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The Role of Acid in the Cerium (IV) Oxidation of Carbohydrates

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THE ROLE OF ACID IN THE CERIUM(IV) OXIDATION OF CARBOHYDRATES

A thesis submitted by

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SUMMARY

The mechanism of cerium(IV) oxidation of glucose was studied in nitric and perchloric acids at 20°C.

Quantitative GLC product analysis results showed the major product of the oxidation of excess glucose by cerium(IV) in nitric (0.1 to 1.0M) and perchloric (1.0M) acid to be arabinose, with erythrose as a minor product. The erythrose was subsequently shown to result from the competitive secondary oxidation of the primary product arabinose. At nitric acid concentrations of 1.5 and 2.0M, a second minor product, arabinonic acid, was also found for the glucose oxidation.

Definite evidence for the participation of an intermediate complex in the cerium(IV) oxidation of glucose in 1.0M nitric acid was obtained by kinetic methods. The magnitude of this equilibrium constant for cerium(IV)-glucose complex formation in 1.0M nitric acid was somewhat less than the value determined previously in 1.0M perchloric acid. These values for cerium(IV)-glucose complex formation are, however, considerably larger than values reported for monohydric alcohols in the respective acids. This increase in complex stability exhibited by glucose could be explained by the intermediate complex being a chelate.

The compound 4-O-formyl-D-arabinose was synthesized, and shown to readily undergo hydrolysis to arabinose and formic acid in the acidic reaction media (1.0M nitric acid). Spectroscopic evidence was obtained, however, for this formate ester of arabinose as an intermediate in the cerium(IV) oxidation of glucose to arabinose.

A mechanism for the cerium(IV) oxidation of glucose consistent with the observed kinetic behavior and product analysis results is proposed. Initially, the glucose and cerium(IV) interact in an equilibrium step to form an intermediate complex, possibly a chelate involving the C_1 and C_2 hydroxyls of glucose. The complex disproportionates by homolytic cleavage of the C_1-C_2

bond developing a carbonyl ester linkage at the original C_1 carbon and forming a free radical at C_2. The free radical is rapidly oxidized by a second mole of cerium(IV) to form the intermediate 4-O-formyl-D-arabinose. This intermediate is hydrolyzed by the reaction media to form the primary products, arabinose and formic acid. The arabinose is then subject to oxidation yielding the secondary product, erythrose. At nitric acid concentrations of 1.5 and 2.0M, an additional secondary product, arabinonic acid, is formed. Although the mechanism for this product formation is not clear, it is believed that arabinonic acid results from the oxidation of glucose directly, and not from the oxidation of arabinose.

Quantitative product analysis investigations showed the cerium(IV) oxidation of cellobiose in perchloric and nitric acid at 20°C and 0°C to follow the same general sequence as the glucose oxidations at comparable acid concentrations. With cellobiose as the substrate the yield of the major product 3-O-(β-D-glucopyranosyl)-arabinose was slightly greater (ca. 10%) than the corresponding yield of the major product arabinose from the oxidation of glucose. The minor product in the cellobiose oxidation was 2-O-(β-D-glucopyranosyl)-erythrose.

Only the C_1-C_2 glycol unit was cleaved in the cerium(IV) oxidations of glucose, cellobiose, and the corresponding secondary oxidations of the primary products in each case. Preferential attack of the reducing end group by the ceric ion is therefore indicated.

The cerium(IV) oxidation of glucose was found to be 3.32 times as fast in perchloric acid as compared to nitric acid. This parallels the observed oxidation potential of the cerium(IV)-cerium(III) couple in the respective acid systems.

An increase in hydrogen ion concentration at a constant acid anion concentration was found to increase the rate of cerium(IV) oxidation of glucose in perchloric acid, and decrease the rate in nitric acid. Perchlorate ions had a positive salt effect, while nitrate ions had an inhibitory effect on the cerium(IV) oxidation of glucose in nitric acid at constant acidity. These results are related to the equilibria which exist in acidic solutions involving the formation of cerium(IV) inorganic complexes with acid anions, hydroxide ions, and water molecules. In general, the reactivity of cerium(IV) decreases as the ability to form inorganic complexes increases.

INTRODUCTION

GRAFT COPOLYMERIZATION

The use of the acidic ceric ion redox system for initiating the graft copolymerization of vinyl monomers onto wood pulp, cotton, rayon, paper, and regenerated cellulose, as well as starch and polyvinyl alcohol has received much attention during the past decade. Despite intensive research efforts, the mechanism of the ceric ion-initiated graft copolymerization is still in doubt, and numerous contradictory proposals have been advanced. The various mechanisms proposed for initiation are, however, characterized by the common feature that a free radical is produced as a result of cerium(IV) oxidation.

The original concept of ceric ion grafting as developed by Mino and Kaizerman (1) proposed that a ceric ion-cellulose complex is initially formed, which then disproportionates unimolecularly generating a free radical on the cellulose backbone. When vinyl monomers are present this radical then initiates graft copolymerization. Although oxidation could occur at C_6, Arthur, et al. (2), from ESR spectra, obtained evidence supporting cleavage of the C_2-C_3 glycol group of the anhydroglucose unit by the ceric ion to generate the free radicals which serve as the grafting site. The importance of glycol groups along the cellulose chain was demonstrated by Hebeish, et al. (3,4) who found that partial blocking of these groups decreased the rate of grafting. Other workers (5,6) concluded the hemiacetal group of the end unit of the cellulose molecule to be the site of initial cerium(IV) attack. Initiation at this reducing end group leads to formation of block copolymers (7), while C_2-C_3 glycol cleavage yields a true graft copolymer. A discrepancy exists, therefore, as to the relative importance of the hemiacetal group versus the anhydroglucose unit and

location of the free radical generated in cerium(IV) cellulose grafting. Incorporation of hydroxyl groups in polymers formed in alcohol-ceric ion systems indicates that the initiating species is the carbon radical, $\dot{R}OH$, rather than the alkoxy radical, RO• (5).

Terasaki and Matsuki (8) attributed the initial fast rate of ceric ion consumption which is observed during grafting to the presence of the hemiacetal units in the cellulose chains. Kulkarni and Mehta (9) explained this observation by the formation of a cerium(IV) complex with the hydroxyl groups present in cellulose.

Ogiwara, et al. (10,11) concluded that the total carbonyl content is an important aspect in obtaining maximum graft polymerization. As a result of the strong adsorption of ceric ion to cellulose, Ogiwara and Kubota (12) suggested that cerium(IV)-cellulose complexes of the chelate type were formed.

Gaylord (13) has recently proposed a new mechanism in which it is claimed graft copolymerization onto cellulose using ceric salts as catalysts results from the termination of growing chains on the cellulose rather than from initiation at radical sites on the cellulose.

Investigations (14) have shown that not only are the concentrations of ceric salt and mineral acid employed in cellulose copolymerizations important in achieving maximum grafting, but also the particular combination of ceric salt and acid. Hebeish and Mehta (15) and Kamogawa and Sekiya (16) found ceric ammonium nitrate (CAN)-nitric acid solutions to be the most efficient of the various cerium(IV) redox systems studied for graft initiation in terms of graft yields obtained. The polymerization rate with CAN has been observed to vary with nitric acid concentration (17), a narrow optimum range for obtaining

maximum grafting was observed by Kamogawa and Sekiya, while Rao and Kapur (18) found a maximum graft yield at 0.6N nitric acid. Ionic strength and nitrate ion concentration were found to affect the polymerization rate by Mino and Kaizerman (19).

Gugliemelli, et al. (20,21) studied cerium(IV)-starch complex formation and disproportionation as a function of nitric acid concentration. These complexes were found to disproportionate more rapidly as the acid concentration was increased (0.01 to 10N). Presumably the rate of graft initiation depends on the rate of complex disproportionation, hence the polymerization rate should increase with acidity. Santappa (22) observed the polymerization rates with ceric salts as initiators to parallel the oxidation potentials of the cerium(IV)-cerium(III) couple in the respective acid media (perchloric, nitric, and sulfuric).

In summary there are many details of the acidic ceric ion redox catalyst system which have not been elucidated as yet. Numerous factors have prevented this method from becoming of commercial importance. They include a relatively low grafting efficiency, a heterogeneous system, grafted branches of high molecular weight, a maximum of one branch on each cellulose molecule, the problem of competitive oxidation and homopolymerization, and acidic degradation of the cellulose due to the nature of the system.

PROPERTIES OF CERIUM(IV) IN ACID SOLUTIONS

The oxidation potential of the cerium(IV)-cerium(III) couple depends upon the acid anion and the acid concentration as shown in Table I (23). The oxidation potential, at a given concentration, decreases in the order, perchloric > nitric > sulfuric. With perchloric acid, increasing the acid concentration increases the oxidation potential, while the reverse is true for nitric and sulfuric acids.

TABLE I

CERIUM(IV)-CERIUM(III) HALF CELL POTENTIALS (23)

Acid Normality	$HClO_4$	HNO_3	H_2SO_4
1	-1.70	-1.61	-1.44
2	-1.71	-1.62	-1.44
4	-1.75	-1.61	-1.43
6	-1.82	-1.56	--
8	-1.87	--	-1.42

The nature of cerium(IV) species in perchloric and sulfuric acid solutions has been extensively studied; however, less is known about nitric acid systems. Although the coordination number of cerium(IV) has not been definitely established (it could possibly be 6, 8, 10, or even 12), the reactive species at moderately high acid concentration (1.0M), and low cerium(IV) concentrations (0.01M), in perchloric acid media is assumed to be the hexahydrated ceric ion, $Ce(H_2O)_6^{+4}$ (24-26). These conditions shift the following equilibria to the left.

$$Ce^{+4} + H_2O \rightleftharpoons Ce(OH)^{+3} + H^{\oplus} \quad (1)$$

$$Ce(OH)^{+3} + H_2O \rightleftharpoons Ce(OH)_2^{+2} + H^{\oplus} \quad (2)$$

$$Ce(OH)^{+3} + Ce(OH)^{+3} \rightleftharpoons (Ce\text{-}O\text{-}Ce)_2^{+6} + H_2O. \quad (3)$$

In sulfuric and nitric acid solutions, additional equilibria exist due to cerium(IV) complexing with the acid anion. The perchlorate anion has shown little tendency to coordinate with cerium(IV), while the sulfate anion forms stable complexes with cerium(IV). Hardwick and Robertson (27) explained the state of the cerium ion in 1.0M sulfuric acid solution by the following equilibria.

$$Ce^{+4} + HSO_4^{\ominus} \underset{}{\overset{k_1}{\rightleftharpoons}} Ce(SO_4)^{+2} + H^{\oplus} \qquad k_1 = 3500 \qquad (4)$$

$$Ce(SO_4)^{+2} + HSO_4^{\ominus} \underset{}{\overset{k_2}{\rightleftharpoons}} Ce(SO_4)_2 + H^{\oplus} \qquad k_2 = 200 \qquad (5)$$

$$Ce(SO_4)_2 + HSO_4^{\ominus} \underset{}{\overset{k_3}{\rightleftharpoons}} Ce(SO_4)_3^{-2} + H^{\oplus} \qquad k_3 = 20. \qquad (6)$$

It is apparent that the relative amounts of each species present will depend upon the concentration of sulfate and hydrogen ions.

The information available on the state of cerium(IV) in nitric acid is meager. In the presence of nitrate ions several cerium(IV)-nitrate complexes are known to form. The general equilibrium of Equation (7) becomes more important at high nitrate concentrations

$$Ce^{+4} + mNO_3^{\ominus} \rightleftharpoons Ce(NO_3)^{(4-m)\oplus}, \quad m \leq 6 \qquad (7)$$

(1.0 to 4.0M). Nitrate ions have been observed to reduce the oxidation potential of the cerium(IV)-cerium(III) system (28). Hydrolysis of nitrated forms of cerium(IV), if they exist, can also occur.

$$Ce(NO_3)_m^{(4-m)} + nH_2O \rightleftharpoons Ce(OH)_n(NO_3)_m^{(4-m-n)} + H^{\oplus}, \quad (m+N) \leq 6. \qquad (8)$$

The oxidation potential, therefore, decreases as the ability of the acid anion to form stable complexes with cerium(IV) increases. This presence of cerium(IV) inorganic complexes reduces the complexing ability of cerium(IV) with organic substrates and, therefore, can retard the oxidation of organic compounds by cerium(IV).

CERIUM(IV) OXIDATIONS

Cerium(IV) is a powerful one-electron oxidant capable of oxidizing alcohols, glycols, aldehydes, ketones, and unsaturated hydrocarbons. Pottenger (29,30),

Hintz (31,32), and Richardson (33) have reviewed the cerium(IV) oxidations of organic compounds; therefore, only the aspects pertinent to this work will be discussed in the present paper. Much of the knowledge concerning the possible behavior of cerium(IV) during grafting has been obtained from studies of simple organic compounds.

A proposed mechanism for cerium(IV) oxidations of alcohols and glycols in acid media is:

$$Ce(IV) + RCH_2OH \overset{k}{\rightleftharpoons} \text{complex} \xrightarrow[\text{slow}]{k} Ce(III) + R\dot{C}HOH + H^{\oplus}. \qquad (9)$$

1. The oxidant and substrate interact in an equilibrium step to form a coordination complex.
2. The complex disproportionates homolytically in the rate-controlling step, with the oxidant gaining one electron, and the substrate becoming a free radical.
3. The free radical is then rapidly oxidized by a second Ce(IV) species.

$$Ce(IV) + R\dot{C}HOH \xrightarrow{\text{fast}} Ce(III) + R\overset{O}{\overset{\|}{C}}H + H^{\oplus}. \qquad (10)$$

In all cases the predicted stoichiometry, two moles cerium(IV) consumed per mole alcohol oxidized, has been observed and the products are carbonyl compounds.

THEORY OF OXIDATIONS INVOLVING INTERMEDIATE COMPLEXES

Many investigators have made use of the theory originally developed by Duke (34) to establish the involvement of complex intermediates in cerium(IV) oxidations. The assumption is made that only a 1:1 cerium(IV)-substrate complex exists, and that formation of the equilibrium complex is rapid. The rate expression for the above mechanism [Equation (9)] can then be written as

$$d[Ce(IV)_T]/dt = [kK[S]/(1 + K[S])]\ [Ce(IV)_T] \quad (11)$$

where $[Ce(IV)_T]$ is the total cerium(IV) concentration. In the presence of excess substrate the rate expression becomes pseudo-first-order with respect to total cerium(IV) concentration

$$-d[Ce(IV)_T]/dt = k'\ [Ce(IV)_T] \quad (12)$$

where
$$k' = kK[S]/(1 + K[S]). \quad (13)$$

The equilibrium constant for complex formation, K, and the rate constant for disproportionation k, can be experimentally evaluated by determining the pseudo-first-order rate constant, k', at a number of substrate concentrations, $[S]$. Then since

$$1/k' = 1/k + 1/kK[S], \quad (14)$$

K and k can be calculated from the slope and intercept of a plot of $1/k'$ versus $1/[S]$, generally referred to as a reciprocal plot. The finding of a linear reciprocal plot with significant intercept provides evidence for complex intermediates. Also, if the intermediate complex mechanism is operative, from Equation (13), a plot of k' versus $[S]$ will be nonlinear, concave downward and pass through the origin.

If, however, a linear relationship between k' and $[S]$ is found, second-order kinetics are in effect. This is normally the case with cerium(IV) oxidations in sulfuric acid media. When this occurs, the equilibrium constant may be too small, complex formation may be rate determining, or a direct bimolecular oxidation mechanism may be involved. The rate expression then becomes

$$-d[Ce(IV)_T]/dt = K_{II}[S]\ Ce(IV) \quad (15)$$

$$k_{II} = kK. \quad (16)$$

If second-order kinetics are observed the participation of complex formation cannot be evaluated.

The significant point is that the dependence of the pseudo-first-order rate constant on substrate concentration provides a method for distinguishing between the two mechanisms, i.e., complex formation or direct oxidation, although evidence for second-order kinetics cannot be rigorously interpreted.

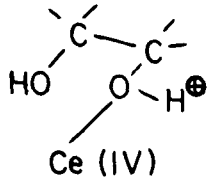
It appears that detection of cerium(IV)-organic complexes is dependent on the stability of the cerium(IV)-inorganic species (acid anion) present. Whether or not such stability effects a change in mechanism with a change in acid is debatable.

PREVIOUS RELATED WORK

Hintz (31,32) studied the oxidation of cyclic alcohols by cerium(IV) in 1.0M perchloric acid and mixed perchloric and sulfuric acids. One significant finding of Hintz was that cyclic 1,2-diols reacted with cerium(IV) by carbon-carbon bond cleavage to form dialdehydes, and in this respect resembled the oxidants lead tetraacetate and periodate which are specific for glycol units. Hintz also found that the values of the equilibrium constants for complex formation for the 1,2-diols were significantly greater than for the corresponding monohydric alcohols. Since it is known that formation of chelate rings enhance the stability of coordination complexes, Hintz concluded from the magnitude of the equilibrium constants determined in perchloric acid media that the cyclic 1,2-diols reacted via chelate complexes.

Trahanovsky and Young (35) state, however, that while the data obtained by Hintz could support chelate formation, the free energy difference associated

with the equilibrium constants (monohydric versus diol) was only 1 kcal/mole, and the results of Hintz's work could be explained by a monodentate complex (I) rather than a bidentate metal-glycol (chelate) complex (II). Furthermore, Trahanovsky, et al. (35,36) explains the results he obtained from studies of



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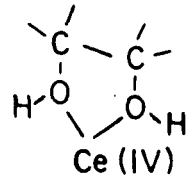


II

the oxidation of 1,2-glycols with CAN (in acetic acid, and acetonitrile-nitric acid) by the formation of a monodentate, and not a bidentate complex.

Pottenger (29,30) concluded the cerium(IV) oxidation of excess glucose in 1.0M perchloric acid was very specific, yielding arabinose and formic acid. Evidence was obtained for the participation of an intermediate complex, and because of the magnitude of the equilibrium constant (as compared with monohydric alcohols), the intermediate complex was concluded to be a chelate. Pottenger also concluded that the hydroxyl at the C_1 carbon atom is the most reactive hydroxyl in the cerium(IV) oxidation of aldoses.

From Pottenger's study and more recent work by Bhattacharyya and Johnson (37) the mechanism of glucose oxidation by cerium(IV) in 1.0M perchloric acid was believed to be that shown in Fig. 1. The first step involves the formation of a chelate complex between cerium(IV) and the glycol pair at C_1 and C_2. The contribution of Bhattacharyya was the demonstration of the location of the free radical at C_2 following cleavage of the C_1-C_2 glycol unit. Although the possibility of a free radical formation at C_1 was not completely eliminated, only the C_2 radicals served as polymer initiators.

