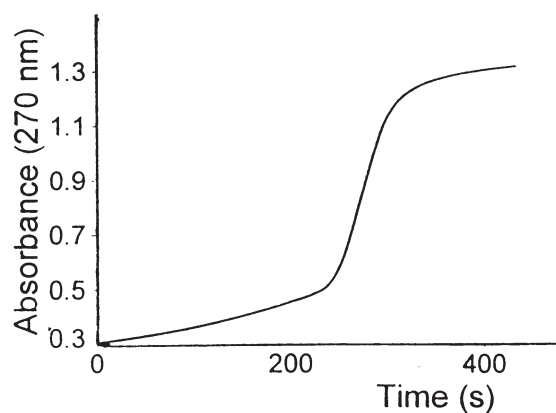
Fig. 4. Plot of the absorbance at 270 nm vs. time for the reduction of TPAP by 2-propanol.

catalysis. Nevertheless, to minimize the potentially large effect of having a small amount of catalyst (RuO$_2$) present at the beginning of a kinetic experiment, freshly prepared solutions were always used.
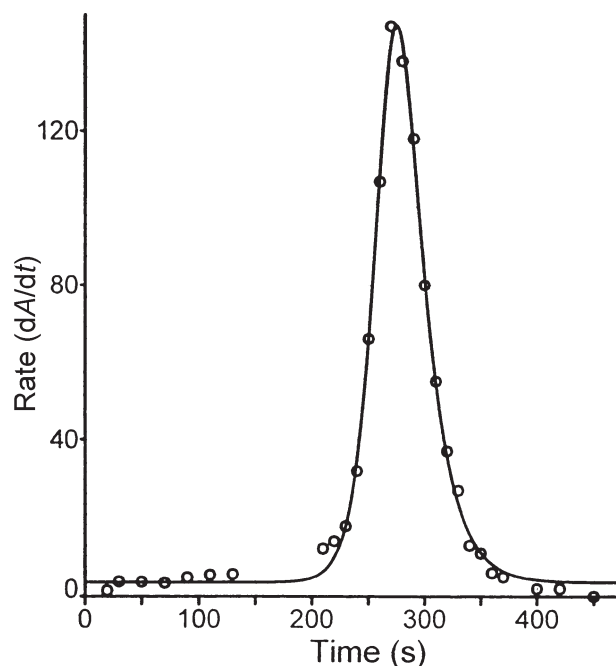
Results

The rate law for the uncatalyzed reaction

The kinetics of an autocatalytic reaction can be analyzed by dividing the rate into two parts — one owing to the uncatalyzed portion of the reaction and one owing to the catalyzed portion, as in eq. [1].

[1]   Rate = Rate$_{uncatalyzed}$ + Rate$_{catalyzed}$

The rate of the uncatalyzed reaction was determined from a study of initial reaction rates. Since the catalyzed reaction is much faster than the uncatalyzed reaction, the rate of the autocatalyzed reaction was determined, as described in the following, from a study of the reaction after a significant amount of product had been formed.

At the start of the reaction no product (catalyst) is present and the observed reaction rate is due, therefore, only to the uncatalyzed reaction between tetrapropylammonium perruthenate (QRuO$_4$) and 2-propanol. Consequently, the rate law and rate constant for the uncatalyzed reaction were determined under initial reaction conditions. The general form of the expected rate law, as given in eq. [2], was simplified by using a great excess of 2-propanol. The resulting pseudo-order rate law is expressed in eqs. [3] and [4].

[2] $(d[RuO_2]/dt)_i = k_u[QRuO_4]_i^m[2\text{-propanol}]^n$

[3] $(d[RuO_2]/dt)_i = k_u'[QRuO_4]_i^m$

[4] $k_u' = k_u[2\text{-propanol}]^n$

Since the absorbance at 270 nm conforms to Beer's Law for both the reactant and the product, the rate law stated in eq. [3] can be expressed in terms of absorbances, as in eqs. [5] and [6].

[5] $(dA/dt)_i = k_u'A_i^m(\varepsilon_{RuO_2}/\varepsilon_{QRuO_4}^m)$

[6] $\ln(dA/dt)_i = m\ln A_i + \ln k_u' + \ln(\varepsilon_{RuO_2} - \varepsilon_{QRuO_4}^m)$

The initial reaction rates ($(dA/dt)_i$) were easily obtained from tangents to plots of absorbance vs. time at zero time. From a plot of $\ln(dA/dt)_i$ vs. $\ln(A_i)$, as in Fig. 7, the reaction was found to be second order with respect to QRuO$_4$. As described in the following, the order with respect to 2-propanol was subsequently found to be unity, resulting in the rate law given in eq. [7] for the uncatalyzed portion of the reaction.

