THE OXIDATION OF D-GLUCOSE AND D-FRUCTOSE WITH OXYGEN IN AQUEOUS, ALKALINE SOLUTIONS

PART I. AN INTEGRAL REACTION SCHEME

H. G. J. DE WILT AND B. F. M. KUSTER

Department of Chemical Engineering, University of Technology, Eindhoven (The Netherlands)

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ABSTRACT

The homogeneous oxidation of D-glucose and D-fructose with oxygen in aqueous, alkaline solutions has been studied, and a reaction scheme is proposed to account for the observed products of reaction. The scheme involves the combination of a number of well-known reaction pathways in this field. Thus, formation of enolate anions is followed by (*a*) non-oxidative reactions (involving double-bond migration and cleavage) and (*b*) oxidative formation of peroxides, leading to the formation, amongst other products, of D-arabinonic, D-erythronic, D-glyceric, glycolic, and formic acids.

INTRODUCTION

The alkaline treatment of carbohydrates is an intrinsic part of a number of important processes such as the ageing of cellulose, the isomerization of D-glucose to D-fructose, and the heterogeneous catalytic oxidation of monosaccharides. Reported research in these fields is often product-oriented, and little attention is given to the rather complex mechanisms and kinetics. We now report on the kinetics of the homogeneous oxidation of D-glucose in aqueous, alkaline solutions in order to obtain basic technological information. An integral reaction-model is presented, which has been constructed by the combination of a number of well-known reaction pathways in this field.

An enolate–peroxide mechanism was invoked by Nef[1] to explain the formation of acidic products and the role of the dissolved oxygen in the oxidation of monosaccharides with oxygen in aqueous, alkaline solutions. Later investigations[2,12] have confirmed many of his observations, but also indicated[11] the need to modify his assignments. The first kinetic studies were reported by Bamford *et al.*[7,8] who showed that the autoxidation of D-glucose in the presence of oxygen and the rearrangements of D-glucose and D-fructose in the absence of oxygen could be explained kinetically by pseudo-first-order rate equations in terms of postulated, ionic intermediates. However, their assignments were restricted to hydroxyl-ion concentrations in the range 1–5M, and no attention was paid to the product distribution as a function of the reaction parameters. The latter aspect was considered by Dubourg *et al.*[11] who found that

the simple, first-order, rate equations did not accurately reflect the observed course of the sugar concentration during the reaction. Recently, qualitative studies on the behaviour of mono- and di-saccharides in alkaline media have been published, in particular with regard to formed products[12]. Most authors stress the stability of the formed acids.

In order to illustrate the scope and limits of the present work, the supposed[11], main reaction-steps are shown schematically in Fig. 1. This scheme includes the well-established Lobry de Bruyn–Alberda van Ekenstein transformation, by which monosaccharides can be interconverted easily *via* the various boundary structures of a given enolate ion. In principle, the double bond of an enolate ion can migrate through the whole carbon chain. The cleavage of an enolate ion is generally considered to occur β to the double bond.

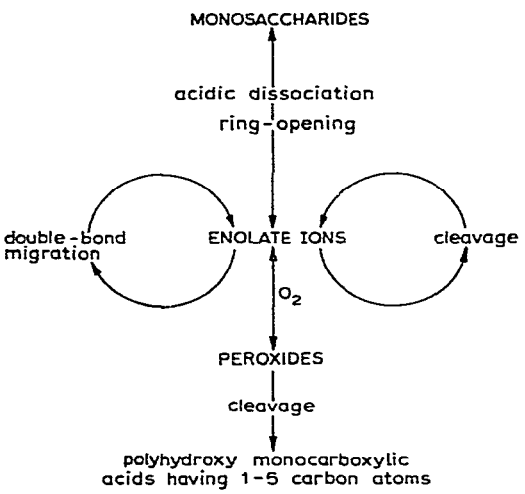


Fig. 1. Schematic representation of the reactions of monosaccharides in the presence of alkali and oxygen.

EXPERIMENTAL

The following parameters were studied with D-glucose or D-fructose: initial hexose concentration, 0–500; hydroxyl-ion concentration, 10–50; oxygen concentration in the liquid [O_l], 0–1 mmole.l^{-1}; and temperature (T), 40–70°.