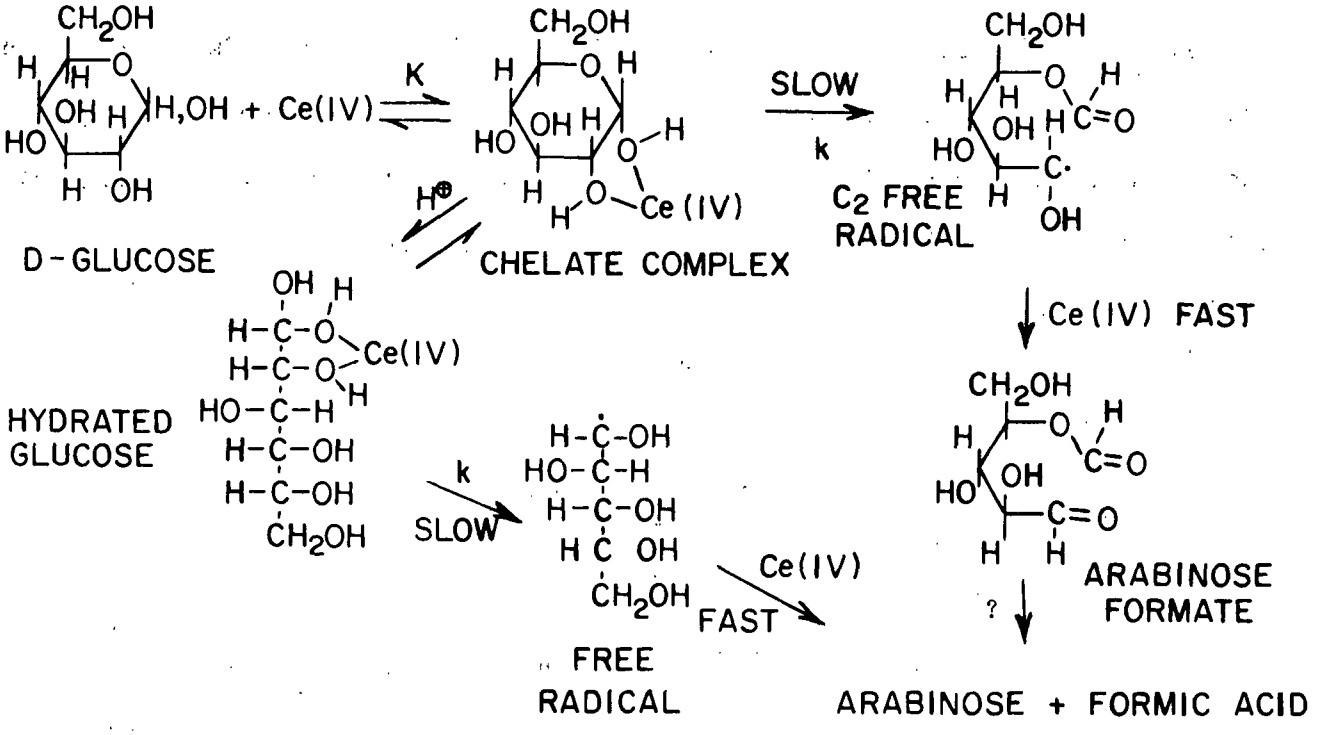
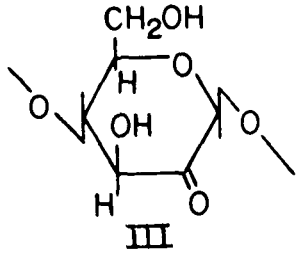


Figure 1. Mechanism of Glucose Oxidation by Cerium(IV) in 1.0M Perchloric Acid

Bhattacharyya's quantitative data for the cerium(IV) oxidation of glucose showed considerably less arabinose than had been expected from Pottenger's work which had indicated virtually quantitative conversion of glucose to arabinose. Although puzzling, this discrepancy was best explained by assuming a lack of rapid hydrolysis of the intermediate 4-O-formyl-D-arabinose to arabinose, and that this arabinose formate then accounted for the product difference. In fact, Bhattacharyya obtained spectroscopic (NMR and IR) evidence for the formation of a formate ester of arabinose as a product of the cerium(IV) oxidation of glucose. The major product, arabinose, could result from the partial hydrolysis of the arabinose formate in the acidic system, or possibly from an alternative open chain type mechanism, implying two pathways of oxidation (Fig. 1).

Kulkarni and Mehta (9) claim that in the CAN nitric acid oxidation of cellulose and methyl-α-D-glucopyranoside, initial cerium(IV) attack occurs at C_2 of the anhydroglucose unit with the formation of a carbonyl group at that position (III). In addition, no erythritol was found (after reduction and hydrolysis) indicating that C_2-C_3 cleavage had not occurred.



III

These findings are not consistent with those of Pottenger who found erythrose (41% of theoretical) and glyoxal as products (after hydrolysis) in the cerium(IV) oxidation of cellulose in 1.0M perchloric acid. Although the reaction was not specific, the results did confirm C_2-C_3 glycol cleavage. The following mechanism was therefore proposed by Pottenger for the cerium(IV) oxidation of the anhydro-D-glucose unit (Fig. 2).

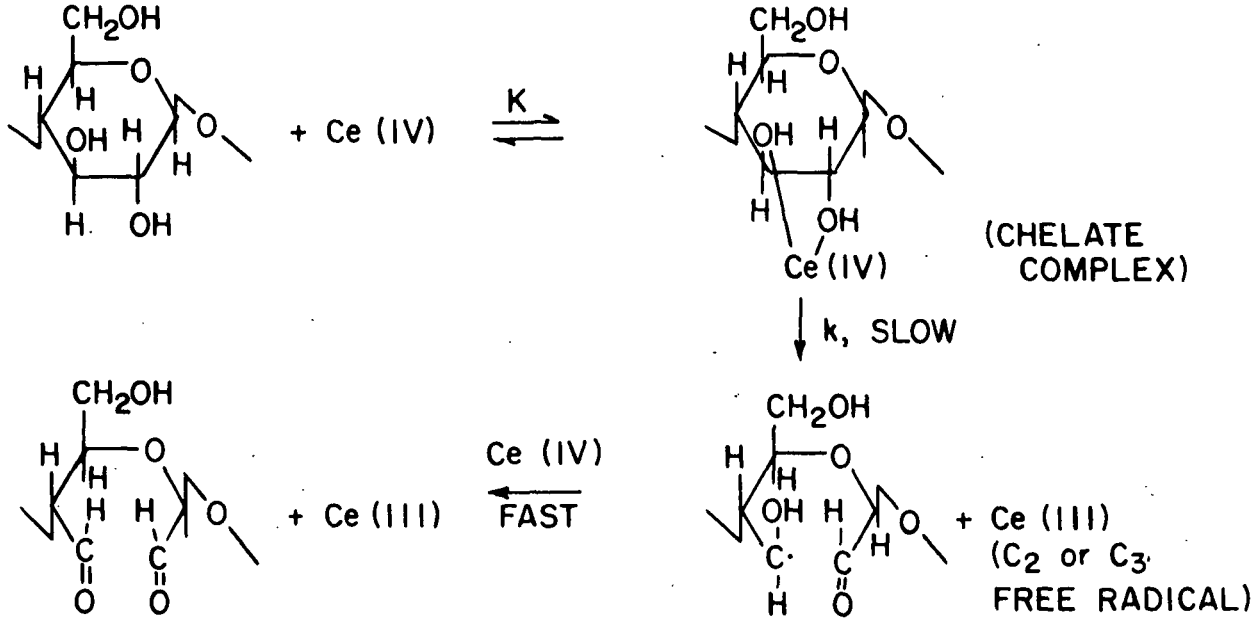


Figure 2. Mechanism of Anhydro-D-glucose Unit Oxidation by Cerium(IV) in 1.0M Perchloric Acid

Pottenger's results from model compound work showed that the reducing end group is 360 times more reactive than the anhydro-D-glucose repeating unit. In relating these results to the oxidative phase of initiating vinyl polymerization onto cellulose by cerium(IV), the favored position of the graft initiation will depend on the relative abundance of the end groups.

Kulkarni and Mehta (9) found two separate rates of ceric ion consumption during the CAN-nitric acid (0.25M) oxidation of glucose, an initial rapid first-order rate, followed by a second slower first-order rate. This general kinetic behavior was not observed by Pottenger, who found excellent pseudo-first-order kinetics for the cerium(IV) oxidation of glucose in perchloric acid.

OBJECTIVE OF THE THESIS

While highly informative, the work of Pottenger, Bhattacharyya, and Johnson (29,30,37) has all been done with only one acid (perchloric), and one acid concentration (1.0M). Cerium(IV)-initiated grafting of vinyl monomers onto cellulose normally involves nitric and sulfuric acid systems. The objective of this thesis was, therefore, to extend the work of Pottenger and Bhattacharyya to the nitric acid system.

The effect of acid (type, concentration, and anion) was investigated in the cerium(IV) oxidation of glucose and cellobiose in the present study. The influence of such factors in model compound studies is necessary before the effect of such variables in polymerization studies can be understood.

Glucose and cellobiose were employed as substrates as they are model compounds for the reducing end groups in cellulose. The reactivity of these end groups versus other glycol units is important because of the discrepancy which exists involving the reactivity of the hemiacetal unit versus the C_2-C_3

glycol unit (anhydroglucose repeating unit) in the initiation step of cellulose copolymerization.

Work on such systems as glucose was necessary to show if any of the documented differences between Pottenger's and Kulkarni and Mehta's (9) work regarding the cerium(IV) oxidation of carbohydrates could be attributed in part to the different acid systems involved, perchloric and nitric.

The existing discrepancies between the work of Pottenger and Bhattacharyya regarding arabinose yields, and the involvement of the intermediate formate ester required examination to obtain a more complete picture of the glucose oxidation. The glucose oxidative mechanism was, therefore, studied in great detail.

An investigation of the reaction mechanism necessarily involves the aspect of cerium(IV)-glucose complex formation. Much discrepancy exists regarding the possible nature of this complex with respect to chelation, including the work of Trahanovsky (35,36), Ogiwara and Kubota (12), Hintz (31,32), and Pottenger (29,30). While the aspect of complex formation was investigated, it must be realized that definite proof for chelation could not be obtained in the present study.

The overall objective of the present study was to provide a more complete understanding of the cerium(IV) oxidation of carbohydrates, which may eventually help in understanding the initiation step of cerium(IV)-cellulose graft copolymerization.

RESULTS AND DISCUSSION

GENERAL

This thesis work can be divided into two parts, a product analysis investigation, and a kinetic study. Quantitative and qualitative GLC procedures were employed in the product analysis studies of the cerium(IV) oxidations of glucose and cellobiose. The quantitative analysis procedures provided mole balances on the carbohydrate portions of the systems studied. A spectrometric technique was employed to study the cerium(IV) oxidations of glucose in the kinetic portion of the work. This technique provided a means for determining pseudo-first-order rate constants, evidence for cerium(IV)-glucose complex formation, and also enabled calculation of the equilibrium constant for complex formation.

The information from product analyses and kinetic work together with NMR results concerning an intermediate reaction product, led to the formulation of a mechanism for the cerium(IV) oxidation of glucose in nitric (and perchloric) acid.

DETERMINATION OF REACTION PRODUCTS

GLUCOSE

Nitric Acid

The cerium(IV) oxidation of glucose(IV) in 1.0M nitric acid at 20°C was very rapid (ca. 120 sec), as evidenced by the disappearance of the color of the ceric solution. For this reason these oxidations were conducted in a reaction apparatus designed to give instantaneous mixing of the cerium(IV) and glucose solutions. The color change of the ceric solution from yellow to reddish brown when added to the glucose solution suggested the formation of a cerium(IV)-glucose complex.

A summary of all the quantitative data obtained by GLC (see Experimental, Determination of Response Factors and Mass Balances, for methods employed) for the cerium(IV) oxidations of glucose conducted in this thesis work is given in Table II (see Table XIV, Appendix II, for original data). With one exception (Reaction 3, Table II), all oxidations were made employing a 2:1 molar ratio of glucose:ceric ion (this represents actually a 4:1 molar excess on an equivalent basis). The variables studied in these oxidations included nitric acid concentration (0.1 to 2.0M), ionic strength (nitrate ion concentration), and type of acid (nitric versus perchloric). In addition, the effect of light on these oxidations was investigated.

The cerium(IV) oxidation of glucose in 1.0M nitric acid at 20°C is referred to as the control oxidation (Reaction 1, Table II), as this reaction is a parallel to the oxidation in 1.0M perchloric acid studied previously (29,30). Quantitative (alditol acetate derivatives) and qualitative (TMS derivatives) GLC investigations showed that the only products of this control oxidation were arabinose (V, ca. 81%) and erythrose (VI, ca. 19%). The finding of a less than a quantitative yield of arabinose, and a small, but significant amount of erythrose as a product indicates that this oxidation in nitric acid is not restrictive to glucose, and that secondary oxidation(s) are important. If the erythrose resulted from the oxidation of glucose via C_2-C_3 glycol cleavage, glyoxal(VIII) should have been a product of the oxidation. No GLC evidence was obtained for glyoxal, or glyceraldehyde(VII) as products, indicating that the C_2-C_3 and the C_3-C_4 glycol units of the glucose molecule are not cleaved by the ceric ion. Furthermore, no evidence was obtained for aldonic acid formation, gluconic or arabinonic acid. It seems, therefore, that only the C_1-C_2 glycol unit of glucose is cleaved by the ceric ion in this oxidation to give the initial primary product arabinose, which then undergoes a small amount of similar competitive secondary oxidation to yield erythrose.

TABLE II

DATA SUMMARY FOR THE CERIUM(IV) OXIDATION
OF GLUCOSE IN NITRIC ACID AND PERCHLORIC ACID AT 20°C

Reaction	Reaction Media[a], M	Parameter Investigated	Arabinose Yield, %	Erythrose[b] Yield, %	Ce(IV)/Glucose Consumed	Cerium(IV)[c] Accounted for, %
1	1.0 HNO_3	Control	81.3	18.7 (18.2)	2.38	99.6
2[d]	1.0 HNO_3	Light	78.3	21.7 (15-16)	2.33	103.0
3[e]	1.0 HNO_3	Glucose:Ce(IV) (1:1)	71.6	28.4 (28.1)	2.55	100.4
4	1.0 HNO_3 + 1.0 $NaNO_3$	Ionic strength	82.1	17.9 (17.4)	2.40	98.1
5	0.1 HNO_3	Nitric acid concentrate	82.9	17.1 (15.1)	2.36	99.1
6	0.5 HNO_3		83.2	16.8 (16.4)	2.42	96.1
7	1.5 HNO_3		88.4[f]	11.6 (12.1)	2.59	86.6
8	2.0 HNO_3		86.2[f]	13.8 (14.4)	2.65	86.0
9	1.0 $HClO_4$	Type of acid	77.2	22.8 (23.2)	2.41	101.4
10[g]	1.0 $HClO_4$		75.8	24.2 --	2.44	102.0

[a] Cerium(IV) concentration 0.05M, glucose concentration 0.10M.

[b] The erythrose yield reported represents the difference between the glucose consumed and arabinose formed. The number in parentheses represents the experimental yield determined from GLC analysis.

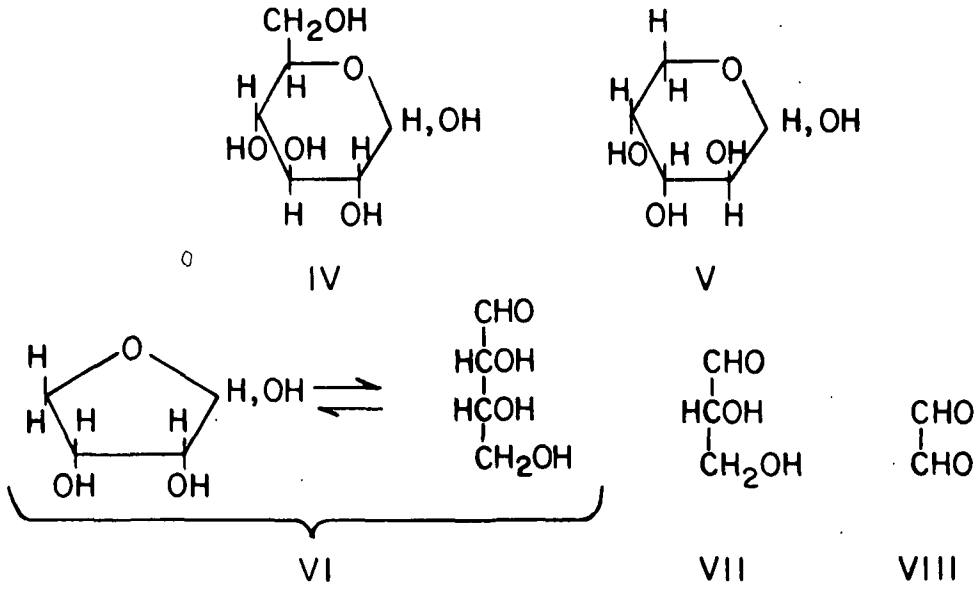
[c] This number was calculated assuming competitive oxidation of arabinose to yield erythrose, requiring an additional 2 moles of Ce(IV) for each mole of arabinose consumed.

[d] Reactions were conducted in black painted flasks, except in this oxidation where the effect of light was investigated.

[e] All reactions were conducted with a 2:1 molar excess of glucose:Ce(IV) with this one exception.

[f] The arabinose yield (Reactions 7 and 8 only) includes an unknown amount of arabinonic acid (see Effect of Nitric Acid Concentration).

[g] Data recalculated from results reported by Bhattacharyya and Johnson (37).



The stoichiometry ratio of cerium(IV) to glucose consumed reported in Table II is an indication of the further oxidation of the initial products. If secondary oxidation is not important, as Pottenger had found in perchloric acid (1.0M), this stoichiometry ratio should be 2.0.

The cerium(IV) accounted for value shown in Table II was calculated with the assumption that the minor product erythrose results from the competitive oxidation of arabinose. In addition to the two moles of ceric ion required for each mole of glucose oxidized (to arabinose), another two moles of ceric ion are also required for each mole of arabinose oxidized. Since erythrose was the only other product detected besides arabinose, for the purpose of establishing mass balances the erythrose yield was taken as the difference between the amount of glucose consumed and arabinose formed. This number is probably more accurate than the experimentally determined yield of erythrose (given in parentheses) from GLC analysis due to the small chromatogram peak areas associated with this product (Fig. 12). Furthermore, it was assumed that the total amount of ceric ion initially present was entirely consumed in the oxidation of carbohydrate material (glucose or arabinose).

The fact that a very good mass balance (in terms of carbohydrate product and ceric ion consumed) was obtained for this oxidation when the data were calculated as stated above, along with the fact that no other products were detected, substantiate the assumption of erythrose resulting from the secondary oxidation of arabinose. If this were not true, and erythrose did result from the oxidation of glucose directly, only two total moles of ceric ion per mole of glucose oxidized would be consumed in the process, and an incomplete ceric ion balance would be the result.

Light did not appear to have a large influence on the oxidation in 1.0M nitric acid with regard to product yields (Reaction 1 versus 2, Table II). Since the product yields and overall mass balance appeared to be somewhat better for the control reaction which was conducted in the absence of light (as compared to Reaction 2 which was not), subsequent oxidations (Reactions 3 to 9) were also run in the absence of light.

When the molar ratio of glucose:cerium(IV) was changed from 2:1 to 1:1 (Reaction 3, Table II), the yield of the major product arabinose (71.6%) was seen to decrease, while the yield of erythrose (28.4%) correspondingly increased. This is what would be predicted on the basis of erythrose resulting from the secondary oxidation of arabinose. As the molar excess of glucose to ceric ion is reduced, the competitive secondary oxidation of arabinose becomes more important. The greater amount of secondary oxidation in this reaction as compared to the normal 2:1 case is also reflected in the higher value of cerium(IV) to glucose consumed (2.55 versus 2.38). Again a good mass balance was obtained with all the ceric ion consumed being accounted for in terms of carbohydrate product.

A cerium(IV) oxidation of arabinose in 1.0M nitric acid was conducted in a similar manner to the oxidations of glucose. This oxidation was very fast (ca. 1 min) and the only product detected by qualitative GLC analysis was erythrose. This along with the previously mentioned observations and results are consistent with the theory that erythrose results from the competitive oxidation of arabinose.