Fig. 6. Plot of the absorbance at 270 nm vs. time for the reduction of TPAP in a methylene chloride solution with no added 2-propanol. Slope = 0.196. Intercept = 6.3×10^{-6}. $r^2 = 0.993$.
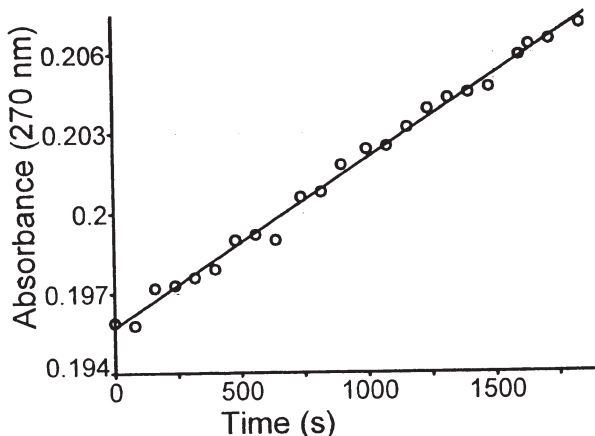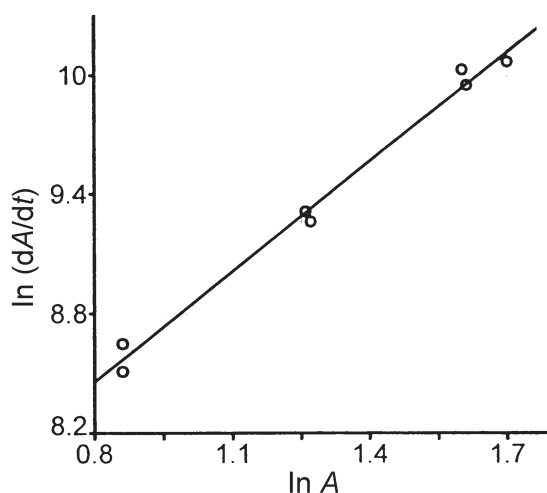

Fig. 7. Plot of the initial rates vs. initial absorbance for the reduction of TPAP by 2-propanol. Slope = 1.8 ± 0.1. Intercept = 6.98. $r^2 = 0.990$.

Fig. 8. Plot for the determination of the rate constant (k_u'). Slope (k_u') = 1.45 ± 0.05. Intercept = 0.231. $r^2 = 0.997$.

[10] $k_c' = k_c[\text{2-propanol}]^r$

The concentrations of $QRuO_4$ and RuO_2 can be calculated at any point along a plot of absorbance vs. time (cf. Fig. 4) by use of eqs. [11] and [12] where A_i is the initial absorbance, A_f is the final absorbance, A_t is the absorbance at any time "t", and $\Delta\varepsilon$ is ($\varepsilon_{RuO_2} - \varepsilon_{QRuO_4}$) (24).

[11] $[QRuO_4] = (A_f - A_t)/\Delta\varepsilon$

[12] $[RuO_2] = (A_t - A_i)/\Delta\varepsilon$

A combination of eqs. [9] and [11] gives eqs. [13] and [14].

[13] $dA_t/dt = k_c'[QRuO_4]^p[RuO_2]^q\Delta\varepsilon$

[14] $\ln(dA_t/dt) = p \ln[QRuO_4] + q \ln[RuO_2]$
$$+ \ln k_c' + \ln\Delta\varepsilon$$

In a series of reactions with differing initial concentrations of $QRuO_4$, rates (dA_t/dt) were measured by taking tangents to the curves at points where the concentration of RuO_2 was constant. Under conditions of constant $[RuO_2]$, eq. [14] is reduced to eq. [15] where C is a constant. The order with respect to $[QRuO_4]$ obtained from a plot of $\ln(dA_t/dt)$ vs. $\ln[QRuO_4]$, as in Fig. 9, was observed to be two. Therefore, the catalyzed portion of the reaction is also second order with respect to the concentration of the oxidant.

[15] $\ln(dA_t/dt) = p \ln[QRuO_4] + C$

Similarly, the apparent order with respect to the concentration of the catalyst (RuO_2) was determined from a series of rate measurements made at constant $QRuO_4$ concentration. Under those conditions, eq. [14] is simplified to eq. [16] where C' is a constant.

[7] $(d[RuO_2]/dt)_i = -(d[QRuO_4]/dt)_i$
$$= k_u[QRuO_4]^2[\text{2-propanol}] = k_u'[QRuO_4]^2$$

The pseudo-second-order rate constants for this reaction (k_u') were then determined from plots of $-d[QRuO_4]/dt_i$ vs. $[QRuO_4]^2$ as in Fig. 8.

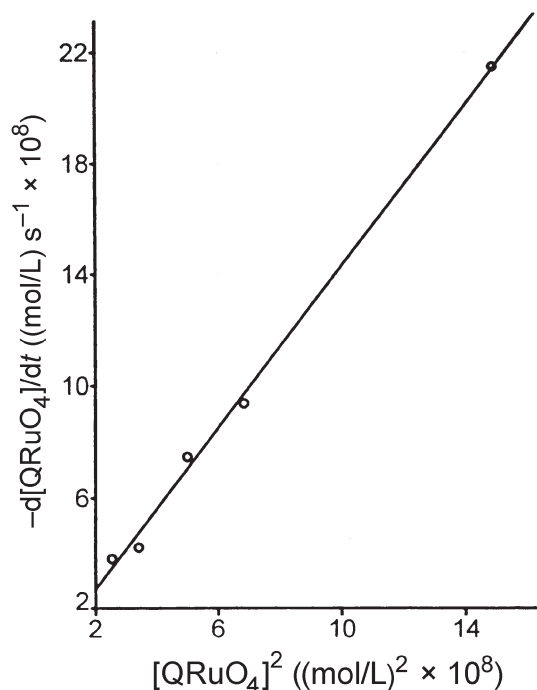**Rate law for the catalyzed reaction**

Rates for the catalyzed reaction were determined by taking tangents to the curve obtained from a plot of the absorbances against time after a significant amount of product (RuO_2) had formed. Under these conditions the contribution from the uncatalyzed reaction is negligible, as indicated from the data plotted in Figs. 4 and 5.

