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THE PREPARATION OF D-GLUCARIC ACID BY THE OXIDATION OF D-GLUCONIC ACID CATALYSED BY PLATINUM ON CARBON

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ABSTRACT

D-Gluconic acid is oxidised with gaseous oxygen (platinum–carbon catalyst) to D-glucaric acid *via* L-guluronic acid. C_1–C_5 mono- and di-carboxylic acids are formed by side and consecutive reactions of D-gluconic acid and D-glucaric acid, respectively. The product distribution (determined by isotachophoresis and ion-exchange chromatography) was studied at pH 8–11 and 45–65°. The highest yield of D-glucaric acid was 50–55% and could be obtained from D-glucose and D-gluconic acid.

INTRODUCTION

D-Glucose (G) can be oxidised to D-gluconic acid (GOZ) and D-glucaric acid (GAZ) by using platinum on carbon (Pt/C) as the catalyst. The kinetics of the first stage have been studied[1] and, depending upon the reaction conditions, the selectivity for D-gluconic acid was 85–95%. There are few reports on the second stage. Poethke[2] reported the formation of C_1–C_5 mono- and di-carboxylic acids from D-gluconic acid with $Pd/BaSO_4$ as catalyst, but D-glucaric acid was not detected. Mehltretter[3] obtained a selectivity of 54% for D-glucaric acid by the oxidation of D-glucose with Pt/C as catalyst, but the by-products were not analyzed.

Oxidation of D-glucitol[4] gave L-gulose, D-glucose, L-sorbose, D-fructose, and polyhydroxy acids, and mannose, mannonic, mannuronic, and mannaric acids have been obtained from mannitol[5].

No quantitative data are given in the literature about the product distribution in the oxidation of carbohydrates or their derivatives with Pt/C as catalyst. We now report such data for the oxidation of D-gluconic acid, which was undertaken to find the optimal conditions for the preparation of D-glucaric acid. Complexes of D-glucaric acid with boric acids are among the strongest sequestering agents known[6] and are consequently of industrial interest.

EXPERIMENTAL

General reaction procedure. — A batch-wise operated, stirred tank-reactor was used (Fig. 1), and the pH was controlled by automatic titration with 4M KOH.

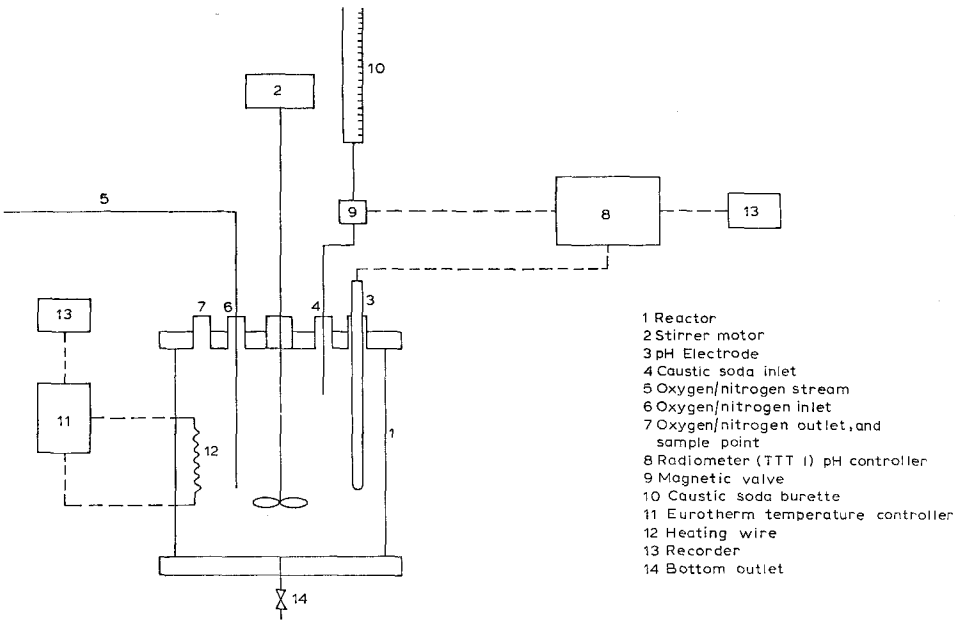


Fig. 1. Diagram of the reaction system.