Effect of Nitric Acid Concentration

After gaining an understanding of the cerium(IV) oxidation of glucose in 1.0M nitric acid, the next step was to investigate the effect of a change in acid concentration on the oxidation. Quantitative data (Reactions 5 to 8) were obtained for the cerium(IV) oxidation of glucose over an acid concentration range of 0.10 to 2.0M (20-fold range). A problem was encountered as ceric salts tended to precipitate at the lower acid concentrations (less than 0.20M, pH 0.7) upon storage. Freshly prepared ceric solutions were therefore used for the oxidations at a 0.1M nitric acid concentration. They were standardized just prior to the actual oxidation. Such solutions were found to be stable with respect to cerium(IV) for about three days after preparation. In contrast, cerium(IV) solutions prepared in 1.0M nitric acid showed no change in cerium(IV) concentration after months (12 to 18) of storage.

In varying the nitric acid concentration, the nitrate ion concentration was also changed. It was necessary, therefore, to examine the effect that the nitrate ion alone could have on these oxidations. An oxidation (Reaction 4, Table II) was conducted with the acid concentration maintained at 1.0M, and the nitrate ion concentration adjusted to 2.0M, the highest nitrate ion concentration that was encountered while varying the nitric acid concentration. Referring to

Table II (Reaction 1 versus 4), such a change in nitrate ion concentration did not appear to affect the oxidation significantly from the standpoint of product yields.

Cerium(IV) oxidations of glucose were then conducted at acid concentrations of 0.1, 0.5, 1.5, and 2.0M. The mass balances (carbohydrate products and ceric ion consumed) at the lower acid concentrations of 0.10 and 0.50M were very good (Reactions 5 and 6, Table II). The product yields of arabinose and erythrose were about the same (within 2%) as those obtained at the 1.0M nitric acid concentration (Reaction 1).

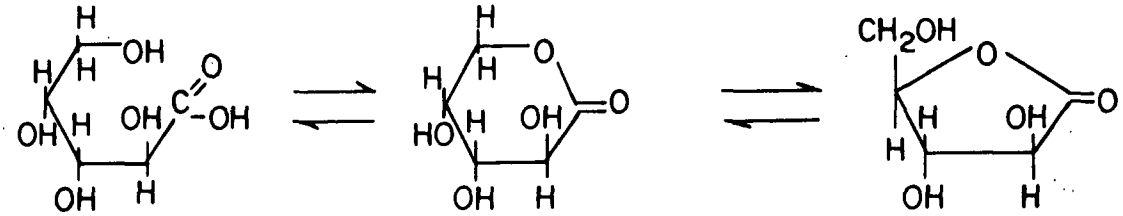
The oxidations at the nitric acid concentrations of 1.5 and 2.0M showed a higher yield of arabinose (86 to 88%), as compared to the control oxidation (1.0M). The ceric ion consumed, however, was not accounted for with these product yields (Reactions 7 and 8, Table II). The higher ratio of cerium(IV) to glucose consumed for Reactions 7 and 8 (2.59 and 2.65) as compared to Reaction 1 (2.38) implies some form of additional secondary oxidation. Since a carbohydrate mass balance existed, the material which consumed or was responsible for the unaccountable ceric ion was masked in the GLC analysis and appeared as either starting material (glucose) or product (arabinose or erythrose).

Qualitative GLC investigations (TMS derivatives) of the cerium(IV) glucose oxidations at high acidity (1.5 and 2.0M) showed the presence of a small peak which had a retention time corresponding to that of arabinonic acid. Glucose is not oxidized to gluconic acid, as no evidence was found for this acid (as glucono-δ-lactone). By analogy, arabinonic acid apparently does not result from the oxidation of arabinose. This acid, therefore, probably results from the direct oxidation of glucose by an as yet unknown mechanism. Kulkarni and

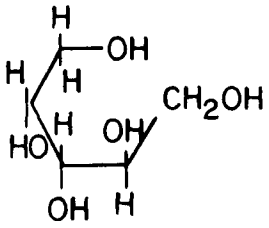
Mehta (9) (see Introduction) have postulated that initial attack occurs at the C_2 position in the CAN oxidation of methyl-α-D-glucoside with the formation of a methyl-α-D-glucosuloside. These workers further speculated that the carbonyl group at C_2 could be converted to a carboxyl group by subsequent C_1-C_2 carbon bond cleavage. Whether or not a similar pattern of oxidation could occur in the present case with glucose which possesses a reducing carbon atom, is not known.

In aqueous solution, arabinonic acid(IX) is in equilibrium with the lactone forms [1,5(X) and 1,4(XI)], the acid-lactone equilibrium being pH dependent. The arabinono-lactones could not be separated from the arabinose peaks by GLC employing TMS derivatives. The peak for arabinonic acid, however, was well removed from other interfering peaks in the GLC chromatograms. When samples from the oxidations at 1.5 and 2.0M nitric acid were neutralized to a low pH (ca. 3.0) prior to TMS derivatization, the equilibrium was shifted toward the lactones, and no evidence was obtained for arabinonic acid (due to the interfering arabinose peaks). When samples from these same oxidations were neutralized to a higher pH (ca. 8.0), the equilibrium was shifted toward the free acid salt, and GLC analysis showed the appearance of a peak corresponding to the retention time of arabinonic acid. In addition, the area ratio of the arabinose anomer peaks changed with this pH change, indicating an equilibrium shift of the arabinono-lactones from under the arabinose peaks to the removed arabinonic acid peak.

Treatment of the known arabinono-lactone with sodium borohydride gave arabinitol(XII). The arabinonic acid, as a result of the GLC work-up procedure for quantitative analysis (see Experimental, Work-up Procedures) would be reduced to arabinitol, and recorded as part of the arabinose (which is reduced to arabinitol for analysis purposes) yield. Four moles of ceric ion are actually required for each mole of acid formed, but due to the work-up procedure



IX X XI



XII

and subsequent analysis as arabinose, the acid would be considered as consuming only two moles of ceric ion. This product could then explain the observed data at high acidities (only 86% ceric ion accounted for).

A ceric ion and carbohydrate mass balance would require a yield of approximately 15% arabinonic acid at the 1.5M nitric acid concentration and 18% at 2.0M.

Perchloric Acid

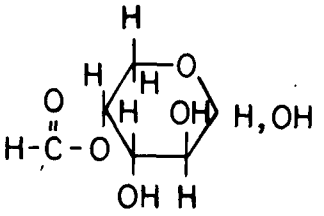
The cerium(IV) oxidation of glucose in 1.0M perchloric acid was conducted primarily to check the present system of quantitative GLC analysis with previous work that had been done with the perchloric acid system (29,30,37). The results of this oxidation (Reaction 9, Table II) show a good mass balance with arabinose (77.2%) and erythrose (22.8%) as products. Results of a similar oxidation made by Bhattacharyya and Johnson (37) have been recalculated on a mmole basis and also reported in Table II (Reaction 10). When expressed on the same basis (mmole) the two sets of data agree rather well regarding the amount of glucose consumed and arabinose yield.

Originally Bhattacharyya's data were puzzling as lower arabinose yields were found than were expected, assuming the oxidation was specific resulting in only arabinose as a product. Bhattacharyya's data, however, can now be explained with the formation of erythrose to account for the low arabinose yields. In addition, the ceric ion consumed is also accounted for with the formation of erythrose. Bhattacharyya did observe traces of erythrose chromatographically.

These results differ from those of Pottenger (29,30), who found the cerium(IV) oxidation of glucose in 1.0M perchloric acid to be very specific yielding only arabinose. Pottenger's results were based on paper chromatography, and when paper chromatography was employed in the present thesis work to qualitatively analyze the products from the cerium(IV) oxidation of glucose in 1.0M nitric acid, only arabinose was detected as a product. It is possible, therefore, that Pottenger was not able to detect erythrose with his techniques, just as this product (erythrose) was not detected in the present study using paper chromatography.

Intermediate Formate Ester of Arabinose

Bhattacharyya and Johnson (37) proposed two mechanistic pathways (Fig. 1) for the cerium(IV) oxidation of glucose to arabinose in 1.0M perchloric acid, depending upon whether or not the oxidation proceeded through the intermediate formate ester of arabinose, and if so, whether this ester was hydrolyzed in the acidic reaction medium to give arabinose. As previously stated, Bhattacharyya's data are now readily explainable with the results obtained in the present study. In order to clarify the role of the possible intermediate 4-O-formyl-D-arabinopyranose(XIII) in these oxidations, however, the properties and behavior of this compound under the reaction conditions required investigation. In this regard, the successful synthesis of this new compound was accomplished.



(XIII)

The results of an NMR study demonstrated the instability of the ester group of the arabinose formate in nitric acid. The hydrolysis of this ester (AF) to formic acid (FA) in 1.0M nitric acid at 20°C was followed very conveniently by repetitive NMR scanning [Fig. 3, (a) to (e)] of the formyl proton peak region (δ8.0 to 8.75 ppm). Due to the hydrolysis of this formate ester of arabinose in the acidic reaction media, detection of such an intermediate product in the glucose oxidations by usual product analysis (chromatographic methods) would, therefore, be expected to be very difficult. Oxidations were, therefore, conducted directly in NMR tubes, and the region of the formyl proton peaks (δ8.1 to 8.5 ppm) was scanned during reaction. Figure 4 represents a repetitive scanning of this region after initiation of a reaction for the CAN oxidation of glucose in 1.0M nitric acid. The sequential series [(a) to (e), Fig. 4] shows the initial formation of arabinose formate in the oxidation reaction, AF in (a), followed by hydrolysis of the formate to formic acid, FA in (e), in the reaction media.

Although the first recording in Fig. 4 [(a) after 3 min reaction time], shows a major formate peak, a significant formic acid peak is also present. The question is, therefore, does this formic acid result entirely from the acid hydrolysis of the ester, or does at least some of the formic acid result directly from the oxidation of glucose through an open chain-type mechanism (Fig. 1). Several problems were encountered with respect to obtaining a good

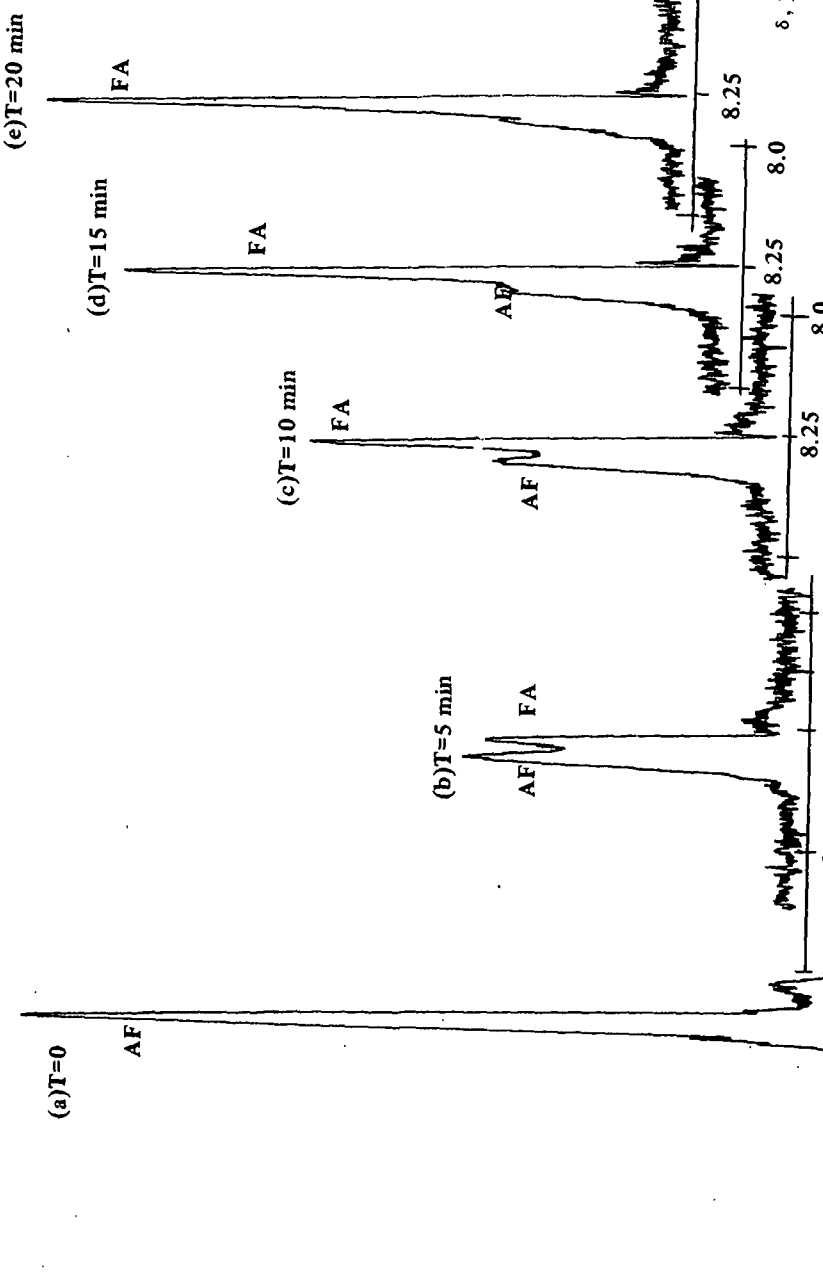


Figure 3. NMR Spectra Showing Formyl Proton Peaks of Arabinose Formate (AF) and Formic Acid (FA)

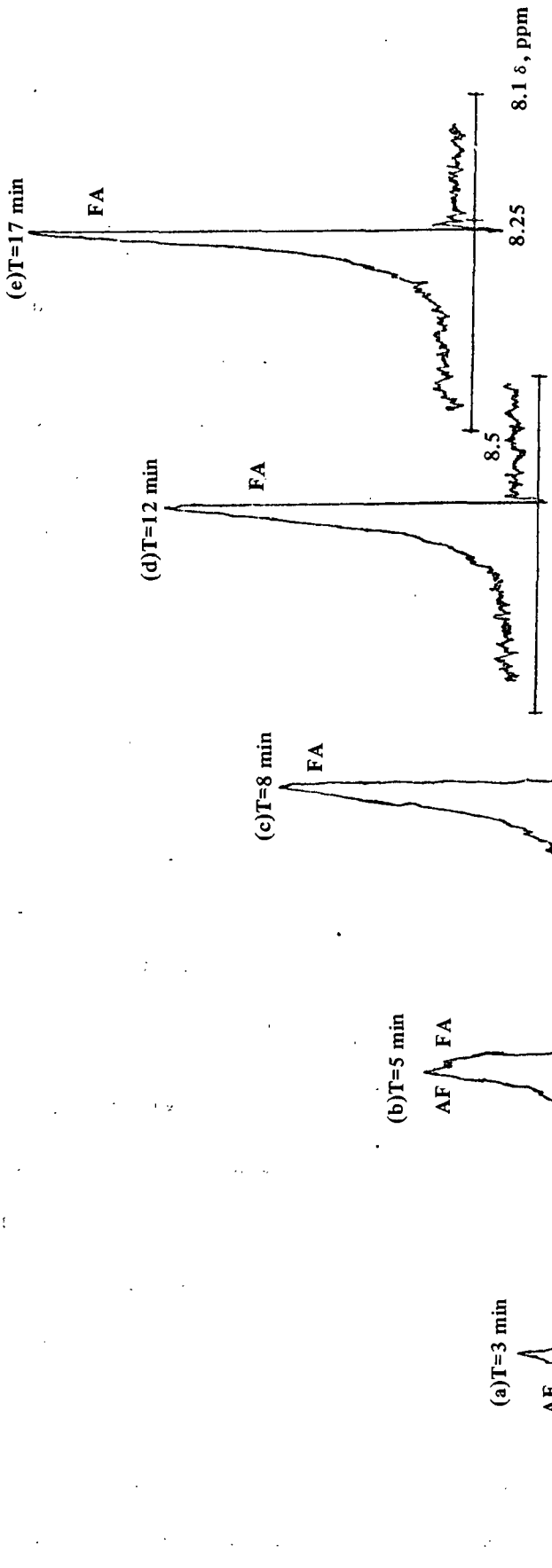


Figure 4. NMR Spectra Showing the Formyl Proton Regions (δ8.1 to 8.5 ppm) for the CAN Oxidation of Glucose in 1.0M Nitric Acid

NMR spectrum in an attempt to clarify this question. The presence of nitric acid and the cerous (+3) ion resulted in chemical shifts of proton signals, and caused problems in the recording of the spectra.

The normally rapid cerium(IV) oxidation of glucose in 1.0M nitric acid at 20°C, was made even more rapid due to the conditions required for conducting the oxidation directly in the NMR tubes, and because of the normal probe temperature (40°C). By the time the first NMR scan was made, therefore, significant hydrolysis of the formate could already have occurred. Although the chemical shift of the formyl proton of the arabinose formate was downfield away from major interference (δ8.27 ppm), the formic acid peak was at δ8.20 ppm, a separation of only 0.07 ppm, and this separation tended to be even less in the actual oxidation samples making spectra interpretation difficult.

The conclusions that can be made from this work are that arabinose formate is indeed an intermediate in the cerium(IV) oxidation of glucose to arabinose, that this intermediate undergoes fairly rapid hydrolysis in the acidic reaction media, and that although the entire reaction may not proceed through this intermediate, at least the major mechanistic pathway does involve the formate ester.

The quantitative GLC data obtained for the cerium(IV) oxidations of glucose in nitric and perchloric acid are compatible with arabinose formate as an intermediate product. Due to the acidic reaction medium, and the subsequent neutralization that is required (see Experimental, Work-up Procedures) prior to derivatization for analysis by GLC, only arabinose (and erythrose) is detected in the normal product analysis.

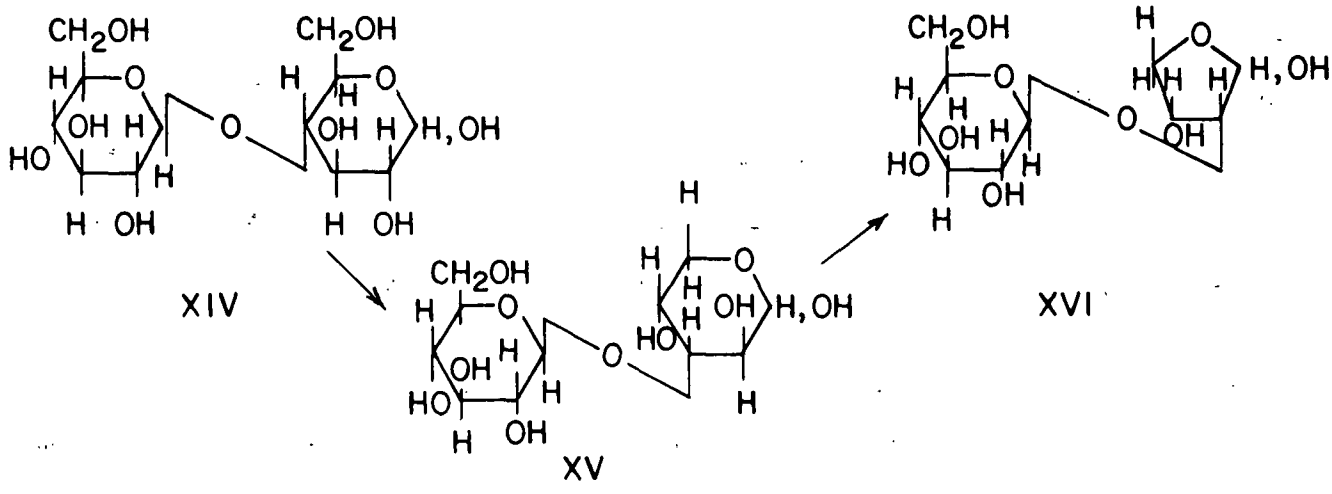
The IR spectra of samples from the cerium(IV) oxidation of glucose in 1.0M nitric and perchloric acid showed a medium strong carbonyl band at 1720 cm^{-1},

when precautions were taken to minimize acid hydrolysis and loss of the formate group during neutralization. These spectra provided further evidence for the ester as an intermediate product, and agree with the work of Bhattacharyya and Johnson (37) who also found IR evidence for the presence of an ester group in the cerium(IV) oxidation of glucose in 1.0M perchloric acid.