Potassium hydroxide was used; the nature of the alkali metal ion can influence the course of the reaction[14]. To study the influence of the interconversion between D-glucose and D-fructose on the overall kinetics of the oxidation reaction, both hexoses were investigated. The initial concentration, [G_0] or [F_0], was limited by the maximum attainable oxygen mass transfer (R_0) from the gaseous to the liquid phase.

The temperature and pH ranges were limited (*a*) by the very low reaction rates below 40° or [OH] = 10, and (*b*) by the maximum allowable rate of oxygen uptake

(see above) and by the occurrence of polymerisation and hydroxyl-migration reactions. All experiments have been carried out batchwise.

Apparatus. — The experiments were carried out in a continuously stirred tank-reactor (Fig. 2), and a general flow-sheet is shown in Fig. 3. The oxygen mass-transfer through the interface between the gaseous phase and the aqueous solution can be represented by $R_O = k.a.([O_l^s]-[O_l])$, where R_O is the oxygen consumption rate (mmole.sec^{-1}), k is the overall mass transfer coefficient (cm.sec^{-1}), a is the interfacial area (cm^2), $[O_l^s]$ is the saturated oxygen concentration in the liquid[22] (mmole.l^{-1}), and $[O_l]$ is the actual oxygen concentration in the liquid.

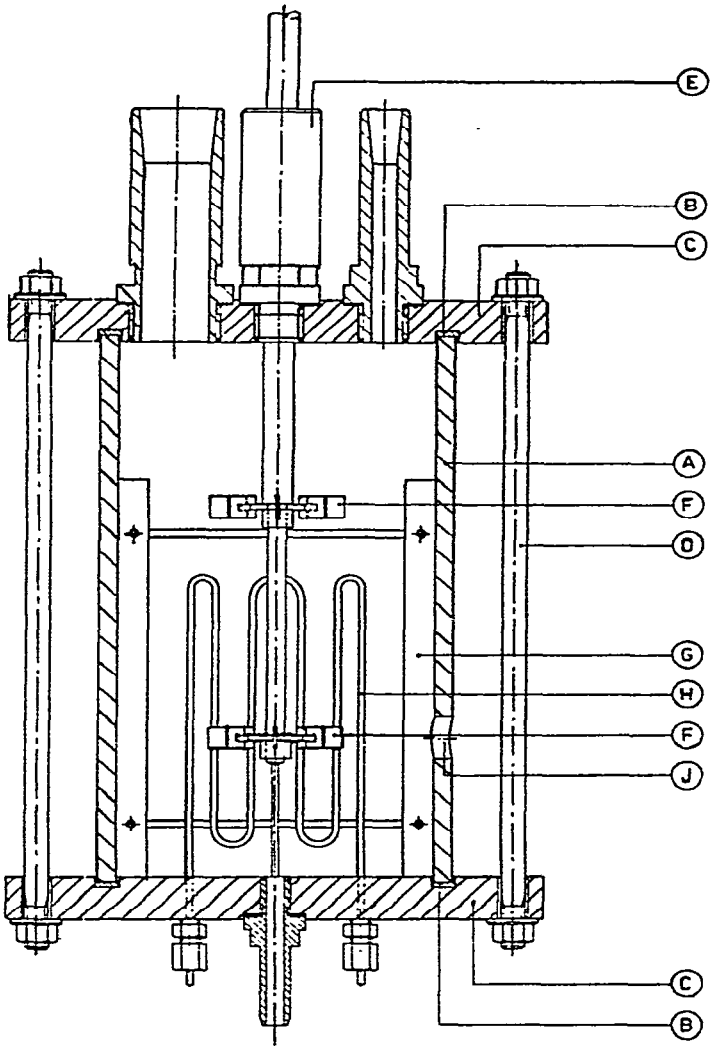


Fig. 2. Stirred tank reactor. A, reactor wall (Pyrex glass, diameter 120 mm, height, 200 mm); B, gasket rings (Teflon); C, flanges; D, studs; E, stuffing box; F, turbine stirrer-blades, Rushton type (4); G, baffles; H, heating wire (thermocoac type 1 NCI 5); J, opening for oxygen-analyser sensing device.