The required amounts of catalyst and water (450 ml) were heated in an oxygen atmosphere (oxygen flow, 1 litre/min) in the reactor to the required temperature. Then, a concentrated D-gluconic acid solution (50 ml), at the required pH and temperature, was added (procedure *A*). Alternatively, the catalyst suspension was heated in a nitrogen atmosphere, the D-gluconic acid was added, and after 10 min, the nitrogen flow was replaced by oxygen at 1 litre/min (procedure *B*). Samples (3 ml) were withdrawn at intervals and stored in a refrigerator until analysed.

Preparation of the catalyst. — A solution of hexachloroplatinic acid (10 g) in water (100 ml) was added to active carbon (72 g, Norit PK 10×30), and water (100 ml) was added to wet the carbon completely. Nitrogen was bubbled through the suspension at room temperature for 5 h, and formaldehyde solution (170 ml) was added to the cooled (0°) suspension. Reduction to platinum metal was effected by the slow addition of 30% KOH during 1 h. During the reduction, the suspension was mixed thoroughly by a stream of nitrogen. The mixture was stored overnight and the catalyst was then collected, washed with distilled water until the filtrate was neutral, dried at 50°, and ground in a mortar to obtain a fine powder. Used catalyst was regenerated by washing with hot water (3 l) at 90°.

Analysis. — Reaction samples were analysed by (*a*) isotachophoresis[8] using a conductivity detector[9] and the following parameters: leading electrolyte, 0.01M chloride (pH 6.02); terminator, 0.005M morpholine ethanesulphonate; capillary, Teflon (20 cm × 0.5 mm); current, 100 μA; injection volume, 1 μl (after dilution 1:4); analysis time, 10–15 min; and (*b*) ion-exchange chromatography using a Technicon

Autoanalyser II single-channel colorimeter (λ 420 nm) with a column (15 cm × 4 mm) of Aminex A27 resin at 75°, elution with 0.08M Na_2SO_4 at 0.6 ml/min, injection volume of 10 μl (after dilution 1:4), and detection with orcinol (1 g/litre in 70% H_2SO_4) at 3.35 ml/min and 95° for 6 min. A typical isotachopherogram is shown in Fig. 2. The distance between two peaks of the differential signal gives qualitative information, and quantitative information is given by the height of the integral signal. Stereoisomers such as xylaric and arabinaric acid are not separated with this analytical system, and therefore the signal belonging to C_5-dicarboxylic acid is referred to as xylaric + arabinaric acid. Gluconic, guluronic, and ketogluconic acids were not separated by isotachophoresis. Ion-exchange chromatography was used for the analysis of guluronic and ketogluconic acids. The concentration of gluconic acid