Perlin (38-40) concluded that the oxidation of glucose by lead tetraacetate and periodate involved intermediate formate esters, the mono-O-formyl-D-arabinose, and di-O-formyl-D-erythrose. This conclusion was based on evidence (NMR and IR) obtained for the formate ester of arabinose in the lead tetraacetate and periodate oxidation of 3-O-methyl-D-glucopyranose (41). The methyl ether substituent prevented oxidation beyond the C_1-C_2 glycol unit, and therefore resembled the present oxidations of cerium(IV) with glucose. The involvement of arabinose formate as an intermediate in the present study, therefore, parallels the results obtained by Perlin with different oxidants.

CELLOBIOSE

The cerium(IV) oxidation of cellobiose(XIV) in 1.0M nitric acid at 20°C (ca. 5 min) was slower than the corresponding oxidation of glucose (2 min) under essentially the same conditions (a 2:1 molar excess of carbohydrate:ceric ion). As in the glucose oxidations, both quantitative (alditol acetate derivatives) and qualitative (TMS derivatives) GLC investigations were made of the cellobiose oxidations. The only products detected were those corresponding to 3-O-(β-D-glucopyranosyl)-arabinose (GA, XV, ca. 89%) and 2-O-(β-D-glucopyranosyl)-erythrose (GE, XVI, ca. 11%). The quantitative data obtained for all the cerium(IV) oxidations of cellobiose conducted in this thesis work are summarized in Table III.



Product identification and the quantitative yield of GA (as arabinose) was based on analytical results obtained after acid hydrolysis of the disaccharide system. This type of analysis was necessary as the known compounds GA and GE were not readily available for reference and response factor determination. The only problem involved in analyzing such a hydrolysis system is the large amount of glucose which results from the hydrolysis of the disaccharides. Although GLC evidence (Fig. 14) was obtained for erythrose after acid hydrolysis, the resulting small peak area made it impossible experimentally to accurately determine a yield for GE as erythrose. Since no other products were detected, the yield of GE was therefore taken to be the difference between the cellobiose consumed and the amount of arabinose formed after hydrolysis of GA.

The cellobiose and disaccharide products appeared to be stable in the acidic reaction medium (1.0M nitric acid), as only a trace amount of glucose could be detected in the unhydrolyzed disaccharide system (Fig. 13).

The difference between the cerium(IV) oxidation of glucose and cellobiose (in addition to cellobiose being slower), is that the yield of the major product GA (Reaction 1, Table III) from cellobiose (ca. 89%) is somewhat higher than the

TABLE III

RESULTS OF THE CERIUM(IV) OXIDATION OF CELLOBIOSE IN NITRIC AND PERCHLORIC ACID

Reaction	Reaction[a] Media	Temperature, °C	GA[b] Yield, %	GE[b] Yield, %	Ce(IV)/Cellobiose Consumed	Cerium(IV)[c] Accounted for, %
1	1.0M HNO_3	20	89.1	10.9	2.28	97.4
2	1.0M HNO_3	0	90.3	9.7	2.34	95.0
3[d]	0.5M HNO_3	0	83.6	16.4	2.40	96.8
4[d]	0.5M $HClO_4$	0	80.8	19.2	2.53	95.0

[a] Cerium(IV) concn., 0.05M; cellobiose concn., 0.10M.

[b] The yield of the major product GA was determined from the amount of arabinose formed after acid hydrolysis of the disaccharide. The yield of GE was assumed to be the difference between the cellobiose consumed (determined from the disaccharide analysis) and arabinose formed.

[c] This figure was calculated assuming 2 moles of Ce(IV) are consumed for each mole of GA formed, and that GA is oxidized to GE requiring an additional 2 moles of Ce(IV) for each mole of GE formed.

[d] These oxidations were conducted employing only a 1:1 molar ratio of cellobiose:ceric ion; in Reactions 1 and 2 a 2:1 molar excess of cellobiose was employed.

corresponding yield of arabinose (ca. 81%) from glucose. This indicates that less secondary oxidation of cellobiose by cerium(IV) occurs, which is also reflected in the slightly lower ratio of ceric ion to cellobiose consumed (2.28) as compared to glucose (2.38).

The lower reactivity of cellobiose as compared to glucose can probably be best explained by considering the additional number of glycol groups associated with the cellobiose molecule. The glycol groups of the second nonreducing glucose molecule of the disaccharide, although not involved in the oxidation process, can effectively tie up ceric ion through complex formation. This reduces the amount of free ceric ion available for complexing and oxidation of the more reactive reducing end group (C_1-C_2 glycol unit), and the result is a lower oxidation rate for cellobiose.

This same aspect of a greater number of cerium(IV) glycol complexes with cellobiose (although only the C_1-C_2 glycol of the reducing end leads to oxidation) can perhaps explain the higher yield of the major product GA versus the lower yield of arabinose from glucose. Free ceric ions would seem to have the same relative opportunity to oxidize cellobiose and glucosyl arabinose as is the case in the analogous glucose oxidation. The new factor with cellobiose, however, is that unreactive complexes of ceric ion and cellobiose which involve the nonreducing glucose ring may be able to transfer (by an intramolecular path) cerium(IV) to the reducing end. This would then result in a more selective oxidation of cellobiose than of glucose.

An alternative possibility to account for the more selective oxidation of cellobiose is that the major product GA is less reactive toward cerium(IV) compared to cellobiose, than arabinose is compared to glucose. A reason as to why such a difference in comparative reactivities should exist, however, is not known.

As in the oxidation of glucose, the minor product (GE in this case) was assumed to result from the competitive secondary oxidation of the major product GA. When calculating the ceric ion accounted for (Table III) four total moles of ceric ion are required for each mole of GE formed, while if GE resulted from the oxidation of cellobiose directly, only two total moles of ceric ion would be required for each mole of GE formed. The fact that the value obtained for the ceric ion accounted for agrees very well (97.4%) with the amount of cerium(IV) consumed (along with the fact that no additional products were found) provides strong evidence that GE results from the competitive oxidation of GA.

A series of oxidations of cellobiose by cerium(IV) was conducted at 0°C. This decrease in temperature decreased the rate of cellobiose oxidation (Reaction 2, 75 min, Table III) substantially compared to the rate at 20°C (Reaction 1, 5 min, Table III), with other conditions remaining constant.

The final cerium(IV) oxidations of cellobiose (Reactions 3 and 4, Table III) were conducted with a 1:1 molar ratio of cellobiose:ceric ion, and an acid concentration of 0.5N, at 0°C. The effect of changing the cellobiose to ceric ion ratio from 2:1 to 1:1 in these oxidations was the same as that observed in the cerium(IV) oxidation of glucose (Reaction 3, Table II). The theory is that the secondary oxidation of the major product GA (or arabinose) to yield GE (or erythrose) becomes more important as the initial carbohydrate to ceric ion ratio is reduced. This is evident by a corresponding higher yield of the minor product and a larger cerium(IV) to cellobiose consumed ratio.

Reactions 3 and 4 (Table III) differ only in the type of acidic reaction media, nitric or perchloric. The data show that there was only a small difference in product yields for the oxidation of cellobiose in these two acid media.

The slightly greater yield (ca. 3%) of the minor product GE in perchloric acid, however, is also in agreement with data found for the oxidation of glucose in both acid systems (Reactions 1 and 9, Table II).

In summary, good mass balances exist for the cellobiose oxidations, in terms of cellobiose and ceric ion consumed, and products formed. This supports the theory that only the C_1-C_2 glycol units of the reducing end groups are attacked by the ceric ion. The same theory that was applied to the glucose system, therefore, readily explains the data obtained for the cellobiose oxidations at similar acid concentrations.

KINETICS OF THE CERIUM(IV) OXIDATION OF GLUCOSE

Since, in all kinetic work, a large excess of glucose to ceric ion was employed the rate of disappearance of cerium(IV) should be pseudo-first-order,

$$-d[Ce(IV)]/dt = k'[Ce(IV)] \tag{17}$$

which on integration gives

$$\ln\{[Ce(IV)]/[Ce(IV)_o]\} = -k't. \tag{18}$$

It was shown (see Experimental Procedures, Calibration of Spectrometer) that spectrometric absorbance is a linear function of cerium(IV) concentration; therefore, Equation (19) is applicable.

$$\ln(A/A_o) = -k't. \tag{19}$$

Plots of $\ln(A/A_o)$ versus time should, therefore, be linear with slope $-k'$.

The effect of ionic strength, acid (nitric and perchloric), acid anion, glucose, and initial cerium(IV) concentration on the pseudo-first-order rate

constant for the cerium(IV) oxidation of glucose at 20°C were each independently studied.

ORDER OF REACTION WITH RESPECT TO CERIUM(IV) CONCENTRATION

All of the cerium(IV) oxidations studied gave excellent pseudo-first-order kinetics (regression coefficients of 1.0). The finding of linear logarithmic plots shows that the order of reaction with respect to cerium(IV) is one. As further confirmation of first-order dependence on cerium(IV), oxidations of glucose were conducted in nitric acid which showed that the pseudo-first-order rate constant is independent of initial cerium(IV) concentration. Pottenger had found this same behavior in perchloric acid. These results are given in Table IV. Representative kinetic plots for the cerium(IV) oxidations studied in this work are given in Fig. 5 (data from Table XXI, Appendix III).

TABLE IV

EFFECT OF INITIAL CERIUM(IV) CONCENTRATION ON THE PSEUDO-FIRST-ORDER RATE CONSTANT FOR OXIDATIONS OF GLUCOSE IN 1.0M PERCHLORIC AND 1.0M NITRIC ACID, AT 20°C

Acid	Ce(IV)[a] Concn., M	Rate Constant k', sec^{-1}
HNO_3	0.00209	0.0487
HNO_3	0.00418	0.0485
$HClO_4$	0.0020	0.161
$HClO_4$[b]	0.00196	0.147
$HClO_4$[b]	0.00392	0.144

[a] Glucose concentration constant, 0.040M.

[b] Data reported by Pottenger (29,30).

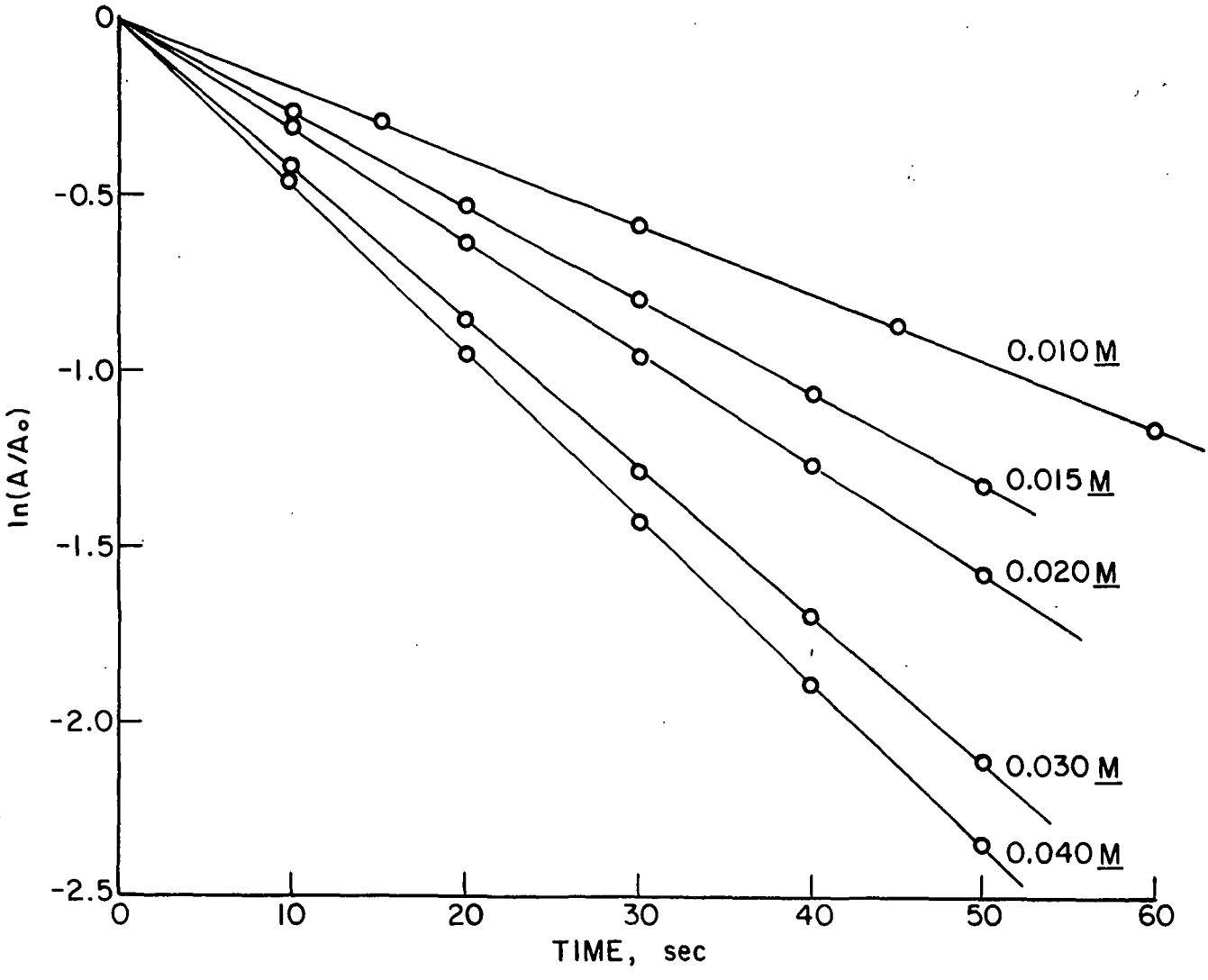


Figure 5. Representative Kinetic Plots for the Cerium(IV) Oxidation of Glucose at 20°C. Initial Cerium(IV) Concentration, 0.00209M. (Glucose Concentrations are Indicated)

EFFECT OF ACID (CONCENTRATION AND TYPE)

Perchloric Acid

The kinetic data in Table V and Fig. 6 show that the pseudo-first-order rate constant for the cerium(IV) oxidation of glucose in perchloric acid at a constant ionic strength increased as the concentration of perchloric acid was increased (0.25 to 1.0M). This type of behavior had been observed by previous workers (42-44) who studied the kinetics of the oxidation of a number of alcohols and aldehydes by ceric ions in perchloric acid.

TABLE V

EFFECT OF ACID CONCENTRATION (PERCHLORIC AND NITRIC) ON THE PSEUDO-FIRST-ORDER RATE CONSTANT FOR THE CERIUM(IV) OXIDATION OF GLUCOSE AT CONSTANT IONIC STRENGTH,[a] 20°C

Perchloric Acid[b] Concn., M	Rate Constant[c] k', sec^{-1}	Nitric Acid Concn., M	Rate Constant k', sec^{-1}
0.25	0.141	0.5	0.0508
0.50	0.148	1.0	0.0477
1.00	0.161	2.0	0.0347

[a] Ionic strength was maintained at 1.0 in perchloric acid with sodium perchlorate. In nitric acid it was kept at 2.0 using sodium nitrate.

[b] Reactions in which the perchloric acid concentration was greater than 1.0M were too rapid to study (reaction time <15 sec).

[c] All rate constants were determined using a glucose concentration of 0.040M, and a cerium(IV) concn. of 0.00209M.

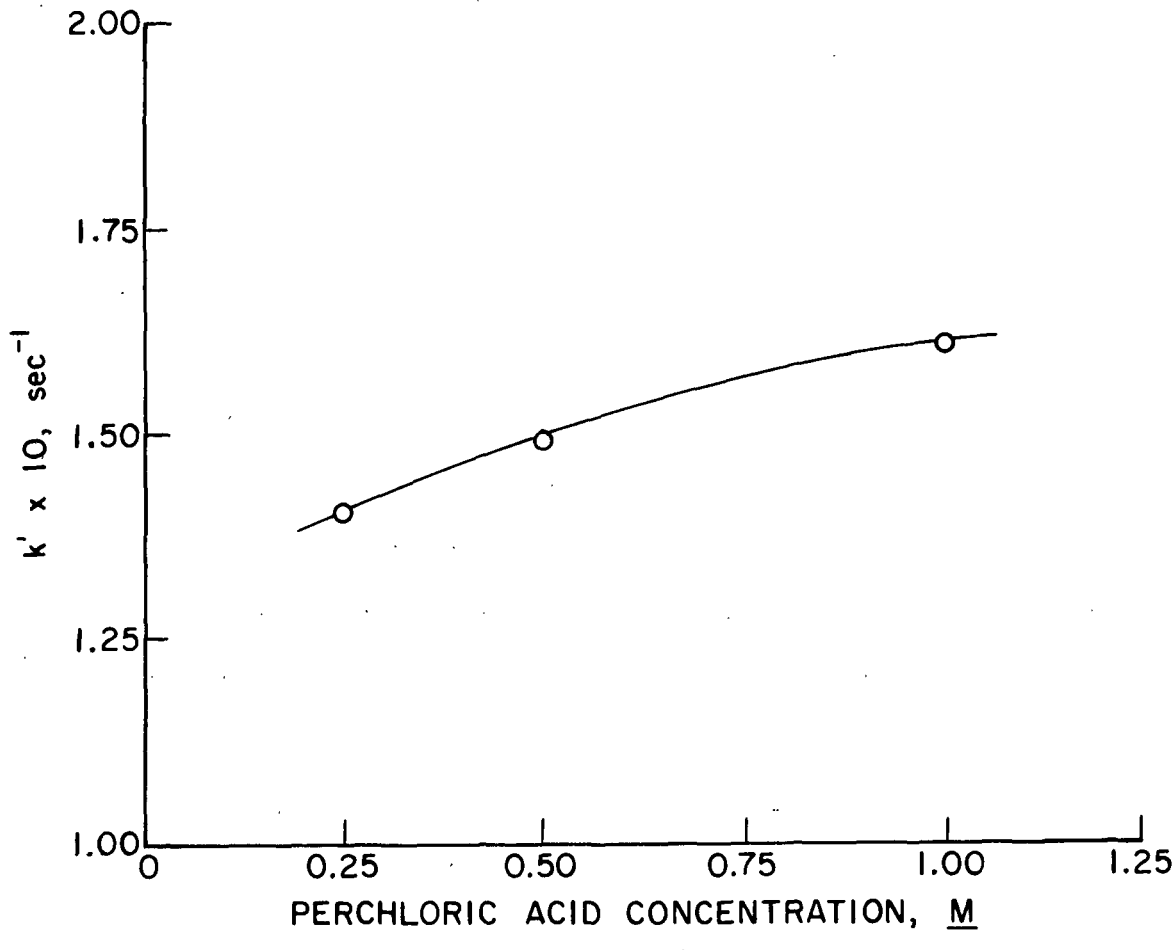


Figure 6. The Effect of Perchloric Acid Concentration on the Pseudo-First-Order Rate Constant for the Cerium(IV) Oxidation of Glucose at 20°C

The increase in reactivity with acidity has been explained by the hydrolysis equilibria [Equation (20)] which occurs with monomeric cerium(IV) species at the acidities used in kinetic studies. The effect of the hydrogen ion is to prevent or retard this hydrolysis,

$$Ce^{+4} + H_2O \rightleftharpoons Ce(OH)^{+3} + H^{\oplus} \qquad (20)$$

resulting in higher concentrations of the more reactive Ce^{+4} species, and therefore an increased rate of oxidation. Normally, a limiting value for the rate is observed at high acidities (1.5 to 2.0M), which corresponds to the maximum concentration of the unhydrolyzed monomeric Ce^{+4}. The cerium(IV) oxidation of glucose in a perchloric acid concentration greater than 1.0M appeared to be complete in less than 15 sec; therefore, rate constants at acidities greater than 1.0M could not be obtained in the present study.

