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A SERIES SECOND-FIRST-ORDER MECHANISM FOR THE OXIDATION OF PRIMARY AND SECONDARY ALCOHOLS BY Cr(VI) REAGENTS

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Abstract : Based on the experimental data, a definite mechanism for the oxidation of primary and secondary alcohols with PCC and two newly synthesized Cr(VI) reagents has been proposed. The reaction has been shown to be a series reaction rather than a simple one step reaction as reported in the literature. The mechanism proposed has been exemplified by taking 2-pentanol as an example. The kinetic isotope studies have also been performed.

INTRODUCTION

Pyridinium chlorochromate (PCC)-Corey's reagent[1] is a potential oxidant for primary and secondary alcohols[2]. The mechanism for the oxidation of alcohols by this versatile oxidant was first reported by Banerji[3], who proposed that a hydride-ion transfer in the rate-determining step may takes place either directly or involve the prior formation of a chromate ester. Subsequently, several kinetic studies were reported to ascertain the definite course of this reaction[4,5,6]. These studies indicated the probable involvement of PCC-substrate ester preceding the C-H cleavage.

However, the experimental data do not enable one to distinguish between the two proposed mechanisms. Investigations by Brown et al[7], showed that PCC is ultimately reduced to either CrO_2 or an intermediate of CrO_2 and pyridinium-chloride is formed. Thus, an overall two electron transfer takes place in the whole process, which rules out the involvement of intermediate valence states of Cr (as in CrO_3 oxidations).

To provide further evidence to exactly ascertain the mechanism of the oxidation of alcohols by PCC, we have also synthesized two new Cr(VI) reagenets, viz. 1-methyl imidazolium chlorochromate (MCC) and imidazolium chlorochromate (ICC) and found that these reagents also show similar selectivity and mechanism for the oxidation of alcohols as with PCC. We have concluded that the mechanism of oxidation of alcohols by PCC is not as simple as reported earlier. It is a series reaction rather than a one step reaction.

We have ascertained this by a semi-kinetic approach for the oxidation of 2-pentanol by PCC and two newly synthesized Cr(VI) reagents in chloroform. The progress of the reaction was followed by UV spectrophotometer at 360 nm for all the three oxidants.

THEORETICAL-TREATMENT

The standard forms of the chemical-equation of a system undergoing series reaction are :

$$A + D \xrightarrow{k_1} B \qquad (1)$$

$$B \xrightarrow{k_2} C + E \qquad (2)$$

The equations (1) and (2) represent the series second-first order reaction. If one of the reactants (D) is taken in large excess, then the equations (1) and (2) take the form:

$$A \xrightarrow{k_1} B \qquad (3)$$

$$B \xrightarrow{k_2} C \qquad (4)$$

The equations (3) and (4) represent the series first-order reaction. In measurements, we have reduced the first step of the reaction to pseudo first-order type by taking one of the reactants (alcohol) in excess. A,B, and C represent the starting material, intermediate and final product respectively. k_1 and k_2 represent the rate constant of first and second step respectively.

The concentrations of A,B and C with time can easily be calculated if the rate constants are known. The following expressions were given by Esson[8] for the above purpose :

$$[A] = [A_o] \; e^{-k_1 t} \qquad (5)$$

$$[B] = \frac{[A_o]k_1}{(k_2-k_1)} \left[e^{-k_1 t} - e^{-k_2 t} \right] \qquad (6)$$

$$[C] = [A_o] \left[1 + \frac{1}{(k_1-k_2)} (k_2 \, e^{-k_1 t} - k_1 \, e^{-k_2 t}) \right] \qquad (7)$$

where $[A_o]$ is the initial concentration of A at t=0. The rate constants (k_1 and k_2) can be calculated from the experimental data by making use of these equations. For the present case, all the oxidants used have maximum absorbance at 360 nm. The intermediate (B) also has the maximum absorbance at the same wavelength. Hence, the total observed absorbance (Δ_{obs}) can be represented as :

$$\Delta_{obs} = \Delta_A + \Delta_B \tag{8}$$

where Δ_A and Δ_B represent the absorbance of reactant (A) and of intermediate (B) respectively. Equation (8) can be transformed to equation (9) as :

$$\Delta_{obs} = \epsilon_A [A] + \epsilon_B [B] \tag{9}$$

where ϵ_A and ϵ_B represent the molar-extinction-coefficients of A and B respectively. From equation (5) and (6) :

$$\Delta_{obs} = \epsilon_A [A_o] e^{-k_1 t} + \frac{\epsilon_B [A_o] k_1}{(k_2 - k_1)} \left[e^{-k_1 t} - e^{-k_2 t} \right] \tag{10}$$