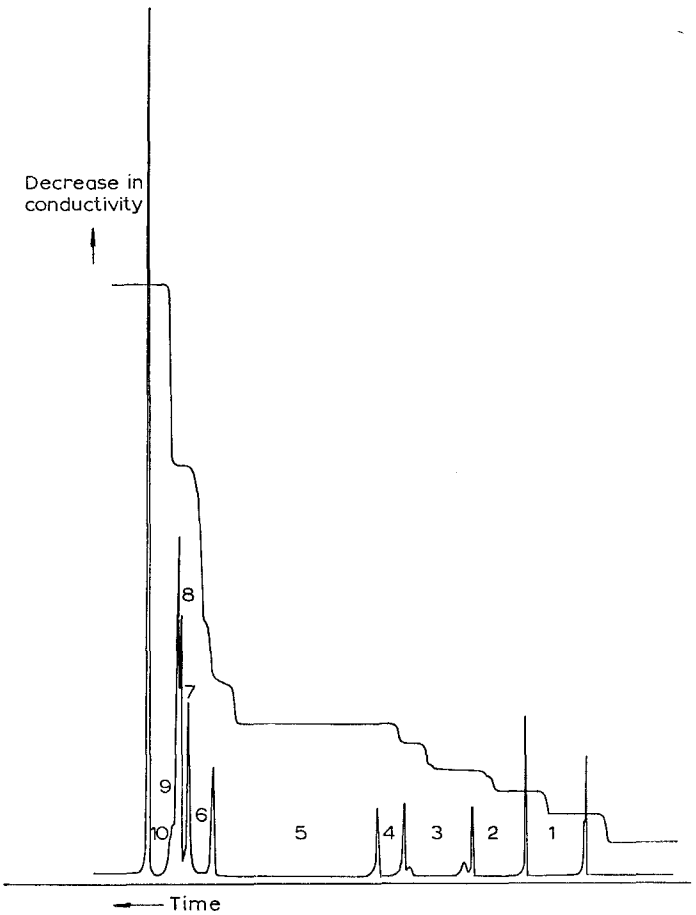


Fig. 2. Isotachopherogram of a reaction sample; 1, oxalic acid; 2, tartronic acid; 3, tartaric acid; 4, xylaric+arabinaric acids; 5, glucaric acid; 6, glycolic acid; 7, glyceric acid; 8, erythronic acid; 9, arabinonic acid; 10, gluconic+guluronic+ketogluconic acids.

was calculated by a combination of the results of isotachophoresis and ion-exchange chromatography.

RESULTS AND DISCUSSION

The experiments were carried out under the following conditions: $[GOZ]_0$, 200 mmol/l; [catalyst], 40 g/l (5% Pt/C); V_0, 500 ml; O_2, 100%. Fig. 3 shows the decline in concentration of D-gluconic acid with time using procedures *A* and *B* at pH 10 and 55°. The reaction rate is relatively low when the catalyst is saturated with O_2 before the start of the experiment (procedure *A*). With procedure *B*, the catalyst is reduced by the substrate, so that the initial degree of occupation of the catalyst by O_2 is very low, which results in a high reaction rate. A similar observation has been reported[10] for the oxidation of 2,3:4,5-di-*O*-isopropylidene-L-sorbose with Pt/C as catalyst: the use of an excess of oxygen deactivated the catalyst after one experiment, whereas a low percentage of oxygen greatly prolonged the catalyst activity. The experiments discussed below involved procedure *B*.

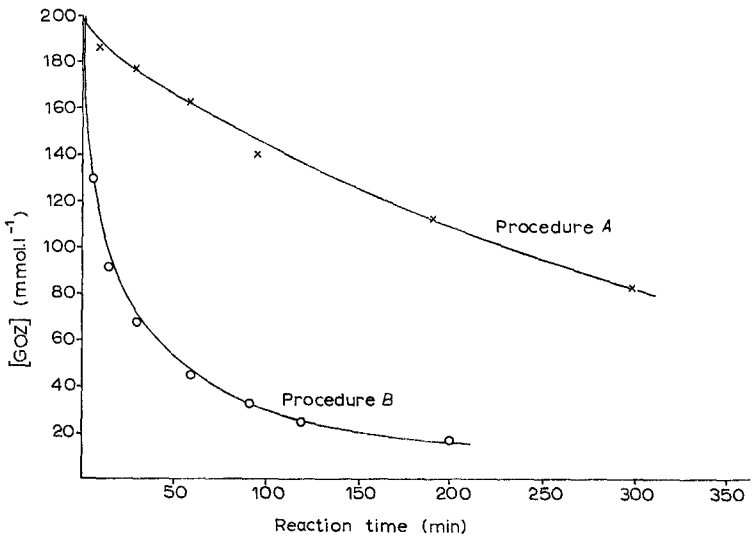


Fig. 3. Concentration of D-gluconic acid as a function of the reaction time for procedures *A* and *B*.