Nitric Acid

The effect of nitric acid (0.5 to 2.0M) on the rate constant (Table V, Fig. 7) for the cerium(IV) oxidation of glucose at constant ionic strength and nitrate ion concentration is opposite of the effect of perchloric acid. This decrease in reactivity with increase in acidity was not unexpected, as literature findings showed a decrease in the rate of the cerium(IV) oxidation of methanol (45), ethanol (45), sec-butanol (46), isopropanol (47), cyclohexanol (48), n-propanol (49), and allyl alcohol (49) with an increase in nitric acid concentration at constant ionic strength (nitrate concentration). Although the specific reason for this decrease in reactivity with increasing hydrogen ion concentration is not known, this result will be discussed in greater detail in a later section [see Mechanism of Oxidation by Cerium(IV)].

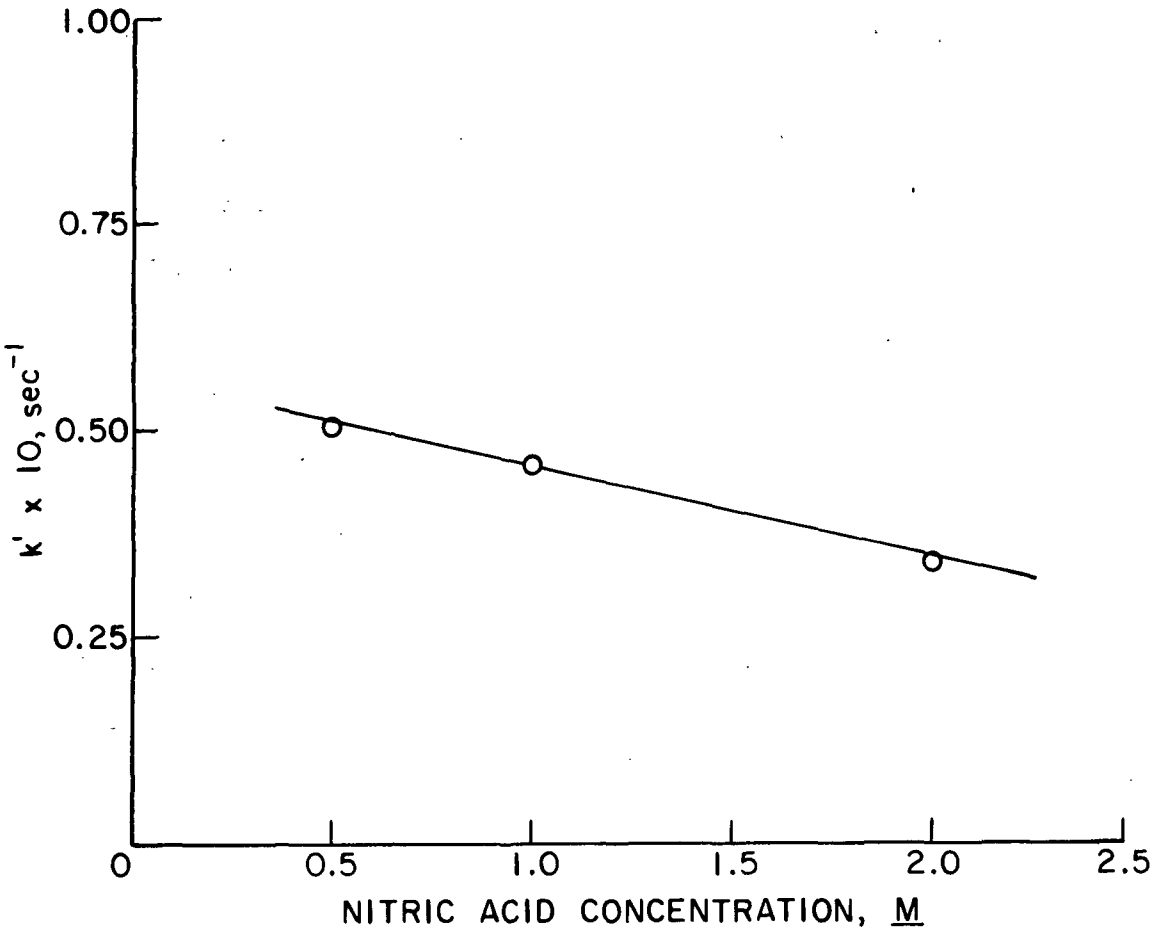


Figure 7. The Effect of Nitric Acid Concentration on the Pseudo-First-Order Rate Constant for the Cerium(IV) Oxidation of Glucose, 20°C

Comparison of Rates in Nitric and Perchloric Acid

The ratio of the pseudo-first-order rate constants (Table IV) for the oxidation of glucose in 1.0M perchloric acid (0.161) and 1.0M nitric acid (0.0487) shows that the oxidation is 3.32 times as fast in perchloric acid. These reaction rates parallel the oxidation potential of the Ce(IV)-Ce(III) couple in perchloric (-1.70) and nitric (-1.61) acid media (23).

Table IV shows that there is a small difference (8.7%) in the rate constants for the cerium(IV) oxidation of glucose in 1.0M perchloric acid as reported by Pottenger (29,30), and as determined in the present thesis work. This difference is not believed to be serious due to possible differences in experimental procedures, techniques, and conditions.

EFFECT OF IONIC STRENGTH (PERCHLORATE ION)

At a constant hydrogen and nitrate ion concentration the pseudo-first-order rate constant for the cerium(IV) oxidation of glucose in nitric acid was found to increase with an increase in ionic strength (1.0 to 2.0, Table VI, Fig. 8). This positive salt effect, acceleration of reaction rate with perchlorate ions, has also been observed by workers (42,43) in the oxidations of alcohols and aldehydes by ceric ions in perchloric acid. The fact that the addition of perchlorate ions did not decrease the rate constant implies that the perchlorate anion does not complex with the cerium(IV) ion, thus leaving the highly reactive cerium(IV) ion free. The increase in rate implies that a normal positive salt effect is operative. Possible reasons for this effect are discussed in a later section [see p. 50, Mechanism of Oxidation by Cerium(IV)].

TABLE VI

EFFECT OF IONIC STRENGTH (PERCHLORATE CONCN.) AND NITRATE ION CONCENTRATION ON THE PSEUDO-FIRST-ORDER RATE CONSTANT FOR THE CERIUM(IV) OXIDATION OF GLUCOSE AT CONSTANT ACIDITY (1.0M)

Acid[a] Concn., M	Nitrate[b] Concn., M	μ[b]	Rate Constant k', sec^{-1}
1.0	1.0	1.0	0.0487
1.0	1.0	1.5	0.0570
1.0	1.0	2.0	0.0630
1.0	0.5	2.0	0.0832
1.0	1.0	2.0	0.0646
1.0	2.0	2.0	0.0465

[a] Hydrogen ion concentration constant at 1.0M.

[b] Ionic strength and nitrate ion concentration were adjusted using the appropriate amounts of sodium perchlorate and sodium nitrate.

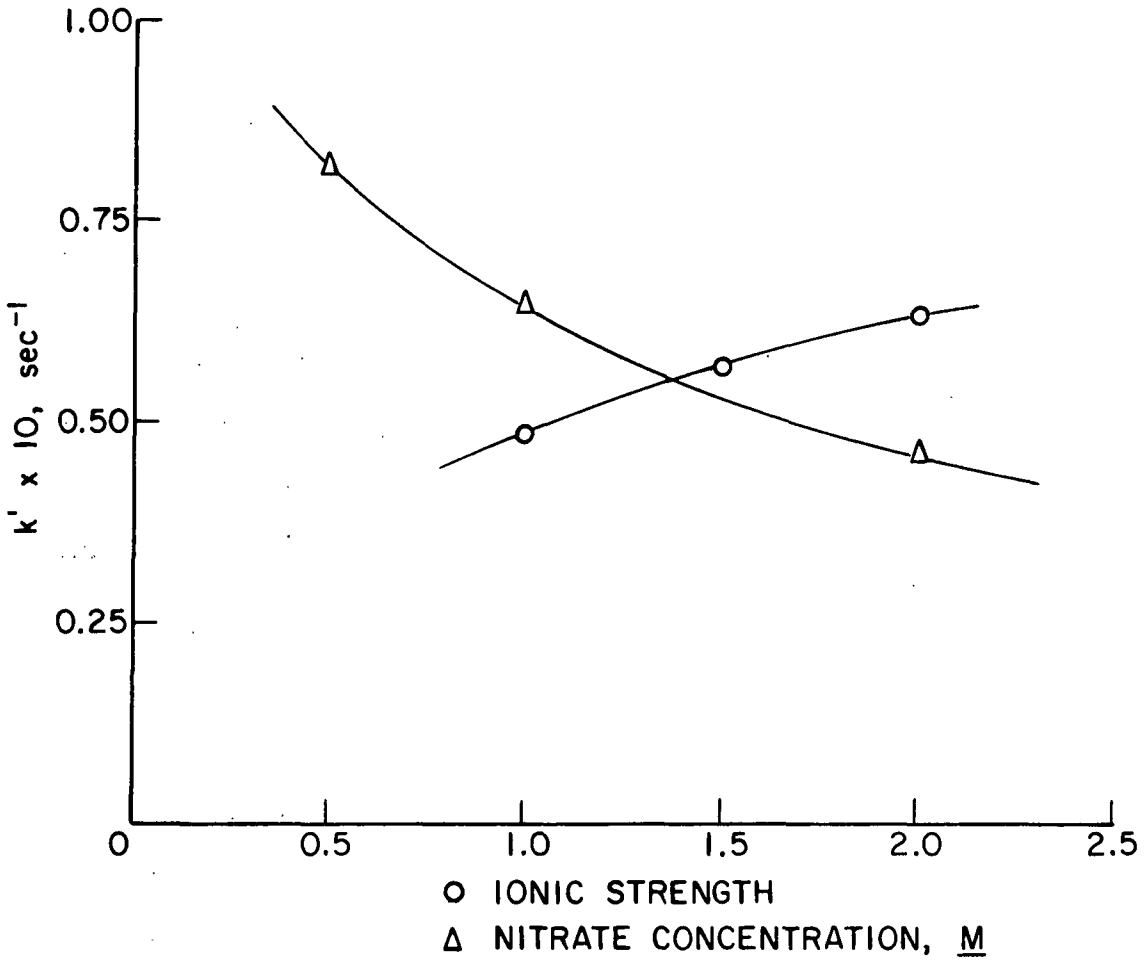


Figure 8. Effect of Ionic Strength and Nitrate Ion Concentration on the Pseudo-First-Order Rate Constant for the Cerium(IV) Oxidation of Glucose, 20°C

EFFECT OF NITRATE ION

The data in Table VI also show the inhibitory effect of the nitrate ion on the cerium(IV) oxidation of glucose in nitric acid. This effect, also shown in Fig. 8, can readily be contrasted with the accelerating effect of the perchlorate ions. This decrease in reactivity with an increase in nitrate ion concentration had been expected from a survey of the literature (45-50).

Although there is unanimous agreement in the literature (45-50) regarding the inhibitory effect of nitrate ions on the cerium(IV) oxidation of alcohols, the specific information available on the state of cerium(IV) in nitric acid is

meager. A general statement that can be made, however, is that in the presence of nitrate ions several cerium(IV) acid anion complexes can form according to Equation (21).

$$Ce^{+4} + mNO_3^{\ominus} \rightleftharpoons Ce(NO_3)_m^{(4-m)\oplus}, \quad m \leq 6. \tag{21}$$

Differences exist, however, regarding the relative reactivity of the various cerium(IV) species, and as to which one(s) are the actual oxidizing species. It is known from previous studies (27,31,32) that as the number of sulfate ions associated with the ceric ion in the form of a complex increases, the reactivity of the cerium(IV) species decreases. This fact, along with previous (45-50) implications suggest that nitrated cerium(IV) species are probably less reactive than the free or hydrated ceric ion, and thus account for the observed inhibitory effect of the nitrate ion. This result is reasonable since incorporation of nitrate ions into the coordination sphere of cerium(IV) (in place of water molecules) reduces the effective positive charge of the cerium(IV) and hence its electrophilic attraction for the reductant molecules.

The final comment to be made concerning the effect of the acid anion is illustrated very clearly in Fig. 8. The two curves contrast the effect of a complexing ($NO_3^{\ominus}$) and noncomplexing ($ClO_4^{\ominus}$) acid anion on the rate constants. It appears, therefore, that reactivity decreases as the ability of the anion to form stable cerium(IV) complexes increases.

The conclusion to be made concerning the nitric acid system is that both hydrogen and nitrate ions decrease the cerium(IV) rate of oxidation of glucose. Referring to Tables V and VI and Fig. 7 and 8, it appears that initially an increase in the nitrate ion concentration has a greater inhibitory effect on the rate constant than does an increase in hydrogen ion concentration.

ORDER OF REACTION WITH RESPECT TO SUBSTRATE CONCENTRATION

Kinetic Evidence for Complex Formation

As discussed in the Introduction section (Theory of Oxidations Involving Intermediate Complexes), determination of the dependence of the pseudo-first-order rate constant on the substrate concentration can provide a means for distinguishing between the various reaction mechanisms.

For reactions proceeding through intermediate complexes, the pseudo-first-order rate constant is given by Equation (13) which predicts that a plot of k' versus $[S]$ (substrate concn.) will be nonlinear, concave downward, and pass through zero. The reciprocal plot [Equation (14)], $1/k'$ versus $1/[S]$ for such reactions, however, will be linear and the equilibrium constant for complex formation, K, and the disproportionation rate constant, k, can be calculated from the slope and intercept. For the direct oxidation mechanism and certain variations of the intermediate complex mechanism as previously described, a plot of k' versus $[S]$ will be linear with slope K_{II} and zero intercept.

A plot of k' versus $[S]$ (Fig. 9) for the cerium(IV) oxidation of glucose in 1.0M nitric acid (data in Table VII) was curved, and concave downward. The definite curvature of the plot indicates intermediate complex formation. Further evidence for the participation of an intermediate complex in this oxidation was obtained from the linear reciprocal plot, Fig. 10.

COMPLEX FORMATION CONSTANTS

The equilibrium constant for complex formation and the disproportionation rate constant calculated from the slope and intercept of Fig. 10 are given in Table VIII. Also included in Table VIII are the equilibrium constants and disproportionation rate constants for the cerium(IV) oxidation of glucose in 1.0M

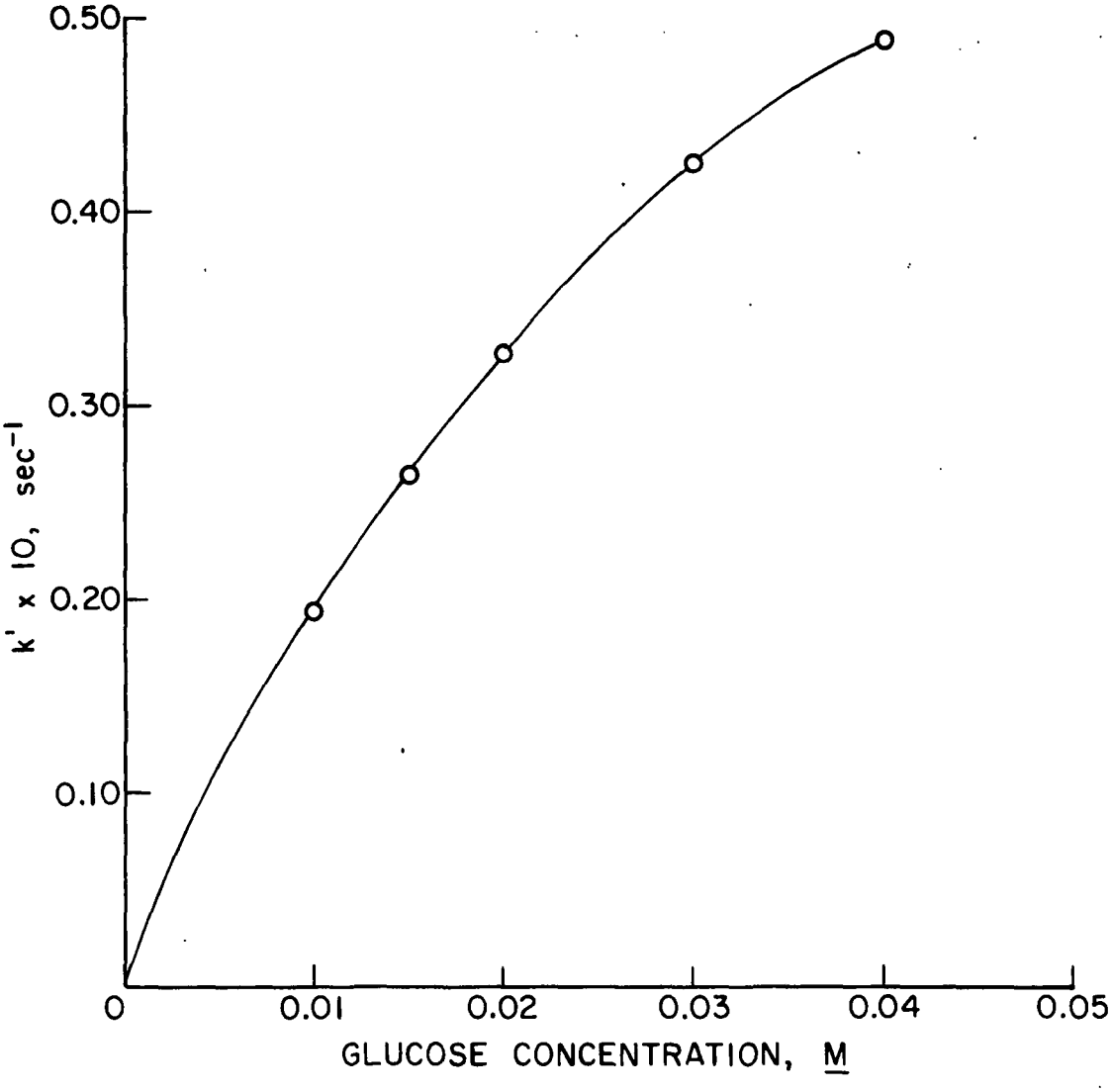


Figure 9. Effect of Glucose Concentration on the Pseudo-First-Order Rate Constant at 20°C. Initial Cerium(IV) Concn., 0.00209M

TABLE VII

EFFECT OF GLUCOSE CONCENTRATION ON THE PSEUDO-FIRST-ORDER RATE CONSTANT FOR THE CERIUM(IV) OXIDATION OF GLUCOSE IN 1.0M NITRIC ACID AT 20°C

Glucose Concn., M	Rate Constant k', sec^{-1}
0.040	0.0487
0.030	0.0424
0.020	0.0326
0.015	0.0264
0.010	0.0194

perchloric acid reported by Pottenger, and several organic substrates (alcohols) in 1.0M nitric acid as found in the literature (references indicated).