Equation (10) has three unknowns, viz. ϵ_B, k_1 and k_2. The calculations were done by using a computer. A graph of Δ_{obs} vs. time was plotted directly and the values for ϵ_B, k_1 and k_2 were chosen in such a way as to best fit in the observed plot.

EXPERIMENTAL

PCC was synthesized by Corey's method[1]. 2-pentanol (koch-light) was redistilled and the fraction distilling at 118-119°C was used in the reactions. Deuterated 2-pentanol (d_{O-H}) was synthesized by standard method. Chloroform (E. Merck) and acetonitrile (E. Merck) were purified, dried and distilled before use by usual methods[9]. Pyridine and 1-methyl imidazole (Fluka) were purified and distilled by standard method[9]. Imidazole (Fluka) was used as such.

Synthesis of two new Cr(VI) reagents :

(a) 1-methyl imidazolium chlorochromate (MCC) : Concentrated hydrochloric acid (12N, 1.84 ml, 0.022 mole) was added dropwise to the cold 1-methyl

imidazole (1.59 ml, 0.02 mole) with constant stirring. This solution was cooled to 0°C and was carefully added to dry chromium-trioxide (2 g, 0.02 mole) with stirring. Recooling to 0°C gave a yellow-orange solid, which was isolated by filtration, pressed between the folds of filter-papers and dried in vacuum. Yield: 3.97 g (91%), mp 115°C.
Anal. ($C_4H_7O_3N_2CrCl$) : N: calcd, 12.84; found 12.78%.

(b) Imidazolium chlorochromate (ICC) : The ICC was prepared and isolated as above by using imidazole (1.3616 g, 0.02 mole). Yield: 2.856 g (70%), mp 136°C.
Anal. ($C_3H_4O_3N_2CrCl$): N: calcd, 13.72; found, 13.69%.

Kinetic-Measurements : The reactions were studied under pseudo first-order conditions by keeping a large excess (x 15 or greater) of the alcohol over oxidants. The reactions were carried out at constant temperature (16±0.1°C) and were followed by UV-spectrophotometer having thermostated cell-compartments (HITACHI-220 S), at 360 nm. The oxidant was dissolved in chloroform (25 ml) except in the case of ICC which was dissolved in the mixture of 24.5 ml of chloroform and 0.5 ml of acetonitrile. The alcohol was added neat to the oxidant solution. The first kinetic-measurement at t=0 was that of oxidant only. The second kinetic-measurement was taken after the addition of alcohol to the oxidant solution, this time was that of mixing alcohol to the reaction mixture and putting it in UV cell for the absorbance measurement.

Method of Calculation : In the computer (PC XT) programme, written in basic language, there are five variables, viz. ϵ_A, ϵ_B, k_1, k_2 and $[A_o]$. For a given reaction with a particular oxidant two variables namely, ϵ_A and $[A_o]$ became constant and the remaining three variables, ϵ_B, k_1 and k_2 were calculated with this programme.

The λ_{max} of the intermediate (B) at 360 nm is the same for the oxidant also. The early rise in absorbance (A_{obs}) for few minutes (Fig. 1) indicated that $\epsilon_B > \epsilon_A$ and is consistent with the proposed mechanism. Larger value of ϵ_B than ϵ_A is due to the fact that an oxidant-substrate ester is formed in the first step of the reaction. The ester obviously has higher molecular weight than the oxidant. The initial rapid increase in absorbance followed by slow decrease with time (Fig. 1) indicated that the first step of the reaction is faster than the consecutive second step of the reaction. From these experimental data it is obvious that $k_1 > k_2$ and $\epsilon_B > \epsilon_A$.