Table I gives the concentrations of the reaction products as a function of the reaction time (pH 10, 55°), and corrected for the dilution by titration with 4M KOH during the reaction. Isotachophoresis showed that formic acid was also formed, but in extremely low concentration. Ketogluconic acid (1–3% of the total reaction products) was detected by ion-exchange chromatography. Carbon dioxide was also formed.

The selectivity for D-glucaric acid is affected by side and consecutive reactions. Side reactions starting from L-guluronic acid can be neglected, as oxidation of the

TABLE I

PRODUCT DISTRIBUTION[a] (mmol/l) AS A FUNCTION OF THE REACTION TIME FOR OXIDATION OF D-GLUCONIC ACID (pH 10, 55°)

Reaction time (min)	*[GOZ]*	*[GLZ]*	*[GAZ]*	*[OX]*	*[TA]*	*[TAA]*	*[XA]+[ARA]*	*[GO]*	*[GY]*	*[ER]*	*[AR]*	*S* (%)
0	200	—	—	—	—	—	—	—	—	—	—	—
6	130	29	22	4	2	4	3	<1	<1	<1	<1	73
15	92	32	43	8	5	7	5	4	2	<1	8	69
30	67	27	63	13	9	11	7	7	2	<1	8	67
60	45	15	84	19	15	18	10	13	3	<1	10	64
90	34	7	96	25	21	23	10	19	5	<1	7	63
120	25	5	101	28	24	24	11	17	6	<1	6	61
200	16	2	104	33	30	28	12	20	6	2	4	58
305	12	1	103	39	34	29	12	21	7	3	<1	56

[a]Key: GLZ guluronic acid, GO glycolic acid, GY glyceric acid, ER erythronic acid, AR arabinonic acid, OX oxalic acid, TA tartronic acid, TAA tartaric acid, ARA arabinaric acid, XA xylaric acid, S (selectivity) = ([GLZ]+[GAZ])/([GOZ]$_0$ − [GOZ]).

isomeric D-glucuronic acid yields ~100% of D-glucaric acid. Non-catalytic reactions starting from D-gluconic and D-glucaric acid can be neglected, because they are extremely slow.

The rate of oxidation of 2-ketogulonic acid is 7–8 times lower than that of gluconic acid; thus, keto acids play only a very minor role in the reaction scheme.

The selectivity for D-glucaric acid is affected by the catalytic cleavage of the C–C bonds of D-gluconic acid. The data in Table I show that, even after short reaction times, more dicarboxylic than monocarboxylic acid degradation-products are present in the reaction mixture. Thus, C–C bond cleavage can yield either two dicarboxylic acids or a mono- and a di-carboxylic acid. Arabinonic acid is oxidised to further products, but glycolic and glyceric acids are stable under the reaction conditions. Formic acid is probably oxidised to CO_2 and H_2O.

The selectivity (Table I) decreases as a function of the reaction time due to catalytic cleavage of D-glucaric acid. The rate of this oxidation is ~10 times lower than that of the catalytic oxidation of D-gluconic acid. The product distribution after the oxidation of D-glucaric acid for 4.5 h was [GAZ] 131, [ARA]+[XA] 4, [TAA] 10, [TA] 42, [OX] 32, [GO] 9, [GY] 3, and [ER] 2 mmol/l. The dicarboxylic acids, which are formed during the reaction, can be oxidised to smaller acids.

When D-glucose was oxidised under conditions similar to those (Table I) for D-gluconic acid, the product distribution as a function of reaction time was as shown in Table II. The maximal productivity for D-glucaric acid is only slightly lower from D-glucose than from D-gluconic acid. Thus, the selectivity for D-gluconic acid in the oxidation of D-glucose is only slightly affected by side reactions, but mostly by consecutive reactions of D-gluconic acid.