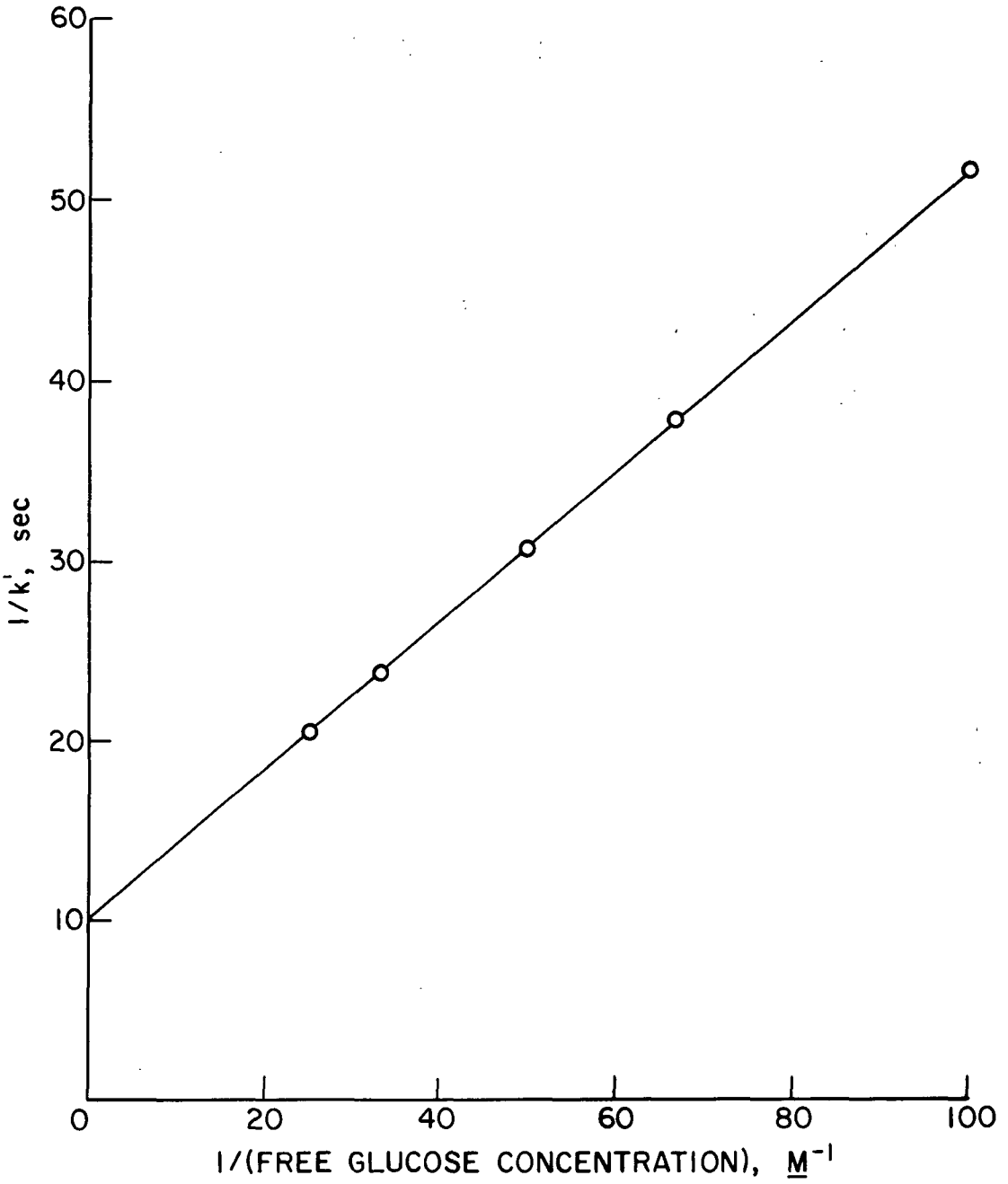


Figure 10. Reciprocal Plot for Reactions of Glucose with Cerium(IV) in 1.0M Nitric Acid at 20°C

TABLE VIII

EVIDENCE FOR COMPLEX FORMATION IN 1.0M NITRIC ACID:
COMPLEX FORMATION CONSTANTS AND RATE CONSTANTS
FOR COMPLEX DISPROPORTIONATION

Compound	Temp., °C	Complex Formation Constant, K, L/M[a] Spectrometric Data	Kinetic Data	Disproportionation Rate Constant k, min^{-1}	Reference
Allyl alcohol	22	--	2.78	--	(49)
n-Propanol	22	--	2.31	--	(49)
Isopropanol	22	--	2.07	--	(50)
Isopropanol[b]	25	--	1.62	0.002	(47)
Isopropanol	28	1.40	1.38	--	(50)
Sec-butanol	22	--	2.21	--	(50)
Sec-butanol[b]	25	--	2.5	0.02	(46)
Sec-butanol	28	1.81	1.84	--	(50)
Cyclohexanol[b]	25	--	6.63	0.067	(48)
Glucose	20	--	25.6	5.94	This work
Glucose[c]	20	--	39.4	14.04	(29,30)

[a] Apparent equilibrium constants.

[b] Actual acid concentration was 1.08M.

[c] 1.0M Perchloric acid.

It must be realized that the equilibrium constants reported in Table VIII obtained by kinetic or spectrometric methods are based on total cerium(IV) concentration, and therefore are actually apparent equilibrium constants which depend on the numerous equilibria and inorganic complexed cerium(IV) species which may be present. The value of this constant is thus an average of the reactivity of all these various cerium(IV) species for complex formation, with not only the C_1-C_2 glycol group (which leads to oxidation), but also with other glycol groups not leading directly to oxidation. Due to the possible complexity of the nitric acid system, therefore, no attempt was made to calculate true equilibrium constants, rather it is valid to compare apparent equilibrium constants for various reductants when the experimental conditions are the same.

The conclusion to be drawn from the equilibrium constants in Table VIII is that although the value for cerium(IV)-glucose complex formation in nitric acid (25.6) is significantly less than the value in perchloric acid (39.4), the nitric acid value is still an order of magnitude greater than reported literature values for cerium(IV) complexes in nitric acid with compounds containing only one hydroxyl group. This larger equilibrium value for glucose which contains a diol group indicates an increased stability for complex formation, which may be explained by chelation. Offner (51) attributed the observed increased stability of cerium(IV) complexes with 1,2- and 1,3-diols to the formation of chelate ring structures, as compared to monohydric alcohols or 1,4-diols which cannot form stable 5- and 6-membered rings. The lead tetraacetate (41,52) and periodate (41) oxidations of glucose which initially resemble the cerium(IV) oxidations in the cleavage of the C_1-C_2 diol to yield the intermediate formate ester of arabinose, are generally believed to involve chelate complexes.

It was not the objective of this thesis to investigate the aspect of chelation. It is realized that arguments exist (35,36) which limit the extent to which the magnitude of the equilibrium constant may be taken as evidence for chelation. The point to be made is that the relatively larger value for the glucose equilibrium constant suggests or at least indicates a possible chelate complex.

The lower value for the glucose equilibrium constant in nitric acid as compared to perchloric acid parallels the lower value of the pseudo-first-order rate constant (less reactive) in nitric acid. Offner consistently found the equilibrium constants for complex formation of a number of alcohols with cerium(IV) to be much smaller in nitric acid solutions than in perchloric acid solutions. Likewise, Sethuram and Muhammad (50) found the cerium(IV) complex formation constant for isopropanol to be lower in nitric acid than perchloric acid. These results demonstrate the reduced affinity of cerium(IV) for organic substrates due to competitive complexing with the nitric acid anion.

MECHANISM OF OXIDATION BY CERIUM(IV)

The product analyses showed that glucose is oxidized by cerium(IV) to produce arabinose and a small amount of erythrose. The erythrose was subsequently found to result from the competitive oxidation of the arabinose. The kinetics of this oxidation demonstrated that initially glucose and cerium(IV) interact in an equilibrium step to form an intermediate complex. This complex, as deduced from the magnitude of the equilibrium constant (Table VIII) and from the fact that only the C_1-C_2 glycol linkage is cleaved in these oxidations, could possibly be a chelate involving the C_1 and C_2 hydroxyls of the glucose molecule.

The second step of the oxidation involves electron transfer in which the intermediate complex disproportionates forming a carbonyl ester linkage at the original C_1 carbon, a free radical site at C_2, and cerium(III). This free radical is then further rapidly oxidized by a second mole of cerium(IV) to form the intermediate 4-O-formyl-D-arabinose, which hydrolyzes in the acidic reaction media yielding arabinose and formic acid. Although evidence was obtained for the intermediate formate ester of arabinose, as was mentioned previously, it is not possible to conclude that the entire reaction proceeds through this intermediate. Therefore, an alternative minor route which produces arabinose and formic acid directly (Fig. 1) cannot be entirely ruled out.

Figure 11 depicts the reaction mechanism described above which best explains the products and kinetics of glucose oxidation by cerium(IV) in perchloric acid (1.0M), and nitric acid (0.1 to 1.0M). This same general sequence can be assumed to occur with that portion of arabinose which is oxidized to erythrose. Furthermore, the mechanism for the oxidation of glucose is readily applicable to the cerium(IV) oxidation of cellobiose.

As discussed previously, the mechanism for the formation of arabinonic acid as a minor product in the cerium(IV) oxidation of glucose at nitric acid concentrations of 1.5 and 2.0M is as yet unknown.

There are two results from the kinetic experiments which remain to be explained. The first is the observed increase in the rate constant for the oxidation of glucose in perchloric acid as the ionic strength was increased, while the second is the decrease in the observed rate constant for glucose oxidation in nitric acid as the acidity was increased at constant ionic strength.

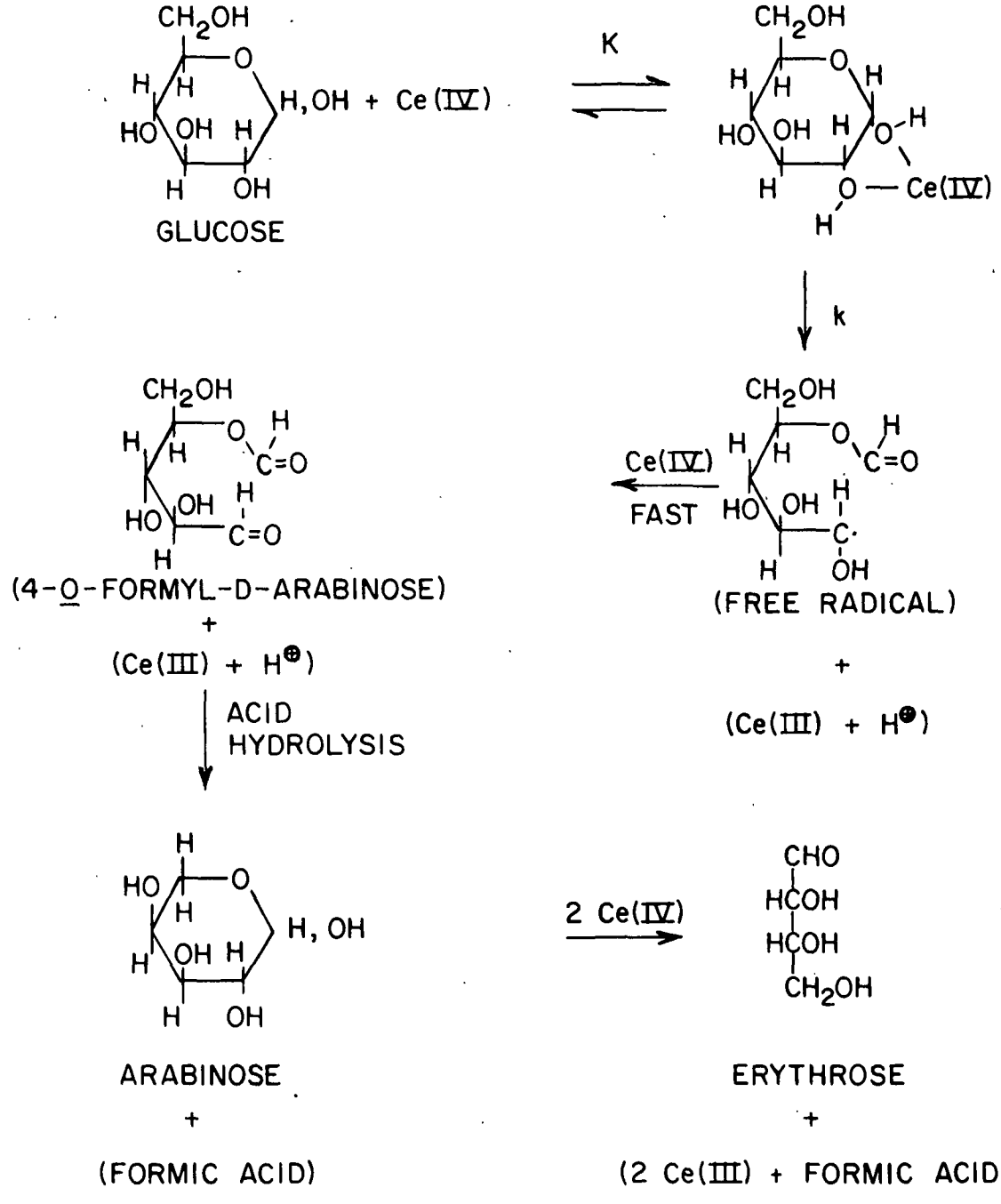


Figure 11. Mechanism of Glucose Oxidation by Cerium(IV) in Perchloric Acid (1.0M) and Nitric Acid (0.1 to 1.0M).

A possible explanation for the accelerating effect of perchlorate ions is that these ions influence the equilibria which exist involving cerium(IV) and nitrate, and/or hydroxyl ions [Equations (7) and (8)]. An increase in the concentration of perchlorate ions could favor the existence, or at least a higher

concentration of the more positively charged cerium(IV) species [equilibria of Equations (7) and (8) shifted to the left]. Since the more positively charged species are regarded as being more reactive, an increase in reactivity should parallel an increase in ionic strength.

A second possible explanation to account for the positive salt effect is that hydration of the perchlorate anions occur (53,54). As the perchlorate concentration increases a decrease in the activity of water results. The water affects the equilibrium constant because the reaction is in fact,

$$Ce(H_2O)_6^{+4} + \text{glucose} \rightleftharpoons Ce^{+4} - \text{glucose complex} + H_2O. \qquad (22)$$

A much higher concentration of the complex at high salt concentrations is, therefore, expected (55). This in turn leads to an increased rate of oxidation.

The decrease in the observed rate constant for the cerium(IV) oxidation of glucose with increase in nitric acid concentration at constant ionic strength is more difficult to explain. Additional work would be necessary to determine whether, and how, the individual constants, the equilibrium constant K, the disproportionation constant k, or both constants, are affected by the hydrogen ion concentration before this kinetic result can be more completely explained. As in the perchloric acid system, the equilibrium constant K should increase with acidity if hydrolysis equilibria were operative. Duke and Forist (56) concluded that the structures of the disproportionating complexes varied with the hydrogen ion concentration of the solution, and that these different complexes were responsible for the observed lowering of the rate constant as the nitric acid concentration was increased (0.2 to 0.5M) in the cerium(IV) oxidation of 2,3-butanediol. It appears that before a definite explanation can be given for the inhibitory effect of nitric acid, more fundamental knowledge must be known as to the specific equilibria which exist in the nitric acid system, regarding ceric ions, nitrate ions, hydroxide ions, and water molecules.

CONCLUSIONS

The cerium(IV) oxidation of glucose in 1.0M nitric acid at 20°C proceeds via an intermediate complex, possibly a chelate involving both the C_1 and C_2 hydroxyls, as indicated by the magnitude of the equilibrium constant determined by kinetic techniques. The oxidation is of first order with respect to cerium(IV).

Oxidation of excess glucose by cerium(IV) in 1.0M perchloric acid and 0.1 to 1.0M nitric acid at 20°C gives arabinose as the major product, and erythrose as a minor product. The erythrose results from the competitive oxidation of arabinose. The yield of erythrose increases as the initial molar excess of glucose is reduced. At higher nitric acid concentrations of 1.5 and 2.0M, arabinonic acid is also a minor product, and probably results from the oxidation of glucose directly. 4-O-Formyl-D-arabinose, which readily hydrolyzes to arabinose in the acidic reaction media, is an intermediate in the cerium(IV) oxidation of glucose to arabinose. This intermediate provides evidence that the oxidation proceeds through the cyclic form of the sugar, rather than the acyclic form.

The rate of cerium(IV) oxidation of glucose is much faster in perchloric than nitric acid. There is no significant difference in product yields for this oxidation in these two acid media.

The increase in the rate of the cerium(IV) oxidation of glucose in perchloric acid with an increase in hydrogen ion concentration is explained by the hydrogen ion preventing or retarding the formation of less reactive hydroxylated cerium(IV) species. More fundamental knowledge must be obtained as to the specific equilibria which exist in the nitric acid system, before the inhibitory effect of hydrogen ions on the glucose oxidation in nitric acid can be explained. Perchlorate anions have a positive salt effect, while nitrate ions have an inhibitory

effect on the cerium(IV) oxidation of glucose in nitric acid. This difference in reactivity is attributed to the fact that nitrate ions form stable complexes with cerium(IV), while the perchlorate ion does not complex with cerium(IV). Reactivity decreases, therefore, as the ability of the acid anion to form stable complexes with cerium(IV) increases.

The cerium(IV) oxidation of cellobiose in perchloric and nitric acid follows the same pattern as the glucose oxidations at comparable acid concentrations, yielding 3-O-(β-D-glucopyranosyl)-arabinose as the major product, and 2-O-(β-D-glucopyranosyl)-erythrose as a minor product. The yield of the major product from the cellobiose oxidation, however, is slightly greater (*ca.* 10%) than the yield of the major product arabinose from the oxidation of glucose, indicating a more selective oxidation of the cellobiose.

Since only the C_1-C_2 glycol unit is cleaved in the cerium(IV) oxidations, preferential attack of the reducing end group by the ceric ion is indicated.

EXPERIMENTAL

GENERAL METHODS

Melting points (m.p.) were determined on a Thomas-Hoover capillary apparatus which had been calibrated against known compounds.

Optical rotations were determined with a Perkin-Elmer 141 MC Polarimeter having a sensitivity of ±0.002°.

Nuclear magnetic resonance (NMR) spectra were determined on a Varian A-60A Spectrometer at normal probe temperature (40°C), unless otherwise specified. Sodium 2,2-dimethyl-2-silapentane-5-sulfonate was employed as the reference standard. Infrared spectra (IR) were determined on a Perkin-Elmer Model 700 spectrophotometer.

Gas-liquid chromatography (GLC) was performed on a Varian Aerograph 1200-1 gas chromatograph equipped with a hydrogen flame ionization detector (57). Chromatograms were recorded on a Honeywell Electronik 16 recorder equipped with a disk integrator. Prepurified nitrogen (Matheson Gas Products) was used as the carrier gas. Two columns, both 5% SE-30 on 60/80 mesh chromosorb W (1/8 inch by 5 ft and 1/8 inch by 10 ft, ss) were used for all analyses. The operating conditions varied depending on the system being analyzed and are given in the product analysis section.

Spectrometric absorbance (A) measurements were made on a Cary Model 15 recording spectrophotometer.

Qualitative descending paper chromatography was done using ethyl acetate: pyridine:water (8:2:1, v/v) as the developing solvents, and silver nitrate-sodium hydroxide-sodium thiosulfate as detection reagents (58).

SOLUTIONS AND REAGENTS

WATER

Ordinary distilled water was redistilled from alkaline potassium permanganate and dilute sulfuric acid (59) for use in the preparation of all solutions, analytical work, and kinetic studies.