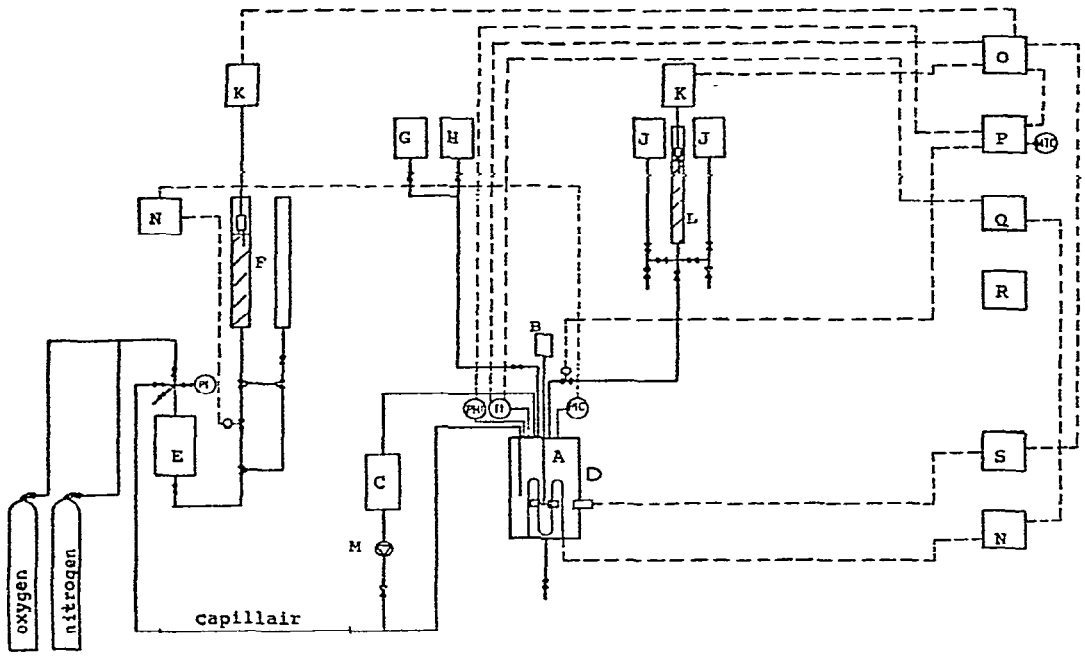


Fig. 3. Flow scheme. A, reactor; B, stirrer motor; C, gas buffer; D, sensing device to measure the oxygen concentration in the liquid phase; E+F, oxygen supply burette; G, water supply buffer; H, D-glucose solution; J, potassium hydroxide solution; K, level indicating device; L, KOH burette; M, gas circulation pump; N, powering relays; O, multi-channel recorder 10 mV; P, automatic pH controller with manual temperature control MTC; Q, temperature controller; R, thermostat to store pH electrode when not in use; S, polarographic oxygen analyser.

A plot of R_O against $([O_i^s]-[O_i])$, where R_O is high, gave a straight line, of which the slope represented a value of ~ 500 cm^3/sec for $k.a$ at a standardised stirrer speed of 2000 r.p.m. A more accurate determination of $k.a$ is not of interest, because the value of 500 cm^3/sec is so much higer than the actual oxygen consumption rate (expressed in cm^3/sec) that, during normal experiments, $[O_i]$ almost was equal to $[O_i^s]$. Thus, $[O_i] \cong [O_i^s] \cong$ constant during the reaction, from which it follows that the oxidation reaction always took place in the bulk of the liquid phase.

Procedure. — After the reactor had been filled with 600 ml of distilled water, the gas circulation pump was started and the air was replaced by oxygen (or by the desired mixture of oxygen and nitrogen). The desired reaction temperature was established, and a calculated quantity of alkali was added by means of a micro-burette in order to attain the desired hydroxyl-ion concentration. The reading of the pH meter was checked against the calculated hydroxyl-ion concentration. The reaction was then started by adding a heated solution of the desired quantity of hexose in 100 ml of distilled water. The uptakes of oxygen and alkali were measured continuously at constant values of [OH], $[O_i]$, and T. Periodically, 1-ml samples were taken from the bottom outlet of the reactor.

Analytical methods. — Qualitative and quantitative analyses of the unconverted hexoses and the acidic reaction products were carried out as described elsewhere[15,16].