The general form of the rate law for the catalyzed portion of the reaction, given in eq. [8], can be simplified to eqs. [9] and [10] by using a large excess of 2-propanol.

[8] $-d[QRuO_4]/dt = k_c[QRuO_4]^p[RuO_2]^q[\text{2-propanol}]^r$

[9] $-d[QRuO_4]/dt = k_c'[QRuO_4]^p[RuO_2]^q$

Fig. 9. Plot for determining the order of the catalytic reaction with respect to the oxidant. Slope (order) = 2.0 ± 0.1. Intercept = 11.7. r^2 = 0.986.

Fig. 10. Plot for determining the apparent order of the catalytic reaction with respect to the catalyst (RuO$_2$). Slope = 2.1 ± 0.3. Intercept = 13.7. r^2 = 0.957.
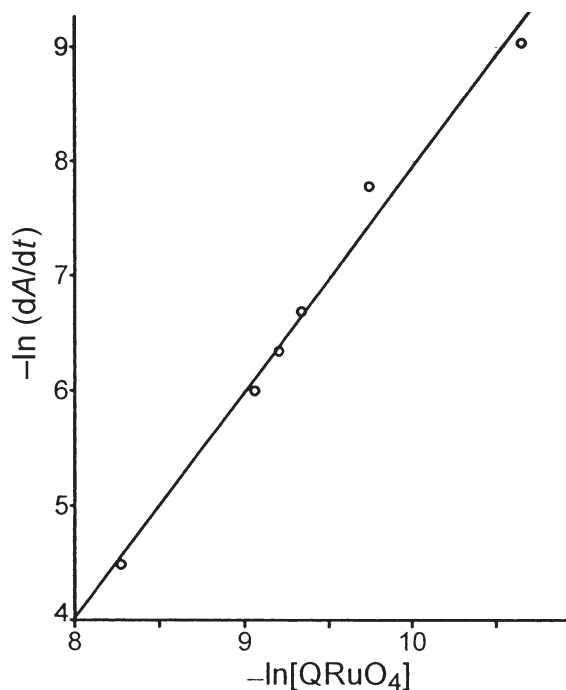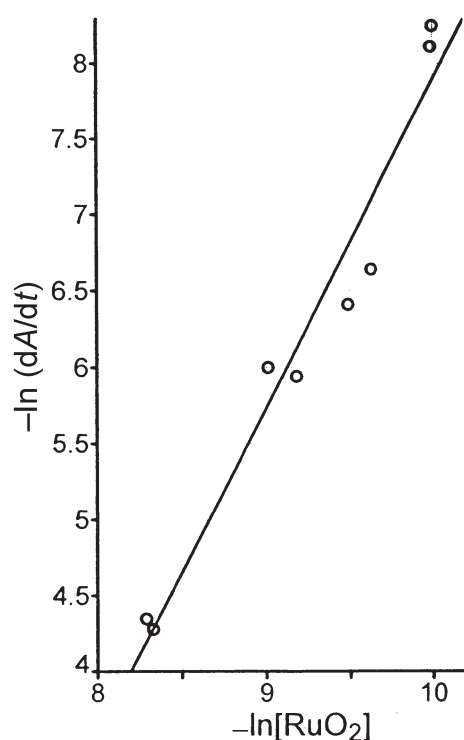

$$[16] \quad \ln(\mathrm{d}A_t/\mathrm{d}t) = q \ln[\mathrm{RuO_2}] + C'$$

The plot of eq. [16], in Fig. 10, indicates that the apparent order with respect to RuO$_2$ is about two. As described below, the order with respect to 2-propanol was subsequently found to be unity, resulting in the rate law given in eq. [17] for the catalyzed portion of the reaction.

$$[17] \quad -\mathrm{d}[\mathrm{QRuO_4}]/\mathrm{d}t = k_c[\mathrm{QRuO_4}]^2[\mathrm{RuO_2}]^2[\text{2-propanol}]$$

The pseudo-fourth-order rate constant (k_c') was then obtained from a plot of $-\mathrm{d}[\mathrm{QRuO_4}]/\mathrm{d}t$ vs. $[\mathrm{QRuO_4}]^2[\mathrm{RuO_2}]^2$ as in Fig. 11.

The complete rate expression for the reaction determined from this analysis, therefore, is given by eq. [18].

$$[18] \quad -\mathrm{d}[\mathrm{QRuO_4}]/\mathrm{d}t = ([\mathrm{QRuO_4}]^2[\text{2-propanol}])$$
$$\times (k_u + k_c[\mathrm{RuO_2}]^2)$$

Computer-assisted analysis of reaction rates

Obtaining rate constants for the reaction by use of the classical methods described in the previous section is time consuming and somewhat subject to personal biases. The use of computer-based models for the reaction can eliminate personal biases and greatly reduce the time required for analysis. Accordingly, software written in Turbo Pascal was developed to assist in the analysis of the raw time vs. absorbance data.