ACID SOLUTIONS

Stock solutions (2.0M) of nitric and perchloric acid were prepared by appropriate dilution of the commercial reagent grade (70%) acid. These stock solutions were standardized with a sodium hydroxide solution which had been standardized with primary standard potassium acid phthalate. Deuterated nitric acid solutions (2.0M) were prepared by the addition of commercial reagent grade (70%) nitric acid (130 µl) to deuterium oxide (1 ml).

CERIUM(IV) STOCK SOLUTIONS

Stock solutions of 0.05M cerium(IV) in the appropriate nitric acid concentration (0.20 to 2.0M) were prepared by dissolving ceric ammonium nitrate (55 g, certified, obtained from G. Frederick Smith Chemical Co.) in the required amount of stock nitric acid solution (2.0M) and triply distilled water (final volume 2 liters) to give the desired acid concentration. For NMR work, cerium(IV) solutions were prepared by dissolving CAN (1.2 g) in deuterium oxide (2 ml) and nitric acid (0.25 ml, 70%).

Stock solutions of 0.05M cerium(IV) in 1.0M and 2.0M perchloric acid were prepared by appropriate dilution of a commercial ceric perchlorate solution purchased from G. Frederick Smith Chemical Co. [0.5N cerium(IV) in 6N perchloric acid].

The cerium(IV) concentrations were determined by titration of weighed samples of primary standard arsenic trioxide using osmium tetroxide as a catalyst and 1,10(ortho)-phenanthroline as the indicator (60). The acid concentrations were determined by the procedure of Offner (51).

SOURCE, PREPARATION, AND PURIFICATION OF COMPOUNDS

D-GLUCOSE

Anhydrous dextrose (Mallinckrodt Chemical Works, analytical reagent) was used without further purification. Paper and gas-liquid chromatography of this material showed no detectable impurities. The melting point was 145.5-146°C, $[\alpha]_D^{25}$ + 53.4° (c 1.43, water) [Lit. m.p. 146°C, $[\alpha]_D^{20}$ + 52.5° (water) (61)].

D-ARABINOSE

D-Arabinose was obtained from Matheson, Coleman, and Bell Company, and used without further purification. Paper and gas-liquid chromatography showed the compound to be pure. The melting point was 159-160°C, $[\alpha]_D^{25}$ - 103.5° (c 1.34, water) [Lit. m.p. 160°C, $[\alpha]_D^{25}$ - 104.5° (c 1.0, water) (62)].

meso-ERYTHRITOL

This compound was purchased from Pfanstiehl Laboratories, Inc. The melting point was 118-120°C [Lit. m.p. 120°C (63)].

CELLOBIOSE

The cellobiose sample employed in this work had been purchased from Pfanstiehl and purified by MacLaurin (64). This sample was further purified for use in this thesis by the method of Braun (65). GLC analysis then showed no significant impurity. The melting point was 228-230°C, $[\alpha]_D^{25}$ + 35.0° (c 0.91, water) [Lit. m.p. 225°, $[\alpha]_D^{20}$ + 14.2°→+ 34.6° (c 8, water) (66)].

CYCLOHEXYL β-D-GLUCOPYRANOSIDE (CHG)

This compound was prepared by the deacetylation of cyclohexyl 2,3,4,6-tetra-O-acetyl-β-D-glucopyranoside (17.7 g) with sodium methoxide in dry methanol (67). The crystalline material was purified by three recrystallizations from hot ethyl acetate to yield 7.2 g (ca. 70%) of the cyclohexyl β-D-glucoside. The melting point was 132.5-134.5°C, $[\alpha]_D^{25}$ - 41.0° (c 1.12, water) [Lit. m.p. 133-137°C, $[\alpha]_D^{20}$ - 41.43° (water) (68)].

The cyclohexyl 2,3,4,6-tetra-O-acetyl-β-D-glucopyranoside was obtained by the method of Schroeder and Green (69).

METHYL β-D-GLUCOPYRANOSIDE (MG)

This compound was also obtained from Pfanstiehl Laboratories, Inc. It was purified by dissolving in sodium hydroxide (1N) and heating under reflux (1 hr). The solution was then deionized with IR-120 ion-exchange resin, concentrated to a small volume, and passed through an MB-3 ion-exchange resin column. The sample was then concentrated to dryness and recrystallized twice from absolute ethanol. The purity of this compound was verified by GLC analysis. The compound had a sharp melting point at 111-112°C, $[\alpha]_D^{21}$ - 33.7° (c 2.0, water) [Lit. m.p. 109-111°C, $[\alpha]_D^{20}$ - 32.5° (c 1.0, water) (70)].

1,5-ANHYDRO-XYLITOL

This compound was obtained by deacetylation of the acetate derivative with sodium methoxide in dry methanol (67). The triacetate derivative was obtained by the procedure of Fletcher and Hudson (71). The 1,5-anhydro-xylitol was recrystallized from hot absolute ethanol. The melting point was 113-114°C [Lit. m.p. 116-117°C (71)].

ETHYLENE GLYCOL AND GLYCEROL

These compounds were obtained from Mallinckrodt Chemical Works.

GLYOXAL

A 30% aqueous solution of this compound was obtained from Matheson, Coleman, and Bell Company.

DL-GLYCERALDEHYDE

This compound was obtained from K & K Laboratories.

ERYTHRONIC, ARABINONIC, AND GLUCONIC ACID

Samples of these compounds were obtained from Dr. Green (72). The arabinonic and gluconic acids were in the form of potassium and sodium salts, respectively. The free acids were obtained by treatment with IR-120 ion-exchange resin.

ERYTHRONIC AND D-GLUCONO-1,5-(δ)-LACTONE

Samples of these lactones were also obtained from Dr. Green (72). The melting point of the δ-glucono lactone was 152-156°C. Recrystallization from water and 2-methoxyethanol (73) resulted in a sharper melting point of 151-153°C [Lit. m.p. 150-152°C (73)].

D-GLUCONO-1,4-(α)-LACTONE

This compound was obtained as a syrup by concentrating the D-glucono-1,5-(δ)-lactone from hydrochloric acid (6N) followed by heating under vacuum at 100°C for a short period (74).

CALCIUM CELLOBIONATE

This compound was purchased from the Nutritional Biochemicals Corporation.

CELLOBIONIC ACID

Cellobionic acid was obtained by deionization of the calcium salt with IRC-50 ion-exchange resin.

1,2:5,6-DI-O-ISOPROPYLIDENE-α-D-GLUCOFURANOSE

This compound was prepared by the procedure of MacLeod (75). Powdered anhydrous glucose (123.5 g), anhydrous cupric sulfate (275 g), and dry acetone (3 liters) were placed in an Erlenmeyer flask (4 liters). After mixing, concentrated sulfuric acid (13 ml) was added. The flask was stoppered tightly and stirred vigorously for 21 hours. The result was a two-layered system: the lower being a powder green and the top an oily brown. The remaining cupric sulfate was filtered off and washed with acetone (500 ml). Powdered calcium hydroxide (125 g) was stirred with the filtrate until neutral (pH 6.0). The solution was filtered twice and concentrated *in vacuo*. A white crystalline material (*ca.* 180 g) remained, which was recrystallized from low boiling petroleum ether:acetone (800:200 ml). The final crystalline material isolated (*ca.* 50 g) was shown to be pure by TLC analysis (acetone-*n*-hexane, 4:1, v/v). The melting point was 109.5°C, $[\alpha]_D^{25}$ - 18° (*c* 1.0, water) [Lit. m.p. 110°C, $[\alpha]_D^{24}$ - 18.5° (*c* 5, water) (76)].

1,2:5,6-DI-O-ISOPROPYLIDENE-3-O-BENZYL-α-D-GLUCOFURANOSE

This compound was prepared according to the procedure found in Methods in Carbohydrate Chemistry, Vol. VI (77). The 1,2:5,6-di-O-isopropylidene-α-D-glucofuranose (0.102 mole) was dissolved in dimethyl formamide (300 ml) in a

1 liter flask. Benzyl bromide (48 ml, 0.410 mole) was then added with stirring. Freshly prepared silver oxide (100 g) was added slowly over a period of 1 hr with constant stirring. The flask was covered with aluminum foil and allowed to stand overnight at room temperature. The reaction solution was analyzed by TLC using chloroform-ether (9:1, v/v). There was no evidence of starting material remaining after 12 hours. The mixture was then filtered to remove most of the solid silver oxide, which was washed with DMF (250 ml) and chloroform (250 ml). A 1% solution of potassium cyanide (15 g/1500 ml) was then added to the combined filtrate and washings. The solution was then extracted with chloroform (4 × 250 ml), the combined extracts washed with water (3 × 1000 ml), dried over anhydrous sodium sulfate, filtered, and concentrated *in vacuo*. The excess benzyl bromide was removed by high vacuum distillation. The crude yellow sirup (47 g) remaining was used directly in the following hydrolysis.

3-*O*-BENZYL-D-GLUCOPYRANOSE

The 1,2:5,6-di-*O*-isopropylidene-3-*O*-benzyl-α-D-glucofuranose (47 g sirup) was hydrolyzed with IR-120 ion-exchange resin (50 ml in 150 ml water). The solution was stirred continuously, and the hydrolysis of the isopropylidene groups followed by TLC using chloroform-methanol (10:1, v/v). After complete hydrolysis (4 days) the resin was filtered and washed with water. The combined washings were extracted with chloroform to remove any organic soluble material. Concentration of the water washings yielded a white crystalline material, which was recrystallized from hot 95% ethanol (50 ml). The yield was 6.5 g, melting point 127-128°C, $[\alpha]_D^{25}$ + 40.1° (*c* 0.81, water) [Lit. m.p. 127-128°C, $[\alpha]_D^{25}$ + 16.1→+ 41.8° (water) (*78*)].

4-O-FORMYL-2-O-BENZYL-D-ARABINOPYRANOSE

The procedure of Perlin and Mackie (79) for the periodate oxidation of 3-O-methyl-D-glucopyranose was employed to obtain the desired benzyl formate ester of arabinose from 3-O-benzyl-D-glucopyranose. Sodium metaperiodate (4.0 mM) was added with constant stirring to an aqueous solution (75 ml) of 3-O-benzyl-D-glucopyranose (3.7 mM). TLC using chloroform-methanol (9:1, v/v) showed no evidence of starting material remaining after 24 hours. The oxidation sample was then concentrated to dryness. The residue was extracted with ethyl acetate (3 × 75 ml), the extract filtered, concentrated (ca. 100 ml), and used directly in the following reduction step.

4-O-FORMYL-D-ARABINOPYRANOSE

The solution (ca. 100 ml) of 4-O-formyl-2-O-benzyl-D-arabinopyranose in ethyl acetate was placed in a Parr Bomb along with the catalyst, 10% palladium on carbon (750 mg). The catalyst had been freshly prepared using the procedure of Mozingo (80). The Parr Bomb was then connected to a hydrogen cylinder, and a pressure of 4 psig was maintained, along with vigorous stirring. TLC using chloroform-methanol (9:1, v/v) showed complete removal of the benzyl group after three days.

The contents of the bomb were then filtered twice, the second time with Celite filter aid. The filtrate was concentrated to dryness, extracted with ethyl acetate, and the extract again concentrated to dryness. The crude syrup was dissolved in water, filtered, concentrated to dryness, and dried in a vacuum oven (50°C). The yield was 400 mg (60%).

Characterization

A positive color test was obtained with this compound using ferric hydroxamate solution. A UV absorption maximum was found at 231 nm, while the IR had a strong carbonyl band at 1715-1720 cm^{-1}. The NMR spectrum showed the formyl proton peak ($\underline{H}\overset{O}{\overset{\|}{C}}$-O-) at δ8.27 ppm, the H_1^{β} signal at δ5.25 ppm, and the H_4 ($H\overset{O}{\overset{\|}{C}}OC$-$\underline{H}$) signal at δ5.00 ppm. The sirup had the following physical constants: $[\alpha]_D^{25}$ - 89.9° (c 0.96, water); C, 39.8; H, 6.1 [$C_6H_{10}O_6$ requires C, 40.4; H, 5.6%].

Attempts to make the alditol acetate derivative were unsuccessful, as the formate group was lost during the sodium borohydride reduction step. Analysis by GLC was made, however, employing TMS derivatives. Such analysis showed the presence of 4 to 5 significant peaks, none of which corresponded to the arabinose peaks (Table X, Appendix I).

The acid hydrolysis of the formate group was studied using NMR. A deuterated nitric acid (2.0M) solution (0.5 ml) was added to a sample of the 4-O-formyl-D-arabinopyranose (100 mg) in deuterium oxide (0.5 ml). The region of the formyl peaks (δ8.0 to 8.75 ppm) was then scanned repeatedly with time.

PRODUCT ANALYSIS PROCEDURES

CERIUM(IV) OXIDATIONS FOR PRODUCT ANALYSIS

Glucose

All cerium(IV) oxidations of glucose were conducted in a constant temperature water bath at 20°C ± 0.05°C. With one exception, a 2:1 molar excess of glucose:ceric ion was used. All reactant solutions were purged with prepurified nitrogen for 30 minutes prior to use to prevent possible interference from dissolved oxygen.

A typical cerium(IV) oxidation of glucose in nitric acid (0.1 to 2.0M) was conducted in the following manner. An aqueous solution (25 ml) of glucose (2.50 mM) was pipeted into a 100-ml flask. An equal volume (25 ml) of the 0.05M CAN (1.250 mM) stock solution in nitric acid 0.2 to 4.0M was placed in a second 100-ml flask. After nitrogen purging, the two flasks were connected with an adapter and placed in the constant temperature bath (20°C). After equilibrating (2 hr) the ceric ion-acid solution was rapidly poured into the aqueous glucose solution with the entire apparatus remaining submerged. The oxidation solution was then poured back and forth between the two flasks several times to ensure a uniform mixture. When the oxidation was completed, as evidenced by the disappearance of the reddish-brown color of the cerium(IV)-glucose solution, the reaction apparatus was removed from the water bath, and the oxidation solution analyzed as described in the following sections.

Modifications made in the above procedure include the use of ceric perchlorate and perchloric acid in place of CAN and nitric acid, the use of a 1:1 molar ratio of glucose (1.250 mM):ceric ion (1.250 mM), and the use of an ammonium nitrate solution (25 ml, 2.0M) in which glucose (2.50 mM) was dissolved prior to oxidation with CAN (1.250 mM) to study ionic strength effects. For some of the oxidations, the reaction flasks were painted black, and the oxidations conducted in a dark room, to observe the effect of light on the cerium(IV) oxidations.

For NMR investigations, glucose (1.1 mM) in deuterium oxide (0.5 ml) was placed in the NMR tube. CAN (0.55 mM) in deuterated nitric acid (0.5 ml, 2.0M) was then added to the NMR tube, and the spectrum of the formyl proton region (δ8.1 to 8.5 ppm) was then scanned repeatedly (Fig. 4).

Cellobiose

The cerium(IV) oxidations of cellobiose were conducted in a manner similar to the oxidations of glucose, the only difference being the actual amounts of reactants involved. For a typical oxidation, cellobiose (1.0 mM) was dissolved in triply distilled water (10 ml) in a 50-ml flask. In a second 50-ml flask was placed an equal volume (10 ml) of the desired cerium(IV) salt (0.5 mM) in nitric (or perchloric) acid (1.0 or 2.0M). These cerium(IV) oxidations of cellobiose were also conducted in an ice bath to study the effect of temperature (0°C).

WORK-UP PROCEDURES

Glucose

For quantitative product analysis, three 5-ml aliquot samples (ca. 45 mg, 0.250 mM) were taken from the cerium(IV) glucose oxidation solution (50 ml total volume) and worked up for GLC analysis. These 5-ml samples were neutralized in beakers (100 ml) with Amberlite IRA-400 ($HCO_3^{\ominus}$) ion-exchange resin (15 ml). With continued stirring, neutralization was complete in 15 min, as evidenced by cessation of gas evolution, precipitation of cerous hydroxide, and a final pH of 5.5.

At this point in the procedure, the addition of the internal standard, CHG (5 ml, 0.0750 mM) was made to the neutralized oxidation mixture in the beaker. The entire mixture was then passed through a column (10 by 500 mm) containing a bed (10 ml) of the same resin. The column was eluted with water (75 ml), and the effluent containing the carbohydrates was then concentrated to a small volume (30 ml). The resin retained most of the precipitated cerous hydroxide. The presence of cerous ion (by conducting blank oxidations with cerous ammonium nitrate) was shown to have no effect on the oxidation, work-up procedure, or quantitative results obtained.

The conversion of IRA-400 ion-exchange resin to the bicarbonate form was accomplished by eluting a column containing a bed of the purchased commercial resin ($Cl^{\ominus}$ form) with a saturated (ca. 0.6M) sodium bicarbonate solution.

A modification of the alditol acetate method (81) was used to derivatize the sugars present to make possible their analysis by GLC. Sodium borohydride (200 mg) was added to the concentrated oxidation sample (ca. 30 ml) in a beaker (100 ml). The solution was stirred briefly with a magnetic stirrer, covered with a watch glass, and allowed to stand overnight (minimum time 2 hr).

After standing for the desired time, small quantities (10 ml total) of washed IR-120 ion-exchange resin were added to the solution with stirring until hydrogen evolution ceased and the final pH was about 4.0. The solution was then filtered, the resin washed with water (50 ml), and the entire filtrate concentrated to dryness (60°C). The white bulky residue was reconcentrated to dryness twice from methanol (100 ml) to yield a colorless sirup. This sirup was redissolved in water (50 ml) and passed through a column (20 by 500 mm) containing MB-3 ion-exchange resin (25 ml). The column was then eluted with water (75 ml), and the effluent containing the reduced sugars (alditols) was concentrated to a small volume (20 ml), transferred to a 50-ml flask and concentrated to dryness. The contents of the flask were reconcentrated from absolute ethanol (25 ml), dried in a vacuum oven (100°C for 15 min), and cooled to room temperature.

A slight addition was made to the above procedure for the cerium(IV) oxidations involving a high nitrate ion concentration. Samples from these oxidations were batch treated with IR-120 ion-exchange resin (5 ml for 5 min with stirring) to bring the pH down to 4.5 prior to the sodium borohydride reduction step. This step was necessary to remove the nitrate ions which were shown to interfere with subsequent steps in the work-up procedure.

The dried residue in the flasks was acetylated by adding a mixture of pyridine (6 ml) and acetic anhydride (5 ml), and shaking for 15 hr at room temperature. At the end of 15 hr, ice water (40 ml) was added to the acetylation solution, and the mixture stirred until the ice melted. This entire solution was then extracted with chloroform (3 × 20 ml), and the combined extracts washed successively with 1N hydrochloric acid (2 × 60 ml), distilled water (60 ml), saturated sodium bicarbonate (2 × 60 ml), and distilled water (2 × 60 ml). The chloroform extract was dried with sodium sulfate, filtered, and the filtrate concentrated to dryness. The dried extract was then redissolved in chloroform (5 ml) for GLC analysis.

The work-up procedure for qualitative product analysis with paper chromatography and gas chromatography employing TMS derivatives (74) was much simpler. In the case of paper chromatography, the samples were ready for analysis following appropriate concentration (ca. 1% solution) after the initial neutralization step with IRA-400 ($HCO_3^{\ominus}$) ion-exchange resin.

The preparation for TMS derivatization involved taking 0.5-ml samples (4.5 mg) of the cerium(IV)-glucose oxidation solution. Two different methods were employed to neutralize these acidic (1.0M) samples. Initially, a batch neutralization with IRA-400 ($HCO_3^{\ominus}$) ion-exchange resin was performed; however, to prevent possible loss of acidic carbohydrate material by this resin treatment, subsequent samples were neutralized with ammonium hydroxide (ca. 1.0M).