ϵ_B for deuterated alcohol is slightly higher than that of undeuterated

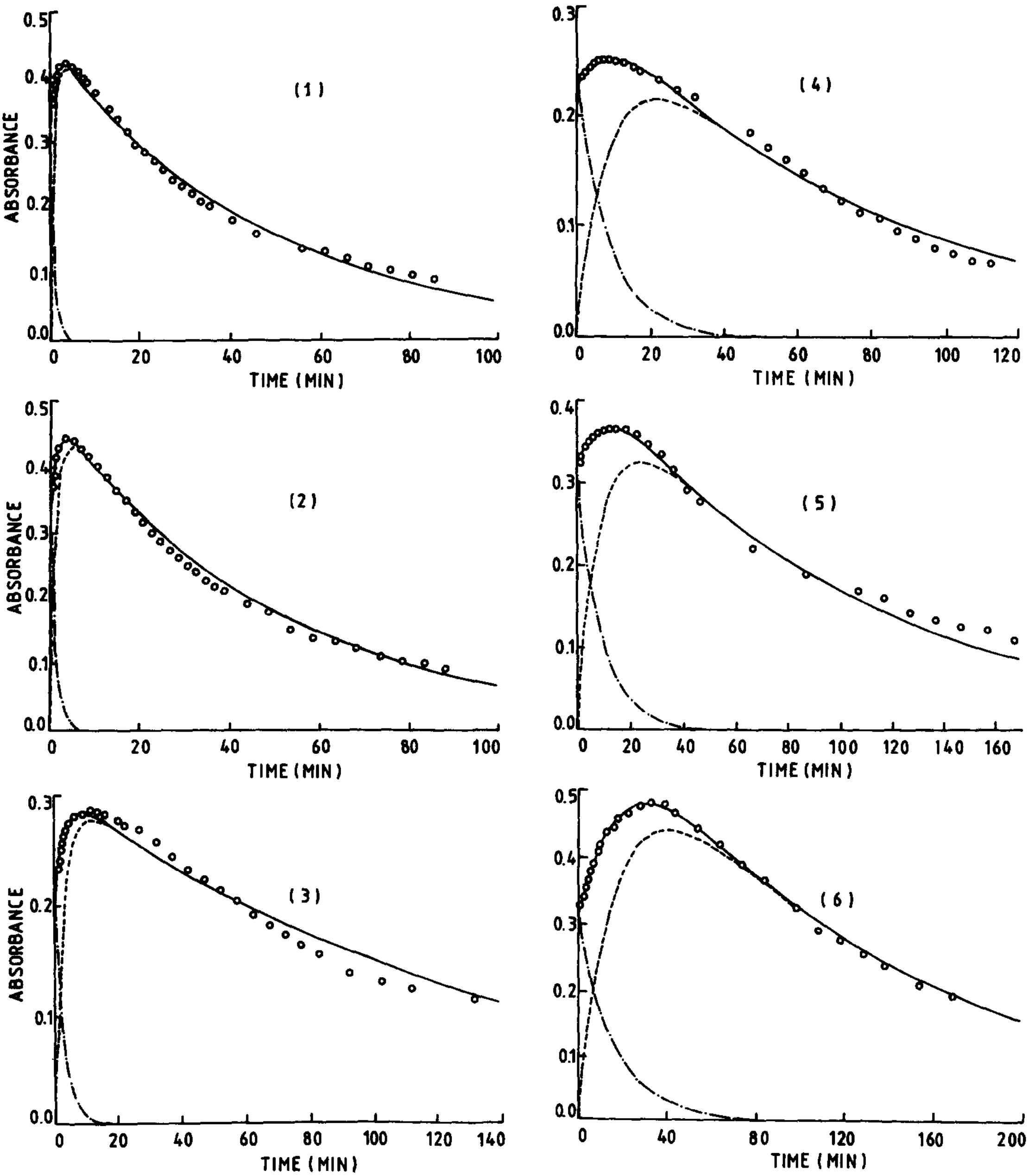


FIG.1 Oxidation of 2-pentanol with Cr(VI) reagents. Experimental points are shown with circles, solid curve (——) is calculated for Δ_{obs}; dashed curve (----) is for Δ_B and dashed with dots curve (—·—) is for Δ_A. (1) PCC, $k_1 = 1.1\ min^{-1}$, $k_2 = 0.021\ min^{-1}$; (2) PCC, $k_1 = 0.8\ min^{-1}$, $k_2 = 0.02\ min^{-1}$; (3) PCC, $k_1 = 0.35\ min^{-1}$, $k_2 = 0.0075\ min^{-1}$; (4) MCC, $k_1 = 0.115\ min^{-1}$, $k_2 = 0.013\ min^{-1}$; (5) MCC, $k_1 = 0.11\ min^{-1}$, $k_2 = 0.01\ min^{-1}$ and (6) ICC, $k_1 = 0.06\ min^{-1}$, $k_2 = 0.0075\ min^{-1}$.

alcohol due to small rise of molecular weight in deuterated alcohol. By making use of equation (10) and the two conditions mentioned above ($k_1 > k_2$ and $\epsilon_B > \epsilon_A$), the values of ϵ_B, k_1 and k_2 were so chosen as to best fit in the observed plot of Δ_{obs} vs. time (Fig. 1).

The absorbance values of A and B with time were calculated (see Fig. 1) by making certain changes in computer programme. In case of A, the equation (10) changes to:

$$\Delta_{obs} = \Delta_A = \epsilon_A [A_o] e^{-k_1 t} \qquad (11)$$

and for the B, the equation (10) changes to:

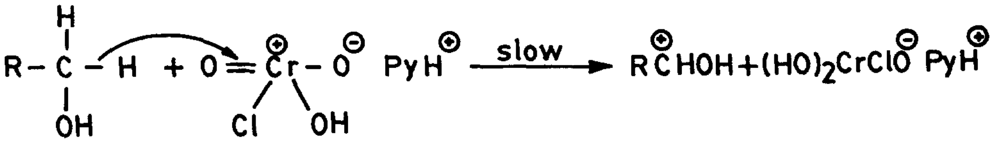
$$\Delta_{obs} = \Delta_B = \frac{\epsilon_B \; [A_o]k_1}{(k_2-k_1)} \left[e^{-k_1 t} - e^{-k_2 t} \right] \qquad (12)$$

RESULTS AND DISCUSSION

The reactions were followed under pseudo first-order conditions, ie., [alcohol] $\gg$ [oxidant]. The rate constants of the first step for the pseudo first-order k_1 and of the consecutive second step for the first order k_2 and ϵ_B were calculated with the help of a computer programme. The second-order rate constant ($k_3 = k_1/[S]$) for the first step of the reaction was also calculated (Table I).