The computer program initially estimated pseudo-order rate constants (k_u' and k_c'), and then completed a least-squares regression using an analytic function derived from eq. [19].

$$[19] \quad -\mathrm{d}A/\mathrm{d}t = (k_u' + k_c'[\mathrm{RuO_2}]^2)[\mathrm{QRuO_4}]^2$$

Fig. 11. Plot for the determination of the rate constant (k_c'). Slope = 4.34 ± 0.05. Intercept = 0.245. r^2 = 0.999.
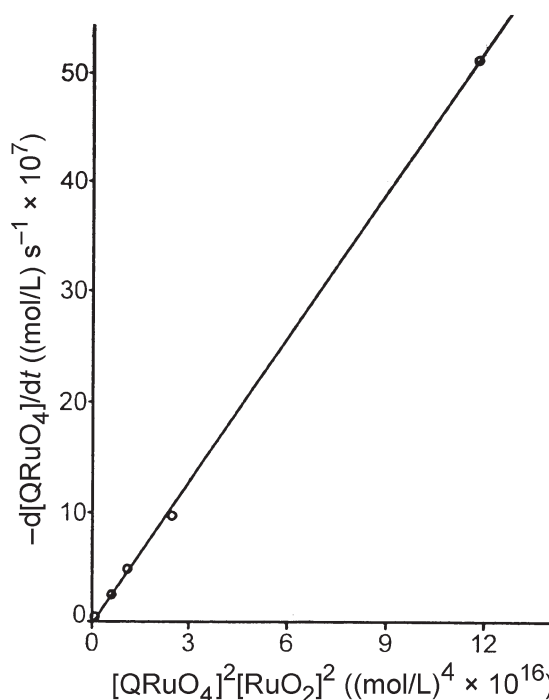
The variable parameters (k_u' and k_c') were then subjected to an iterative regression until the best correlation coefficient was obtained. In this way, it was possible to reproduce the experimental data very closely. The rate constants produced

Table 1. Comparison of rate constants obtained by graphical and computer-assisted analysis.

Rate constant	Graphical analysis[a]	Computer-assisted calculation[b]
k_u' $((mol/L)^{-1}\ s^{-1})$	1.46±0.05	1.57
k_u $((mol/L)^{-2}\ s^{-1})$	123±5	120
k_c' $((mol/L)^{-3}\ s^{-1} \times 10^{-9})$	4.21±0.05	4.79
k_c $((mol/L)^{-4}\ s^{-1} \times 10^{-9})$	354±6	366

Note: Temp. = 25.0 ± 0.1 °C.
[a][2-Propanol] = 0.0119 mol/L.
[b][2-Propanol] = 0.0131 mol/L.

from this computer-assisted analysis compare satisfactorily with the results obtained from the classical analysis described previously. See the data for a typical example given in Table 1.

The data in Table 1 confirm that this approach gives consistent values for the rate constants, with somewhat greater uncertainty in the values for the catalytic rate constants. In an additional test of this approach, an attempt was made to fit the data to a simpler rate law that is first order in oxidant and catalyst, as in eq. [20].

[20] $-dA/dt = (k_u'' + k_c''[RuO_2])[QRuO_4]$

The rate constants obtained using eq. [20] were less consistent and the correlation coefficients obtained were much lower than those for eq. [19]. All subsequently reported rate constants are those obtained from computer-assisted analysis of absorbance vs. time data.

From eq. [4], it can be seen that a plot of k_u' vs. [2-propanol] should be linear with a slope equal to k_u, and an intercept near zero, if the initial reaction rate is first order with respect to the concentration of 2-propanol. Similarly, it can be seen from eq. [10] that if the catalytic portion of the reaction is also first order with respect to the concentration of 2-propanol, a plot of k_c' vs. [2-propanol] should be linear with a slope equal to k_c and a zero intercept. The linearity of the two plots, presented in Figs. 12 and 13, confirms that the rate of this reaction is first order in the concentration of 2-propanol throughout.

Isotope effects

Rate constants for the oxidation of 2-propanol-2-*d* and 2-propanol-O-*d* are compared with that of the non-deuterated compound in Table 2. The data indicate that primary kinetic isotope effects are observed for the oxidation of both 2-propanol-2-*d* and 2-propanol-O-*d*.

Substituent effects

Rate constants for the oxidation of 2-propanol and five-substituted 2-propanols were determined to test the sensitivity of the reaction to changes in the nature of the substituents (25). From the data in Table 3 and the corresponding Taft plots in Figs. 14 and 15, it is apparent the rate constants are rather insensitive to substituent effects. The ρ* value for the uncatalyzed reaction is 0.18 and ρ* for the catalytic reaction is –0.43.