Results and qualitative conclusions. — In order to discuss the results, it is useful to define the following characteristic quantities.

$$TAC = \frac{\text{alkali uptake (mmoles of KOH)}}{\text{initial quantity of hexose (mmoles)}}$$

$$TOC = \frac{\text{oxygen uptake (matoms of O)}}{\text{initial quantity of hexose (mmoles)}}$$

ΔTAC = the quantity of KOH which had to be added to the reactor, just after the addition of hexose, in order to reset the hydroxyl-ion concentration to the original value ($\Delta TAC = TAC$ at a reaction time $t \rightarrow 0$, by extrapolation).

$\left(\frac{dTAC}{dt}\right)_m$ = maximum rate of total acid production (unit 1/h)

$\left(\frac{dTOC}{dt}\right)_m$ = maximum rate of total oxygen consumption

TAC_e = total acid production at the end of the reaction

TOC_e = total oxygen consumption at the end of the reaction

$[F]_m$ and $[G]_m$ = maximum concentration of D-fructose or D-glucose. $[H_0]$ is taken as unit.

The comparison between the reactions of D-glucose (A) and D-fructose (B) is presented graphically (Figs. 4–6) and involves typical data. The numerical values of the defined units and the product distribution at the end of the reaction for experiments A and B are given in Table I.

TABLE I

THE EFFECT OF THE TYPE OF HEXOSE: CHARACTERISTIC UNITS AND PRODUCT DISTRIBUTION

Expt.	ΔTAC	$\left(\frac{dTAC}{dt}\right)_m$	$\left(\frac{dTOC}{dt}\right)_m$	TAC_e	TOC_e	$[F]_m$	$[G]_m$
A	0.32	0.28	0.38	2.22	2.32	0.14	—
B	0.44	1.20	2.10	2.32	2.48	—	0.23

Product[a] distribution at the end of the reaction

	$[C]_e$	$[Fo]_e$	$[Go]_e$	$[Gy]_e$	$[Er]_e$	$[Ar]_e$	$[R]_e$
A	0.23	0.70	0.44	0.24	0.22	0.53	—
B	0.22	0.72	0.46	0.24	0.26	0.50	—

[a]See Fig. 6 for key to symbols; C, carbonic acid.

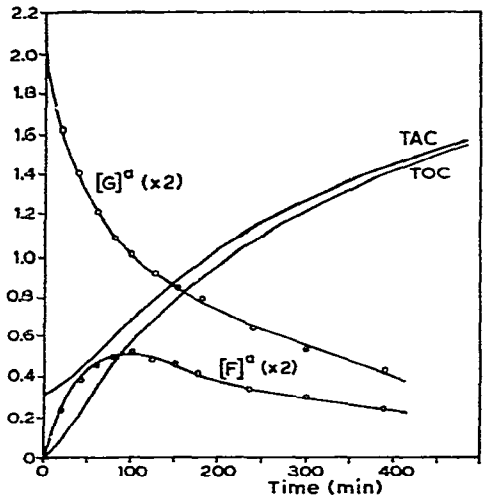


Fig. 4. Oxidation of D-glucose; T 50°, [OH] 26, [O_i] 0.85 [H_0] 215.

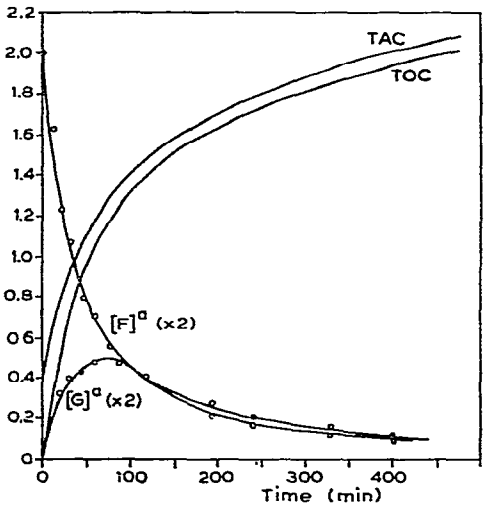


Fig. 5. Oxidation of D-fructose; T 50°, [OH] 26, [O_i] 0.85, [H_0] 215.