TABLE II

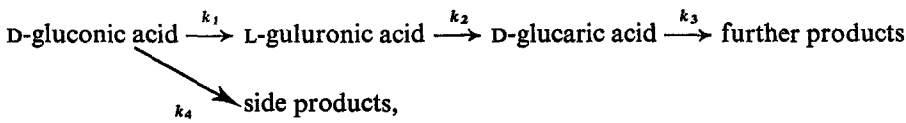
PRODUCT DISTRIBUTION[a] (mmol/l) AS A FUNCTION OF THE REACTION TIME FOR OXIDATION OF D-GLUCOSE (pH 10, 55°)

Reaction time (min)	[G]	[GOZ]	[GLZ]	[GAZ]	[OX]	[TA]	[TAA]	[XA]+[ARA]	[GO]	[GY]	[ER]	[AR]
0	200	—	—	—	—	—	—	—	—	—	—	—
2	151	48	—	2	<1	<1	<1	<1	<1	<1	<1	<1
6	109	97	—	2	<1	<1	<1	<1	<1	<1	<1	<1
10	86	103	—	2	<1	<1	<1	<1	<1	<1	<1	<1
15	23	122	28	5	4	1	1	1	1	1	2	8
30	—	83	45	41	11	5	10	5	5	3	3	11
60	—	49	26	75	22	12	15	8	11	4	2	13
90	—	36	15	89	29	16	18	10	14	5	3	12
122	—	27	9	99	36	21	23	10	18	7	3	12
180	—	18	4	98	41	26	26	11	19	7	3	10
240	—	11	3	97	46	30	28	11	21	6	4	9
300	—	8	2	95	51	34	30	12	22	8	4	8

[a]For Key, see Table I.

The data in Tables I and II show that the product distributions from D-glucose and D-gluconic acid are similar.

Using the reaction scheme:



the concentrations of GOZ, GLZ, and GAZ can be described by the equations *1–3*.

$$-\frac{d[\mathrm{GOZ}]}{dt} = \frac{(k_1+k_4)[\mathrm{GOZ}]}{f[\text{reactants}]}.[\text{catalyst}] \qquad (1)$$

$$+\frac{d[\mathrm{GLZ}]}{dt} = \frac{k_1[\mathrm{GOZ}]-k_2[\mathrm{GLZ}]}{f[\text{reactants}]}.[\text{catalyst}] \qquad (2)$$

$$+\frac{d[\mathrm{GAZ}]}{dt} = \frac{k_2[\mathrm{GLZ}]-k_3[\mathrm{GAZ}]}{f[\text{reactants}]}.[\text{catalyst}] \qquad (3)$$

These equations are readily derived from a Langmuir–Hinshelwood model, in which all reactions take place on the same type of active sites on the catalyst surface. The expression f[reactants] describes the adsorption effects of the different reactants and products on the catalyst surface.

$$f[\text{reactants}] = 1 + \sum K_{A_i}[\mathrm{i}],$$

where K_{A_i} is the adsorption constant of component i, and [i] is its concentration. The kinetics of the reaction are complex, because the catalyst is deactivated by a slow change in the degree of occupation of the active sites by oxygen, so that the number of effective sites [catalyst] on the catalyst surface decreases. This problem can be avoided by dividing equations *2* and *3* by equation *1*, to give equations *4* and *5*, *i.e.*, by looking only at the ratios of the reaction rates.

$$\frac{d[GLZ]}{d[GOZ]} = \frac{k_2[GLZ]}{(k_1+k_4)[GOZ]} - \frac{k_1}{k_1+k_4} = K_2\frac{[GLZ]}{[GOZ]} - K_1 \tag{4}$$

$$\frac{d[GAZ]}{d[GOZ]} = \frac{k_3[GAZ]}{(k_1+k_4)[GOZ]} - \frac{k_2[GLZ]}{(k_1+k_4](GOZ]} = K_3\frac{[GAZ]}{[GOZ]} - K_2\frac{[GLZ]}{[GOZ]} \tag{5}$$