Fig. 12. Plot for determining the rate constant (k_u) for the uncatalyzed portion of the reaction. Slope (k_u) = 107 ± 5. Intercept = 0.09. r^2 = 0.976.
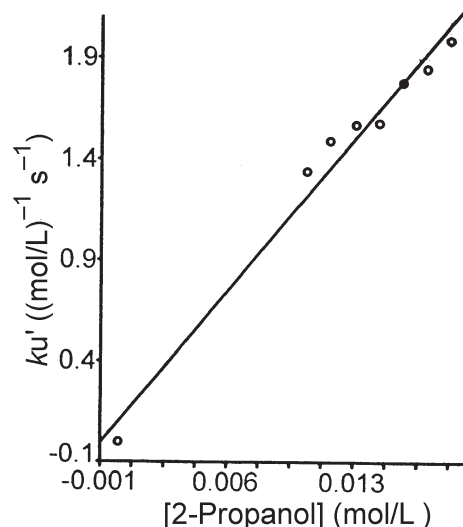
Fig. 13. Plot for determining the rate constant (k_c) for the catalytic portion of the reaction. Slope = (3.81 ± 0.06) × 10^11. Intercept = 0.005. r^2 = 0.994.
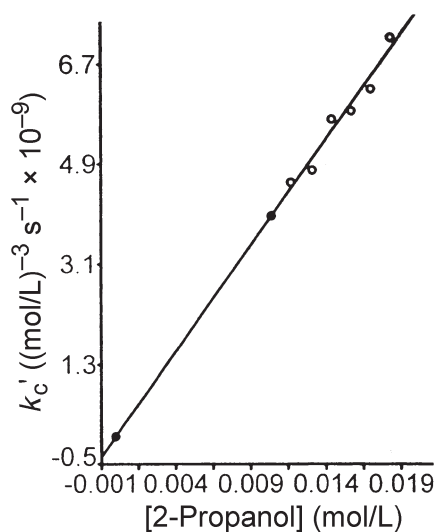
The oxidation of tetrahydrofuran by QRuO_4

When the oxidation of tetrahydrofuran (THF) was studied under similar conditions and with concentrations comparable to those used with 2-propanol in this study, the rates were found to be immeasurably slow. When the concentration of THF was drastically increased (6.14 mol/L), an autocatalytic reaction with a very long induction period was observed, as in Fig. 16.

The effect of moisture

The rate of oxidation of 2-propanol was found to be sensitive to the presence of moisture. When small amounts of water were added under typical reaction conditions, the autocatalytic nature of the absorbance vs. time plots was greatly diminished, as illustrated by the plots in Fig. 17.

Table 2. Isotope effects.

Alcohol	k_u' ((mol/L)$^{-1}$ s^{-1})	k_c' ((mol/L)$^{-3}$ s^{-1} × 10^{-9})	k_{uH}'/k_{uD}'	k_{cH}'/k_{cD}'
2-Propanol	1.57±0.14	4.79±0.76		
2-Propanol-O-d	1.17±0.09	1.97±0.76	1.3±0.1	2.4±0.6
2-Propanol-2-d	0.47±0.06	1.38±0.76	3.2±0.5	3.5±0.8

Note: Temp. = 25.0 ± 0.1 °C. [ROH] = 1.31 × 10^{-2} mol/L.

Table 3. Substituent effects.

Alcohol	[ROH] (mol/L × 10^2)	k_u ((mol/L)$^{-2}$ s^{-1} × 10^{-9})	k_c ((mol/L)$^{-4}$ s^{-1} × 10^{-9})
2-Butanol	1.09	114±6	282±35
2-Pentanol	0.919	125±10	216±61
2-Hexanol	1.02	104±3	208±3
2-Propanol	1.04	120±13	267±73
1-Methoxy-2-propanol	1.02	135±4	232±9
1,3-Dichloro-2-propanol	1.05	204±15	254±50

Note: Temp. = 25.0 ± 0.1 °C.

Fig. 14. Taft plot for the uncatalyzed reaction. Slope (ρ*) = 0.18. Intercept = 2.08. r^2 = 0.977.
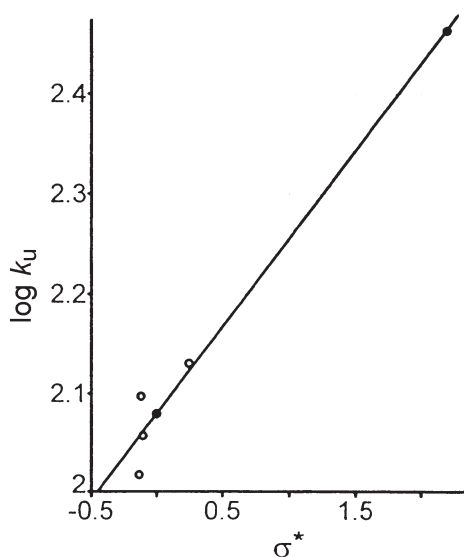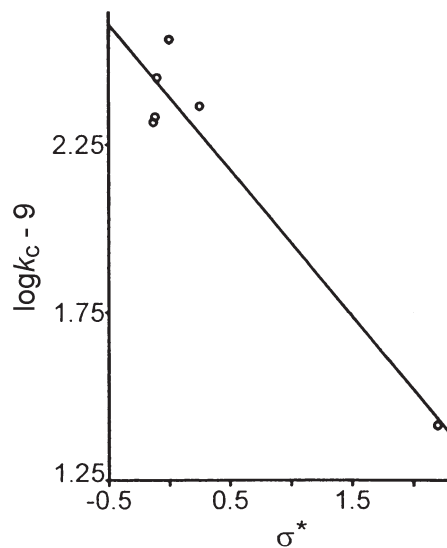

Fig. 15. Taft plot for the catalytic reaction. Slope (ρ*) = –0.43. Intercept = 2.39. r^2 = 0.924.