Remarkable differences between D-glucose and D-fructose are the shape of the TOC and TAC curves, and the higher reaction rate in the case of D-fructose. The product distribution is approximately independent of the initial hexose. From Fig. 6, it can be seen that the product distribution is constant during the reaction.

From a series of experiments[15], the following conclusions were drawn: (*a*) The initial hexose concentration does not influence the relative reaction velocity, nor the product distribution. (*b*) The effect of the hydroxyl-ion concentration on the reaction rate and the product distribution is the same for D-glucose and D-fructose. At higher values of [OH], the reaction rate and ΔTAC increase. The product

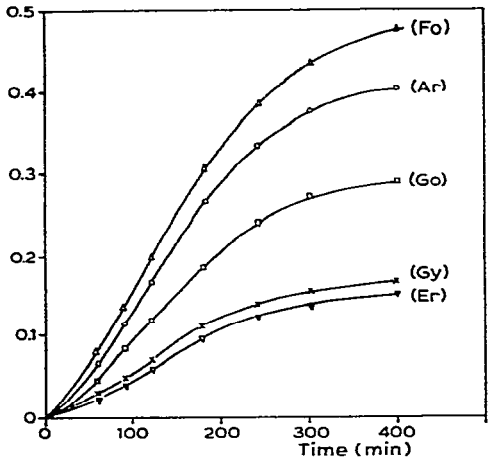


Fig. 6. Relative product concentration as a function of time for experiment A; Fo, formic acid; Ar, D-arabinonic acid; Go, glycolic acid; Gy, D-glyceric acid; Er, D-erythronic acid.

distribution moves in favour of D-arabinonic acid and formic acid. (*c*) The effect of the oxygen concentration in the liquid phase is equal for D-glucose and D-fructose. At lower values of $[O_l]$, the reaction rate decreases but ΔTAC is not influenced. The product distribution changes to the detriment of D-arabinonic acid and formic acid. The quantity of unidentified products increases. (*d*) The effect of the temperature is the same for D-glucose and D-fructose. At higher temperatures, the reaction velocity increases and ΔTAC decreases slightly. The product distribution moves in favour of glycolic acid and D-glyceric acid.

On the basis of the reaction steps summarized in Fig. 1 and the data reported herein and in the literature, the integral reaction scheme as represented in Fig. 7 was developed. Fig. 7 is not a detailed organo-chemical mechanism of the autoxidation of monosaccharides in aqueous, alkaline solutions, but a simplified reaction scheme by which the observed phenomena may be explained, both qualitatively and quantitatively. If the distinction between stereoisomers is neglected, the enolate ions of the model represent all the E^- forms which can arise, because then E^-_{64} is equal to E^-_{62} and E^-_{65} is equal to E^-_{61}. The appearance of di-ionic species is improbable under moderate alkaline conditions[7]. No hexoses other than D-glucose, D-fructose, and D-mannose were detected by g.l.c. No distinction is made between hexose anomers, although this was necessary in quantitative studies[17]. Recently, Samuelson and Thede[12] reported the formation of an appreciable amount of D-arabinose. From the integral scheme, this can be understood by the formation of E^-_{51}, which is the open-chain form of the D-arabinose anion. This phenomenon is more noticeable at lower concentrations of oxygen in the liquid phase[18].

Although, at the end of the reaction, ~0.1 mole of carbon dioxide was formed per mole of hexose, carbon dioxide formation is not included in the scheme; it is not known whether carbon dioxide is formed solely by Ruff degradation[13] or by, for example, the disintegration[19] of lower aldehydes (GyA, GoA).