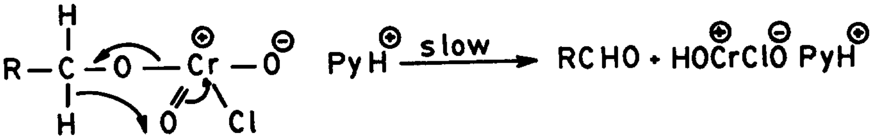
The isotope studies were also carried out by oxidizing deuterated 2-pentanol (d_{O-H}) with the Cr(VI) reagents. The results are presented in Table I. From the data in Table I, it is evident that the reactivity of the three oxidants is in the order of PCC>MCC>ICC. This can be explained on the basis of electron-density in the nucleus of the oxidants which is of the order imidazole>1-methyl imidazole>pyridine.

For the purpose of comparison, Banerji's mechanism[3] involving two alternative pathways is listed below :



$$R\overset{\oplus}{C}HOH \xrightarrow{fast} RCHO + H^{\oplus}$$

Pathway I



Pathway II

However, the major evidence against the pathway I is the positive isotope effect, observed by us on the first rate constant (k_1) of the reaction. This isotope effect confirms the fission of O-H (or O-D) bond in the first step of the reaction and rules out the pathway I, involving the hydride-ion transfer in the first step. Further, the absence of any isotope effect on the second rate constant (k_2) clearly indicates that O-H (or O-D) group is not involved in the consecutive second step of the reaction. This again contradicts the pathway I. The chromate ester (pathway II), proposed by Banerji, could only be formed by the elimination of one molecule of water from the action of alcohol on the protonated oxidant. This seems quite unlikely, because the water deactivates the oxidant and the reaction would retard and would come to halt after some time. That it does not happen, clearly indicates the chromate ester proposed by Banerji is not formed as an intermediate.