The relative ratio constants are $K_1 = k_1/(k_1+k_4)$ (for GOZ → GLZ), $K_2 = k_2/(k_1+k_4)$ (for GLZ → GAZ), and $K_3 = k_3/(k_1+k_4)$ (for GAZ → consecutive products). K_1 is the maximum selectivity for glucaric acid (*i.e.*, the selectivity which would be obtained if no consecutive reactions of glucaric acid occurred). Equations *4* and *5*, which do not give information about the reaction rates, can be written as equations *6* and *7*.

$$[GLZ] = \int_{[GOZ]_0}^{[GOZ]} \left(K_2\frac{[GLZ]}{[GOZ]} - K_1\right) d[GOZ] \tag{6}$$

$$[GAZ] = \int_{[GOZ]_0}^{[GOZ]} \left(K_3\frac{[GAZ]}{[GOZ]} - K_2\frac{[GLZ]}{[GOZ]}\right) d[GOZ] \tag{7}$$

K_1, K_2, and K_3 were calculated by stepwise integration of equations *6* and *7*, and minimising the sums

$$\sum_n \left(\frac{[GLZ]_{ci} - [GLZ]_{ei}}{[GLZ]_{ci}}\right)^2 \quad \text{and} \quad \sum_n \left(\frac{[GAZ]_{ci} - [GAZ]_{ei}}{[GAZ]_{ci}}\right)^2,$$

where n is the number of samples, and, for sample i, $[GLZ]_{ei}$ is the measured [GLZ], $[GLZ]_{ci}$ the calculated [GLZ], $[GAZ]_{ei}$ the measured [GAZ], and $[GAZ]_{ci}$ the calculated [GAZ].

The calculated values of K_1, K_2, and K_3, with a statistical confidence interval of 95%, and the maximum productivity for glucaric acid ($P_{max} = [GAZ]_{max}/[GOZ]_0$) are recorded in Table III as a function of pH and temperature. P_{max} and K_1 (initial selectivity) both slightly decrease with increase in temperature. At pH 11, P_{max} is very low; in the range pH 8–10, P_{max} slightly increases with increase in pH. Fig. 4 gives the experimental and calculated [GLZ] and [GAZ] as functions of [GOZ] at pH 10 and 55°. A reasonable description of the experimental results with the above reaction model is obtained.

TABLE III

DATA FOR OXIDATION OF D-GLUCONIC ACID

Temp. (*degrees*)	*pH*	K_1	K_2	K_3	$P_{max}([GAZ]_{max}/[GOZ]_0)$
45	10	0.75 ±0.05	4.0 ±0.5	0.13 ±0.04	0.55
55	10	0.70 ±0.05	2.5 ±0.3	0.13 ±0.04	0.51
65	10	0.65 ±0.05	2.0 ±0.3	0.14 ±0.04	0.46
55	8	0.62 ±0.04	1.8 ±0.2	0.10 ±0.03	0.47
55	9	0.60 ±0.07	2.9 ±0.6	0.24 ±0.05	0.49
55	11	0.63 ±0.15	2.5 ±1.0	0.45 ±0.25	0.29

The initial reaction rate $r_0 = -(d[\mathrm{GOZ}]/dt)_{t=0}$ increases with increase in pH and temperature (Fig. 5). From Fig. 5B, an activation energy of 17 kcal/mol was calculated for the overall reaction D-gluconic acid → products. Table IV gives the product distribution as a function of pH and temperature at a conversion of 80%. The product distribution is not strongly influenced by the temperature. However, with increase in pH, the amount of tartronic, tartaric, and xylaric + arabinaric acids increases strongly, whereas the amount of arabinonic acid strongly decreases.