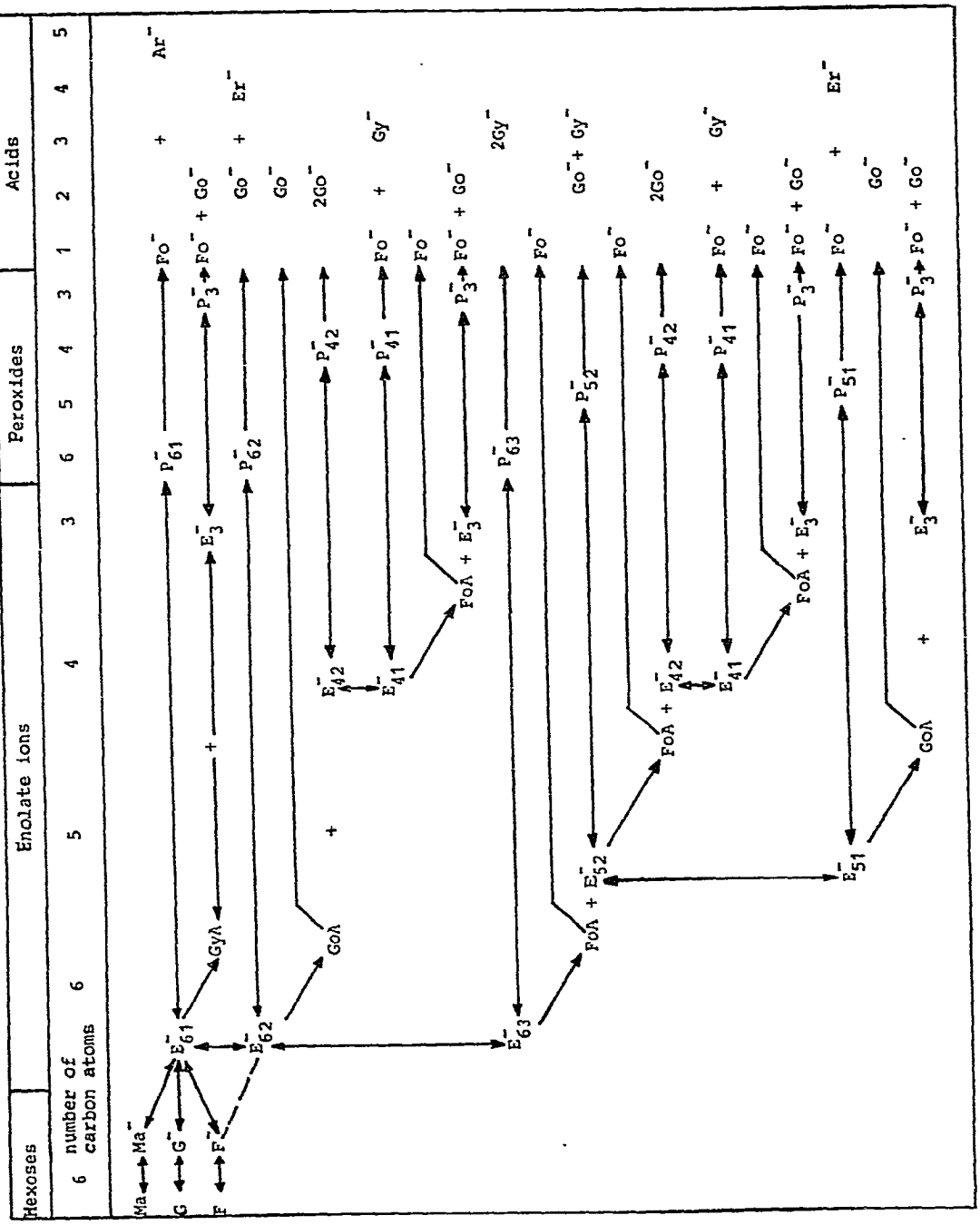
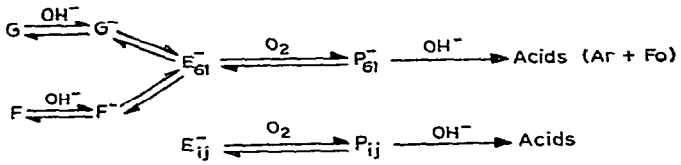


Fig. 7. An integral reaction model. E_{ij}^- enolate ion, where i is the number of carbon atoms and j is the position of the double bond between carbon atoms j and j+1; Ma, D-mannose; G, D-glucose; F, D-fructose; GyA, D-glyceraldehyde; FoA, formaldehyde; GoA, glycolaldehyde; other abbreviations as in Fig. 6.