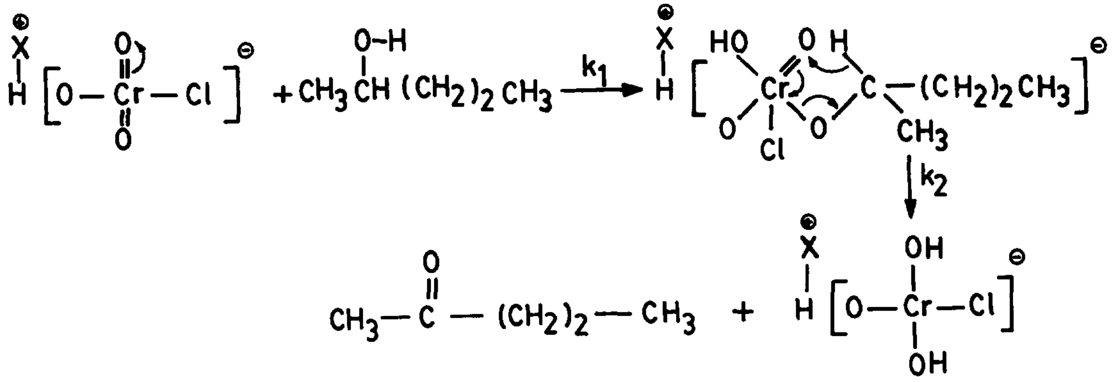
Further, the identical values of λ_{max} (360 nm) for the oxidant and the intermediate is indicative of same oxidation state (+) VI of chromium in both of these. This rules out the involvement of intermediate valence states of chromium, as in the case of CrO_3[10,11] oxidation where three electron transfer is involved.

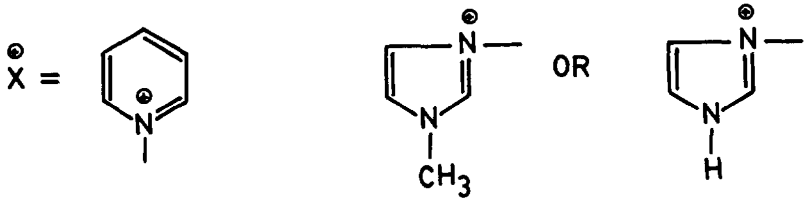
The primary kinetic-isotope-effect (KIE) studies for the oxidation of alcohol by PCC has been carried out for the first time by Banerji. He has oxidized ethan-1,1-d_2-ol by PCC and followed the reaction iodometrically. The deuterium KIE (k_H/k_D) for the C-D bond was found to be 5.72[3]. Recently, Pascal et al have measured the same deuterium KIE by oxidizing 1-propanol with PCC. They have followed the reaction by recording the ^2H NMR spectra. The deuterium KIE (k_H/k_D) for the C-D bond was found to be 6.7[12]. We have also studied the primary KIE for the oxidation of deuterated 2-pentanol(d_{O-H})

with PCC and MCC. The deuterium KIE (k_H/k_D) for the O-D bond was found to be 1.3 and ~1 for PCC and MCC respectively. Thus, it is very clear that the deuterium KIE measured by us for the O-D bond is very small as compared to the Banerji's and Pascal et al's observations for the C-D bond.

Thus, two major conclusions about the mechanism can be easily drawn from the above deuterium KIE observations: First; the low value of k_H/k_D for the O-D bond clearly indicates that the fission of O-H (or O-D) bond should not be the rate-determining step of the reaction. Also, since we have observed the deuterium KIE in the first step of the reaction thereby confirming that O-H fission must be the first step of the reaction. Secondly, the large value of k_H/k_D for the C-D bond, as observed by Banerji and Pascal et al, confirms that it must be the rate-determining step of the reaction and since we have not found deuterium KIE in the second step of the reaction clearly indicated that the fission of C-H bond should occur in the second step of the reaction.