Consequently, precautions were taken to maintain anhydrous conditions at all times.

Demonstration of catalysis by the product (RuO$_2$)

The catalytic nature of the product of the reaction was also demonstrated in an experiment in which additional QRuO$_4$ was added after all of the oxidant initially present had been reduced by an excess of 2-propanol. As indicated by the plot in Fig. 18, the reaction resumed at an accelerated rate without an induction period. After 72 h, however, a fine black solid precipitated and the solution no longer exhibited autocatalysis.

The oxidation of cyclobutanol by QRuO$_4$

Tetrapropylammonium perruthenate (0.097 g, 0.29 mmol) was added to a 100 mL round-bottomed flask containing cyclobutanol (0.10 g, 1.4 mmol) in 50 mL of methylene

Fig. 16. Plot of the absorbance at 270 nm vs. time for the oxidation of THF (6.14 mol/L) by TPAP.
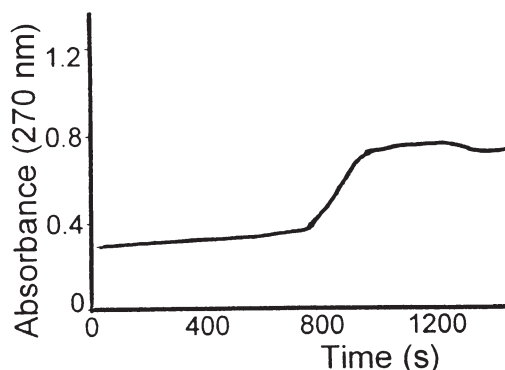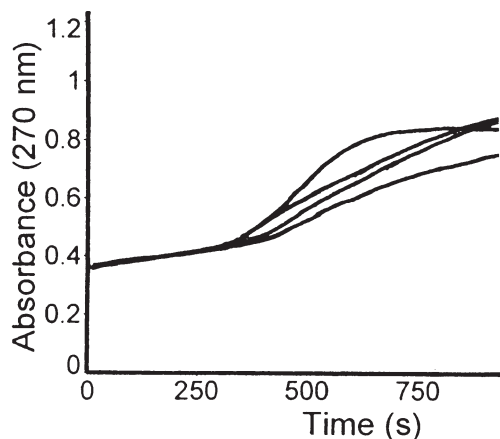
Fig. 17. Plots illustrating the effect of water on the reaction rates. The top plot was obtained in the absence of added water. The plots below it were obtained for reactions to which 0.5, 1.0, and 1.5 μL of water had been added, respectively.

Fig. 18. Plot illustrating the effect of adding additional TPAP after the initial reaction had stopped.

chloride. The solution was stirred at room temperature until all of the oxidant had been reduced and a brown suspension of RuO_2 remained. After filtering to remove the RuO_2, a clear solution was obtained. Evaporation of the solvent left a product (0.096 g) that was determined by ^{1}H NMR to contain a nearly quantitative amount of cyclobutanone.

Discussion

Autocatalysis

The autocatalytic nature of the reaction between tetrapropylammonium perruthenate and 2-propanol is evident from the plots presented in Figs. 4 and 5. The rate of reaction is initially slow because no product (catalyst) is present. However, as the concentration of the product increases, the rate accelerates, with the result that product is produced more and more rapidly. This results in continuous rate increases until the concentration of $QRuO_4$ diminishes, causing the rate to decrease and, finally, to stop.

Although the identity of the product responsible for the autocatalytic nature of the reaction has not been unequivocally established, it is in all likelihood ruthenium dioxide. Evidence in support of this conclusion was obtained by demonstrating that the product from the reduction of ruthenium tetroxide in carbon tetrachloride also catalyzed the reaction between $QRuO_4$ and 2-propanol. When tetrapropylammonium perruthenate was added to a solution prepared by the reduction of RuO_4 with excess 2-propanol, a rapid reduction of $QRuO_4$ occurred without an induction period. Since ruthenium tetroxide is known to be reduced to ruthenium dioxide by alcohols, the observation that this product is also a catalyst for the reaction between $QRuO_4$ and 2-propanol is entirely consistent with the assumption that RuO_2 is responsible for the autocatalysis evident in Figs. 4 and 5 (26).