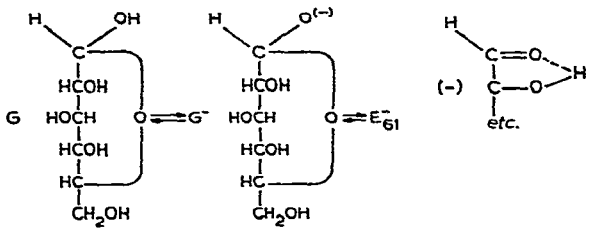
The formation of D-*arabino*-hexosulose has been suggested recently, but it is excluded from the scheme, since D-mannonic and D-gluconic acids could not be detected in the reaction mixture[12,18]. Non-oxidative reactions to sugar-isomeric acids are also excluded, since, at oxygen concentrations in the liquid phase of more than 0.5 mmole.l^{-1}, these reactions yield less than 1% of the total production of acid.

DISCUSSION

In order to check the qualitative experimental results, the following simplified model (*cf.* Fig. 7) is used. In agreement with literature data[13,20], mannose was



detected only in minor quantities, and hence is neglected. The first two steps in the scheme are assumed to involve a rapid, acidic dissociation of the cyclic monosaccharide, followed by a relatively slow ring-opening, which accords with the suggestions



of Bamford *et al.*[7,8]. The same approach has been used successfully[21] in a kinetic investigation of the alkaline degradation of amylose.

ΔTAC can be explained by the rapid de-protonation of the hexose and is therefore controlled by the hydroxyl-ion concentration and independent of the oxygen concentration. The influence of the temperature on ΔTAC can be translated as the temperature dependence of the ionisation constants of the hexoses.

The acidic products are very stable, because the reaction, as measured by the consumption of oxygen or alkali, stops when the concentration of hexose is zero. None of the products passes through a maximum in its concentration–time curve.

The S-shaped TAC and TOC curves for D-glucose can be explained by a relatively slow attainment of the equilibrium $G^- \rightleftharpoons E_{61}^-$, so that the concentration of E_{61}^- eventually passes through a maximum, at which time the maximum reaction rate is reached. Furthermore, the equilibrium $F^- \rightleftharpoons E_{61}^-$ is assumed to be reached almost instantaneously. Thus, the concentration of E_{61}^- will be higher when the reaction is started from D-fructose instead of from D-glucose, and therefore the

reaction rate will be higher for D-fructose. The reaction $F^- \rightleftharpoons E_{62}^-$ must be relatively slow, because the product distribution is almost the same for D-glucose and D-fructose.

The initial hexose concentration has no influence on the kinetic behaviour of the system as expressed by ΔTAC, $(dTAC/dt)_m$, etc., nor on the product distribution. This can be understood if all the initial reactions are first order in the reactants, and if interactions between hexose molecules, enolate ions, peroxides, and acidic products do not occur.

The effect of the oxygen concentration can be analysed as follows. Starting from any enolate ion, there is competition between the oxidation step to a peroxide and the non-oxidative reactions of the enolate ion (double-bond migration and cleavage). As a result, the oxidation of E_{61}^- to D-arabinonic acid and formic acid is favoured at higher concentrations of oxygen. The kinetic, overall order of the oxygen concentration is less than 1, because the oxidation step is only one of the steps in a series of consecutive reactions.

The role of the hydroxyl-ion concentration appears to be more complex. The hydroxyl-ion concentration has a positive effect on the overall reaction rate, because, at a higher value of [OH], the ratio [hexose$^-$] to [hexose], and hence the enolate ion concentration, increases. A second, positive effect is caused by the postulated influence of the hydroxyl-ion on the cleavage of the peroxides into two acidic functions. The effect of the hydroxyl-ion concentration on the product distribution can be explained by means of the following mechanism:

$$E^- \overset{O_2}{\rightleftharpoons} P^- \overset{OH^-}{\rightleftharpoons} P^{2-} \longrightarrow \text{Acids} \qquad K_p = \frac{[P^{2-}]}{[P^-]\,[OH^-]}$$

$$\Big\downarrow$$

non-oxidative reactions

The reaction $P^- \rightleftharpoons P^{2-}$ is assumed to proceed very rapidly, so that cleavage of P^{2-} is the rate-determining step. From this mechanism, it follows that, at higher concentrations of hydroxyl-ion, the ratio $[P^{2-}]/[P^-]$ and the total peroxide concentration $([P^{2-}] + [P^-])$ increases, in agreement with the reported data of Bamford[7,8]. The concentration of P^- decreases, and so the net rate of the direct oxidation of an enolate ion is favoured with regard to double-bond migration and other non-oxidative reactions.

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