From the results described above including the primary KIE studies, the most plausible mechanism for the oxidation of primary and secondary alcohols by Cr(VI) reagents may be formulated as follows:

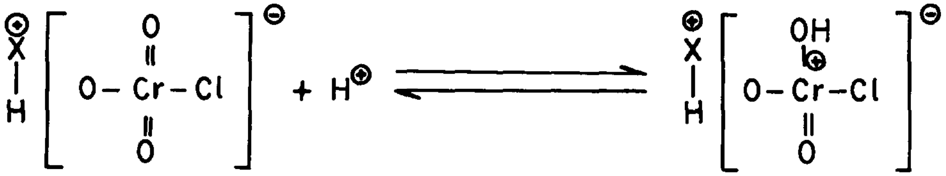




The first step involves the transfer of hydrogen atom from the O-H group of alcohol to the oxidant in order to form the oxidant-substrate ester. In the second step, two electrons are transferred in a cyclic system. This electrocyclic mechanism for the oxidation of alcohol by Cr(VI) reagents involves the six electrons and being a Hückel-type system (4n+2) is an allowed process[13].

The stoichiometric investigations of Brown et al[7] are in conformity with our findings, that the transfer of two electrons is involved in the oxidation of alcohols by PCC and related oxidants.

Our mechanism is consistent with the fact that these oxidations are acid-catalyzed. Protonation of the oxidant will make it more amenable towards nucleophilic attack by alcohol on the electron-deficient chromium of oxidant as shown below:



For a series first-order reaction a theoretical correlation of $K=k_2/k_1$ with τ_{15}, τ_{35}, τ_{70}, $\log t_{35/15}$, $\log t_{70/15}$, and $\log t_{70/35}$ values has been given by Swain[14]. Our results, for a series reaction, compares well with the Swain's theoretically predicted values (Table II). Thus, the mechanism for the oxidation of alcohols by Cr(VI) reagents is a series reaction and is in consistent with the theoretical values as well as with experimental data.

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TABLE I

Rate-constants for the oxidation of 2-pentanol by Cr(VI) reagents in chloroform solution

RUN NO.	OXIDANT	SUBSTRATE	[OXIDANT] x 10^4M	[SUBSTRATE] x 10^3M	k_1 min^{-1}	k_2 min^{-1}	$K=k_2/k_1$	ϵ_A	ϵ_B	$k_3=k_1/[S]$ $mole^{-1}min^{-1}$	% Yield at 168 min.
1.	PCC	2-pentanol	2.18	3.68	1.1	0.021	0.019	1388	2050	298.9	97
2.	PCC	2-pentanol (d_{O-H})	2.25	3.68	0.8	0.02	0.025	1388	2080	217.39	96.4
3.	PCC	2-pentanol (d_{O-H})	1.448	1.842	0.35	0.0075	0.0214	1388	2080	190.2	71.01
4.	MCC	2-pentanol	1.429	3.68	0.115	0.013	0.113	1595	1980	31.25	87.3
5.	MCC	2-pentanol (d_{O-H})	1.981	3.68	0.11	0.01	0.09	1595	2080	29.89	79.5
6.	ICC	2-pentanol	1.18	18.42	0.06	0.0075	0.125	2552	5000	3.26	67.58

TABLE II

Comparison of experimental results with Swain's[14] theoretically predicted values

RUN / SWAIN NO.	$K=k_2/k_1$	τ_{15}*	τ_{35}	τ_{70}	log $t_{35/15}$	log $t_{70/35}$	log $t_{70/15}$
1. (present values)	0.019	0.3586	1.2045	27.83	0.526	1.3637	1.8899
2. (present values)	0.025	0.3586	1.208	21.48	0.529	1.2499	1.7796
3. (present values)	0.0214	0.357	1.2075	24.85	0.529	1.3134	1.826
Swain's values	0.02	0.355	1.173	26.55	0.519	1.355	1.874
4. (present values)	0.113	0.3565	1.2075	5.5775	0.5298	0.6645	1.194
5. (present values)	0.09	0.352	1.21	6.71	0.536	0.7439	1.28
6. (present values)	0.125	0.357	1.206	5.16	0.528	0.6313	1.1599
Swain's values	0.1	0.349	1.078	6.19	0.490	0.759	1.497

* $\tau_{15} = k_1 t$ at 15% reaction.

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