The catalytic nature of the product was further demonstrated by adding an aliquot of $QRuO_4$ in methylene chloride to a solution in which the reaction of $QRuO_4$ with an excess of 2-propanol had proceeded to completion. As indicated by the plot in Fig. 18, the added $QRuO_4$ was very rapidly reduced without an induction period.
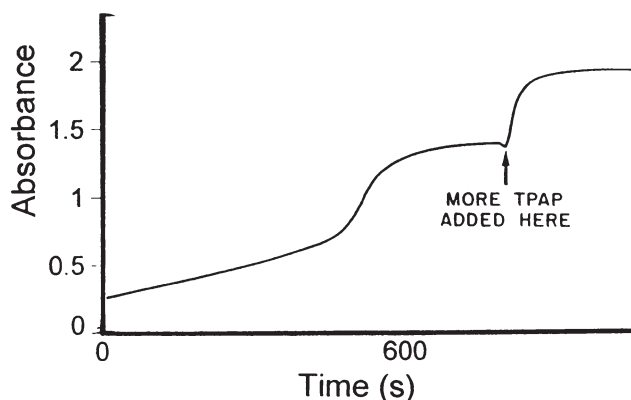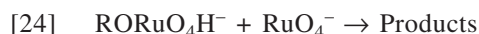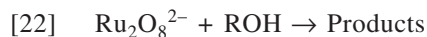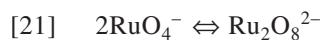
The reaction, therefore, is reminiscent of permanganate reductions in concentrated acid solution that are catalyzed by MnO_2, a product of the reaction (27). In such reactions, the product is a colloid that could act as a surface catalyst.

The observed decrease in catalytic activity in the presence of moisture (Fig. 17) is consistent with the possibility that RuO_2 acts as a surface catalyst whose active sites are blocked by adsorption of water. The observation that the reaction appears to be approximately second order with respect to the concentration of RuO_2 may be an artifact that is related in some way to the average size of the colloidal particles. Other possibilities involving a transition state that includes two molecules of $QRuO_4$, two molecules of RuO_2, and one molecule of 2-propanol are rather speculative (28).

The reaction mechanism

Both the catalytic and noncatalytic portions of the reaction exhibit a similar rate law — first order in 2-propanol and second order in $QRuO_4$. Thus, the transition state must contain two perruthenate ions and a molecule of 2-propanol.

The presence of two perruthenate ions suggests a dimer, similar to those known for other high valent transition metal oxides such as chromate and manganate (29, 30). Two possibilities exist: dimerization of the RuO_4^- ions could take place prior to reaction with the alcohol, as in eqs. [21] and [22], or, an ion of perruthenate and alcohol could react before the second RuO_4^- ion becomes involved, as in eqs. [23] and [24]. Unfortunately, kinetic studies do not help to distinguish between these two possibilities.

[21] $2RuO_4^- \Leftrightarrow Ru_2O_8^{2-}$

[22] $Ru_2O_8^{2-} + ROH \rightarrow Products$

[23] $RuO_4^- + ROH \Leftrightarrow RORuO_4H^-$

[24] $RORuO_4H^- + RuO_4^- \rightarrow Products$

Regardless of the reaction sequence, it appears that 2-propanol must initially react by formation of an ester. Such a conclusion is consistent with the O-D isotope effect and with the observation that ethers are not readily oxidized by $QRuO_4$. Oxidants such as RuO_4 and MnO_4^- that react with alcohols by an initial cleavage of an α-C—H bond, oxidize alcohols and ethers at comparable rates because the α hydrogens of alcohols and ethers have similar chemical properties

Scheme 1.
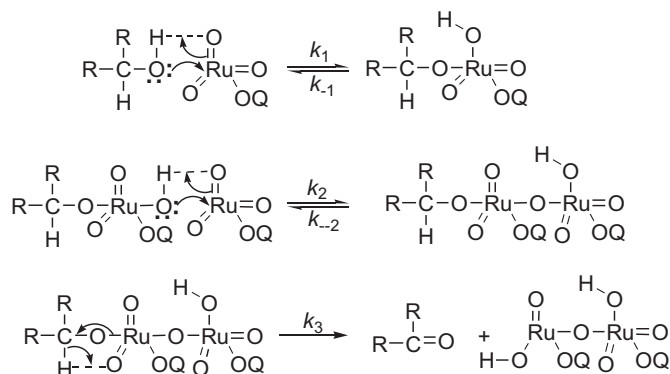
(31, 32). However, the reactions of oxidants, such as chromic acid (H_2CrO_4), that are initiated by ester formation, proceed more rapidly when alcohols are the reductants (33).

The observation that cyclobutanol is oxidized to cyclobutanone indicates that the oxidative process is a two-electron transfer. Previous work has established that hydrogen atom transfer from cyclobutanol produces a free radical that opens very rapidly to give acyclic products (34–36). The oxidation of cyclobutanol to cyclobutanone, therefore, indicates that $QRuO_4$ is a two-electron oxidant.

In addition, the low sensitivity of the reaction to substituent changes displayed in the Taft plots (Figs. 14 and 15), suggests a cyclic process in which there is little charge built up on the α carbon in the transition state. A reaction sequence, consistent with these observations, is presented in Scheme 1.