TABLE IV

PRODUCT DISTRIBUTION[a] (mmol/l) AS FUNCTIONS OF pH AND TEMPERATURE FOR OXIDATION OF D-GLUCONIC ACID AT A CONVERSION OF 80%

pH	*Temp.* (*degrees*)	[*GLZ*]	[*GAZ*]	[*OX*]	[*TA*]	[*TAA*]	[*XA*]+[*ARA*]	[*GO*]	[*GY*]	[*ER*]	[*AR*]
10	45	8	102	27	10	19	8	13	6	1	7
10	55	12	86	19	15	19	9	13	3	<1	9
10	65	15	83	24	18	19	12	17	5	<1	9
8	55	24	74	12	5	4	7	3	3	4	24
9	55	17	81	18	7	7	7	10	3	1	23
10	55	12	86	19	15	19	9	13	3	<1	9
11	55	4	57	20	31	33	14	3	17	9	4

[a]For Key, see Table I.

If the object of the oxidation of D-glucose or D-gluconic acid is the manufacture of products with a high sequestering capacity, products such as tartaric, arabinonic, and C_5-dicarboxylic acids should not be classified as by-products, because they have a reasonable sequestering capacity. The sequestering capacity of tartaric acid is ~60% of that of D-gluconic acid[6], whereas the sequestering capacity of xylaric acid is reported[11] to be even higher than that of D-glucaric acid.

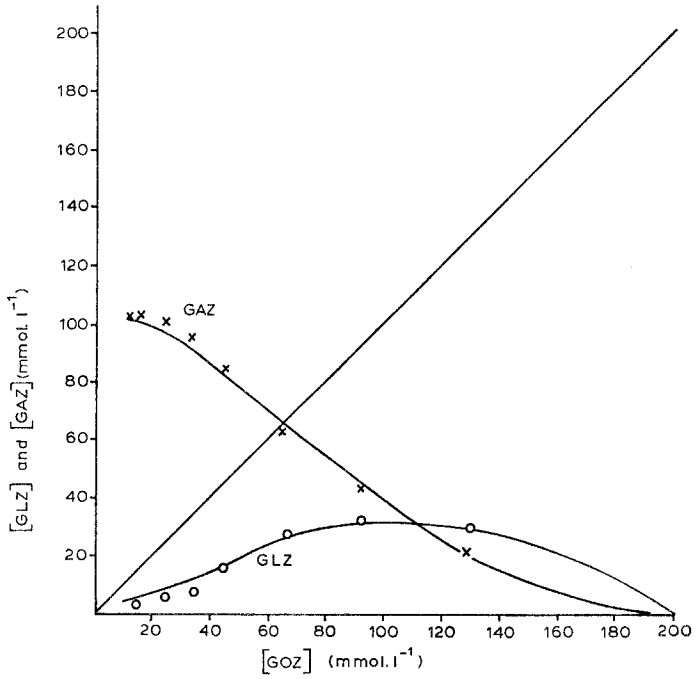


Fig. 4. Measured and calculated [GLZ] and [GAZ] as a function of [GOZ] (pH 10, 55°).

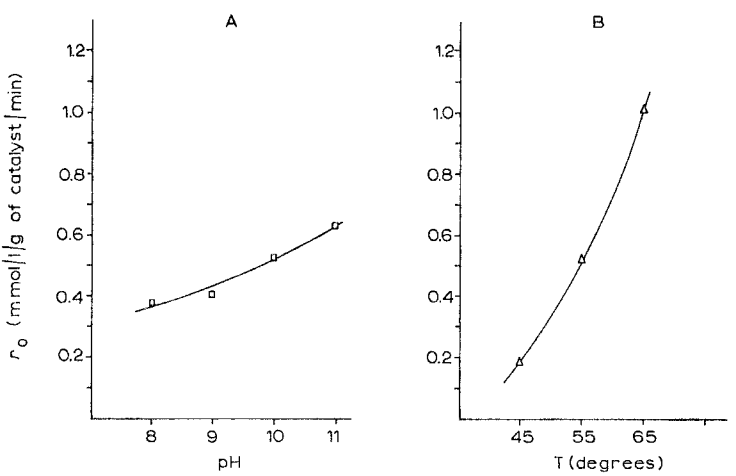


Fig. 5. Initial reaction rates as functions of pH and temperature.

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