The rate law derived from the reaction sequence in Scheme 1 is consistent with the observed isotope effects since the rate constants for O–D cleavage (k_1) and C–D cleavage (k_3) are both in the numerator of the derived rate law, as indicated in eq. [25].

$$[25] \quad \text{Rate} = (k_1 k_2 k_3 [R_2CHOH][QRuO_4]^2)/(k_{-1} k_{-2} + k_{-1} k_3 + k_2 k_3 [QRuO_4])$$

Kinetic studies cannot be used to investigate reactions occurring after the transition state; however, the observed 1:1 stoichiometry allows some speculation with respect to the fate of the co-product ($H_2Ru_2O_8Q_2$). If this product (containing two ruthenium atoms, both with an average oxidation state of +6) was reduced to ruthenium(IV) by reaction with the solvent, the stoichiometry would be, ROH:$QRuO_4$ = 1:2. On the other had, if $H_2Ru_2O_8Q_2$ was reduced by 2 mol of 2-propanol, as in eq. [26], the stoichiometry would be, ROH:$QRuO_4$ = 3:2. Both of these possibilities, therefore, appear to be ruled out.

$$[26] \quad 2R_2CHOH + H_2Ru_2O_8Q_2 \rightarrow 2R_2CO + 2QRuO_4H_3$$

One possibility that results in a 1:1 stoichiometry is the suggestion that $H_2Ru_2O_8Q_2$ could dissociate into two different products, one with ruthenium in an oxidation state of +5 (H_2RuO_4Q) and the other, an oxidation state of +7 ($QRuO_4$), as in eq. [27]. Since a ruthenium(V) species would be expected to be very reactive, it would likely be reduced to ruthenium(IV) by reaction with the solvent. The overall result would be a 1:1 stoichiometry.

$$[27] \quad H_2Ru_2O_8Q_2 \rightarrow QRuO_4 + QRuO_4H_2$$
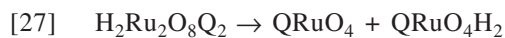
Conclusions

The reaction between alcohols and tetrapropylammonium perruthenate exhibits intense autocatalysis, making it an excellent reagent for synthetic purposes.

The product responsible for the autocatalytic nature of the reaction appears to be ruthenium dioxide.

The presence of moisture decreases the efficiency of the catalyst.

The rate law for the reaction under both noncatalytic and catalytic conditions is first order in the alcohol and second order in the oxidant.

The rate of reaction is much greater for 2-propanol than for THF, suggesting that the reaction involves formation of an intermediate ruthenate ester.

The oxidation of cyclobutanol to cyclobutanone by TPAP indicates that the reaction is a two-electron process.

Primary deuterium kinetic isotope effects are observed for the oxidation of both 2-propanol-2-*d* and 2-propanol-O-*d* by TPAP.

The impact of substituent effects on the reaction rates is not large.

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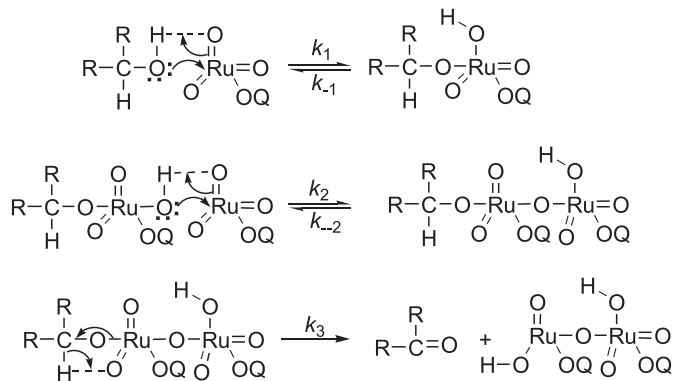# Appendix A

Derivation of eq. [A1] from Scheme A1.

[A1] $\quad$ Rate $= (k_1 k_2 k_3 [R_2CHOH][QRuO_4]^2)/(k_{-1}k_{-2}$
$$+ k_{-1}k_3 + k_2k_3[QRuO_4])$$

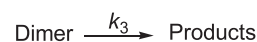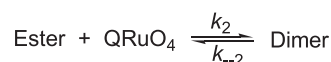Apply the steady state approximation to the intermediates; i.e., to [Ester] and [Dimer].

$$d[Ester]/dt = k_1[R_2CHOH][QRuO_4] - k_{-1}[Ester]$$
$$- k_2[Ester][QRuO_4] + k_{-2}[Dimer] = 0$$

$$d[Dimer]/dt = k_2[Ester][QRuO_4] - k_{-2}[Dimer]$$
$$- k_3[Dimer] = 0$$

Scheme A1.

$$d[Ester]/dt + d[Dimer]/dt = k_1[R_2CHOH][QRuO_4]$$
$$- k_3[Dimer] - k_{-1}[Ester] = 0$$

$$[Ester] = (k_1[R_2CHOH][QRuO_4] - k_3[Dimer])/k_{-1}$$

$$[Dimer] = (k_2[Ester][QRuO_4])/(k_{-2} + k_3)$$

$$[Dimer] = (k_1k_2[R_2CHOH][QRuO_4]^2$$
$$- k_2k_3[Dimer][QRuO_4])/(k_{-2} + k_3)(k_{-1})$$

$$[Dimer] = (k_1k_2[R_2CHOH][QRuO_4]^2)/(k_{-1}k_{-2}$$
$$+ k_{-1}k_3 + k_2k_3[QRuO_4])$$

Rate $= k_3[Dimer]$

$$= (k_1k_2k_3[R_2CHOH][QRuO_4]^2)/(k_{-1}k_{-2}$$
$$+ k_{-1}k_3 + k_2k_3[QRuO_4])$$