The neutralization step was followed by an IR-120 ion-exchange resin treatment to give a slightly acidic condition. After concentration to dryness (10-ml Erlenmeyer flasks), the samples were silylated with TRI-SIL (1 ml), and the flasks shaken for 2 hours. Toluene (1 ml) was then added to the samples,

and the pyridine present removed on a rotary evaporator. The TMS derivatives were then dissolved in hexane (0.5 ml) and analyzed by GLC.

Cellobiose

Quantitative product analysis of the cerium(IV)-cellobiose oxidations was made in two parts. First, analysis of the disaccharide system was made by taking triplicate 2-ml samples (ca. 34 mg) from the oxidation samples and using the same alditol acetate work-up procedure as described for glucose. In place of CHG, however, MG (0.085 mM) was added as an internal standard.

The second part of the quantitative analysis procedure also involved taking triplicate 2-ml samples of the oxidation solution. The neutralization was identical to that employed previously; however, 1,5-anhydro-xylitol (0.033 mM) was added as the internal standard before the neutralization step. These disaccharide samples were then hydrolyzed by treatment with hydrochloric acid (5 ml, 0.75N) under reflux on a steam bath for 12 hours. The remainder of the work-up procedure for these samples was then the same as that described for the glucose samples, beginning with the initial neutralization step.

Samples (0.5 ml, ca. 8.5 mg) of the cellobiose oxidation mixture were taken for qualitative analysis employing the TMS derivatives of the disaccharides. The work-up procedures for these samples was the same as that described in the glucose section. Analyses of the products from the oxidation of cellobiose were also made by taking 0.5-ml samples of the oxidation, subjecting them to the acid hydrolysis procedure described above, and then working them up for analysis as TMS derivatives also using the same procedure described for the glucose system.

DETERMINATION OF REACTION PRODUCTS

All quantitative product analysis for both the glucose and cellobiose systems was done by GLC employing the alditol acetate derivatives. Qualitative work on the glucose system was done with paper chromatography and GLC (TMS derivatives), while qualitative work on the cellobiose system involved only GLC using TMS derivatives. Product identification in all the work was based on comparing retention times with those of known compounds. Retention times of known compounds used as references are given in Tables IX to XIII, Appendix I.

GLC CONDITIONS

The columns employed for GLC were specified in the General Methods section. The 5-ft column was used when analyzing alditol acetate derivatives, and the disaccharide TMS derivatives, while the 10-ft column was used to analyze the monosaccharide TMS derivatives. The actual GLC conditions varied depending upon the system under investigation. The conditions employed for analyzing the glucose oxidation system with alditol acetate derivatives were (see Table IX, Appendix I, for retention times and response factors):

Column temperature: P.R. 120-250°C at 6°C/min
Injector temperature: 255°C
Detector temperature: 270°C
Nitrogen flow rate: 40 ml/min
Hydrogen pressure: 9.5 psig

A typical chromatogram for this system (Fig. 12) shows the peaks for the unreacted glucose(c), the major product arabinose (b), the minor product erythrose (a), and the internal standard CHG (d), all as alditol acetate derivatives.

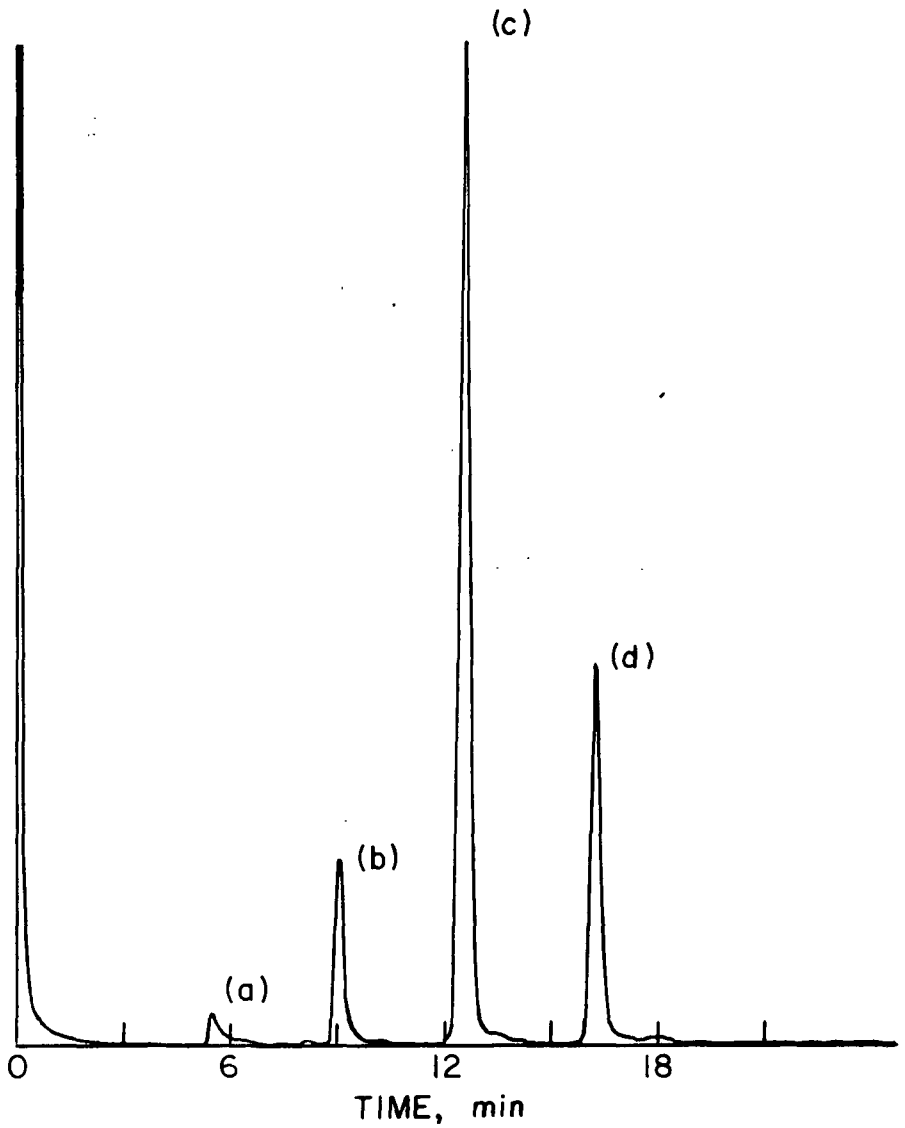


Figure 12. Sample Chromatogram of the Carbohydrate Product System from the CAN Oxidation of Glucose in 1.0M Nitric Acid, Showing Peaks for (a) Erythrose, ($\bar{b}$) Arabinose, (c) Glucose, and (d) CHG, All as Alditol Acetate Derivatives

The conditions for analyzing the glucose system employing TMS derivatives were (retention times given in Table X, Appendix I):

Column temperature: 185°C isothermal
Injector temperature: 220°C
Detector temperature: 300°C
Nitrogen flow rate: 11 ml/min
Hydrogen pressure: 7.5 psig

When analyzing the cellobiose system as disaccharide alditol acetate derivatives, the conditions employed were (retention times and response factors in Table XI, Appendix I):

Column temperature: P.R. 170-305°C at 6°C/min
Injector temperature: 290°C
Detector temperature: 320°C
Nitrogen flow rate: 23 ml/min
Hydrogen pressure: 8.5 psig,

while the conditions for the acid hydrolysis samples from the cellobiose oxidation as alditol acetates were (retention times and response factors given in Table XII, Appendix I):

Column temperature: P.R. 120-250°C at 6°C/min
Detector temperature: 270°C
Injector temperature: 250°C
Nitrogen flow rate: 15 ml/min
Hydrogen pressure: 9.5 psig

The chromatogram in Fig. 13 shows the peaks of the disaccharide system, cellobiose (e), glucosyl arabinose (d), and glucosyl erythrose (c), as alditol acetate derivatives; and the internal standard MG (a) as the acetate derivative. The chromatogram in Fig. 14 shows the cellobiose system after acid hydrolysis of the disaccharides. This chromatogram is comparable with that of Fig. 12, with the exception of the internal standard, 1,5-anhydro-xylitol for the acid hydrolysis analysis.

GLC conditions for the cellobiose system with TMS derivatives of the disaccharides were (retention times, Table XIII, Appendix I):

Column temperature: 230°C isothermal
Detector temperature: 275°C

Injector temperature: 250°C
Nitrogen flow rate: 19 ml/min
Hydrogen pressure: 8.0 psig

For the acid hydrolysis samples of the cellobiose system using TMS derivatives, the GLC conditions were the same as those employed for the glucose system.

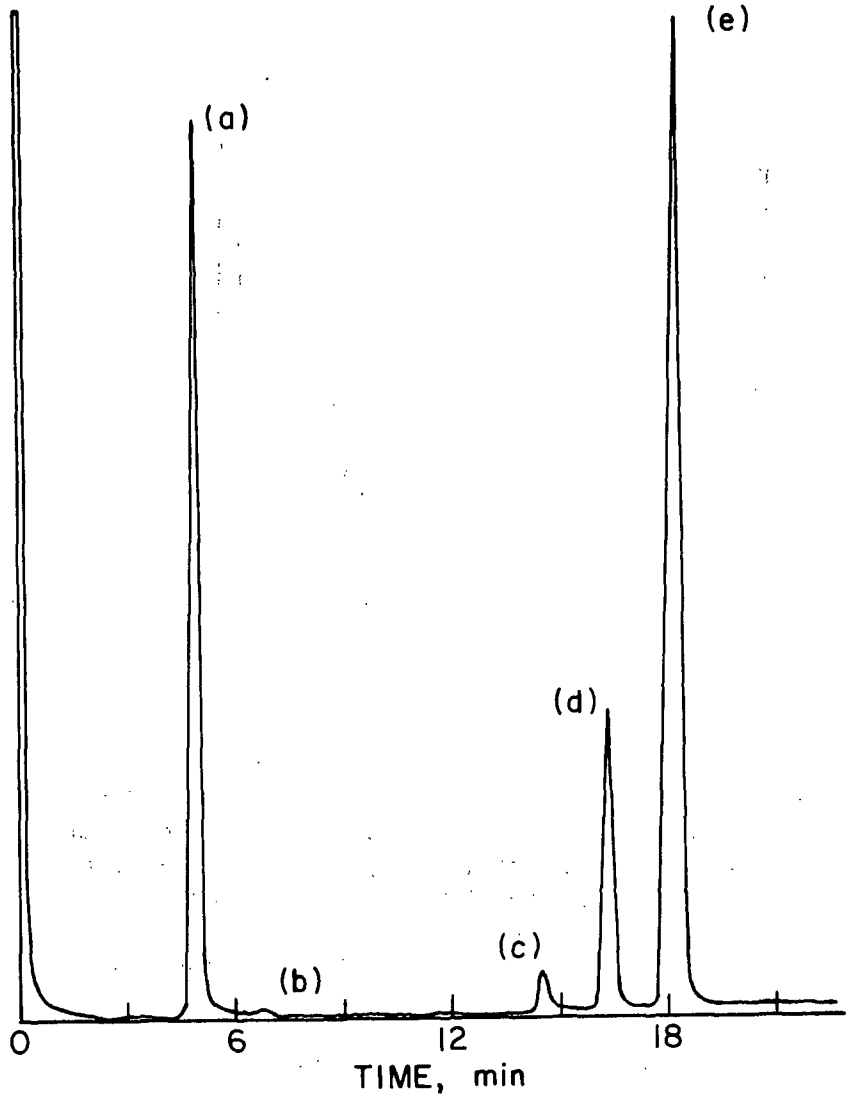


Figure 13. Gas Chromatogram of the Carbohydrate Product System from the CAN Oxidation of Cellobiose in 1.0M Nitric Acid, Showing Peaks for (a) Internal Standard, MG, (b) Glucose, (c) GE, (d) GA, and (e) Cellobiose, All as Alditol Acetate Derivatives

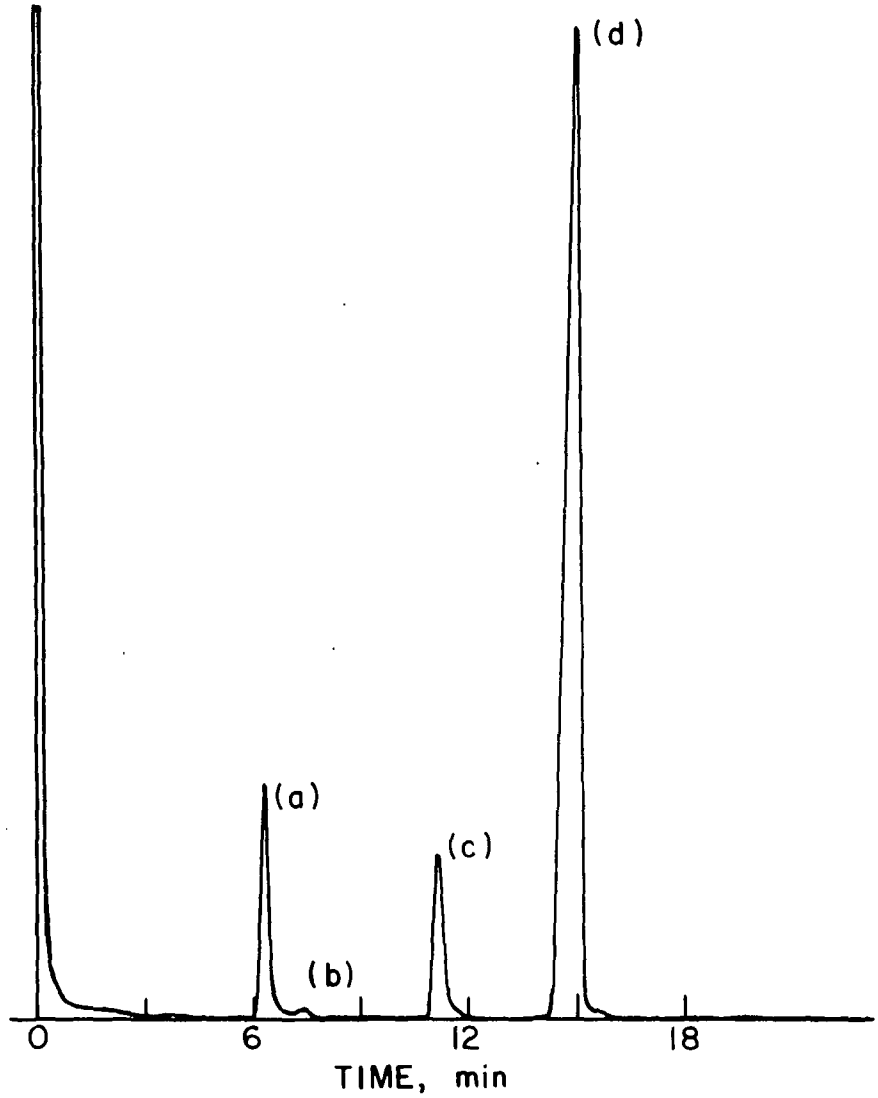


Figure 14. Gas Chromatogram of the Carbohydrate Product System from the CAN Oxidation of Cellobiose in 1.0M Nitric Acid After Acid Hydrolysis of the Disaccharides, Showing Peaks for (a) Internal Standard, 1,5-Anhydro-Xylitol, (b) Erythrose, (c) Arabinose, and (d) Glucose, All as Alditol Acetate Derivatives

DETERMINATION OF RESPONSE FACTORS AND MASS BALANCES

Known synthetic mixtures consisting of the products and reactants in the relative proportions found in the actual cerium(IV) oxidations, plus internal standard were prepared, subjected to the entire alditol acetate work-up procedure for quantitative analysis described above, and analyzed by GLC. The areas of the peaks for these compounds on the chromatograms after GLC analysis were

calculated from the tracings of the disk integrator after correcting for base-line drift. From the area values, the response factors for the given compound relative to the internal standard were calculated. These response factors, and formula for calculation are given in Tables IX, XI, and XII, Appendix I.

Quantitative data, the amount of substrate remaining and product formed, for the cerium(IV) oxidation of glucose and cellobiose, was determined from the GLC results with the use of the above response factors and Equation (23).

$$M_x = f_{s/x} \cdot M_s \cdot (\text{Area } x/\text{Area Standard}) \qquad (23)$$

where M_x = moles of substrate or product in sample

$f_{s/x}$ = response factor for substrate or product x relative to the internal standard, s

M_s = moles of internal standard in sample

Area x = area of the component x peak

Area Standard = area of the internal standard peak in arbitrary units.

Complete mass balances for these oxidations were obtained knowing the initial amounts of substrate and ceric ion present, and assuming,

1. All of the ceric ion was consumed.
2. Two moles of ceric ion are consumed by each mole of reactant.
3. The yield of the minor product (erythrose or GE) was the difference between the amount of substrate (glucose or cellobiose) consumed and major product (arabinose or GA) formed. This assumption was necessary because of the small chromatogram area values obtained for this product from GLC analysis, making accurate calculations difficult.

The quantitative data (Tables XIV and XV, Appendix II) reported for each oxidation represents the average of three separate analyses (samples) made on that oxidation. In addition, at least four GLC analyses (injections) were made on each sample.

In the oxidations of cellobiose, the amount of substrate reacted was determined from analysis of the disaccharide system, while the yield of the major product (GA) was determined from the yield of arabinose, after acid hydrolysis of the disaccharide. This type of analysis was necessary as the compound GA was not readily available for determination of response factors. The data for the cellobiose oxidations at 0°C, however, was determined directly from a disaccharide analysis employing an indirect calculated response factor for GA (Table XI, Appendix I).

KINETIC MEASUREMENTS

The Cary Model 15 recording spectrophotometer was used in studying the kinetics of the cerium(IV) oxidation of glucose. All kinetic experiments were conducted with glucose in a large molar excess over cerium(IV) so that the reactions would be pseudo-first-order. Under these conditions, the possibility of complications due to secondary oxidation of primary products was reduced. Furthermore, the participation of an intermediate complex and the corresponding equilibrium constant for formation were determined by varying the excess of glucose.

TEMPERATURE CONTROL

The reaction temperature was controlled by the use of a thermostatted water bath (20°C ± 0.05°C), and was monitored by the use of a pair of calibrated thermometers. The temperature of the reaction mixture was maintained

by circulating water from the constant-temperature bath through a special cell holder (Cary No. 1540750) and through the walls of the cell compartment of the Cary spectrophotometer. In addition, all kinetic work was performed in a constant temperature-humidity room.

CALIBRATION OF SPECTROPHOTOMETER

Hintz (31,32) and Ardon (55) demonstrated that cerium(IV) reaction rates determined titrimetrically agreed with the rates determined spectrometrically. The spectrometric method of rate determination is based on the fact that the absorbance of cerium(IV) solutions is directly proportional to the cerium(IV) concentration. Solutions of known cerium(IV) concentrations were prepared by successive dilutions of the cerium(IV) stock solution (0.05N). The absorbance of these solutions, measured at a constant wavelength (425 nm), demonstrated that spectrometric absorbance is a linear function of the cerium(IV) concentration range to be used in this work (Fig. 15; Table XXII, Appendix III).

SPECTROMETRIC RATE DETERMINATIONS

The direct injection technique developed by Pottenger (29,30) in which the reactants are mixed within the spectrophotometer cell, was employed to experimentally determine the pseudo-first-order rate constants. As in the oxidations for product analysis, all reactant solutions were purged with prepurified nitrogen for 30 minutes prior to use. All reactant solutions were maintained at reaction temperature by means of the constant temperature bath.

A typical kinetic run was conducted in the following manner. The required amount of 0.05M cerium(IV) (normally 0.12 ml) in the desired acid (nitric or perchloric) concentration was placed in the spectrophotometer cell.

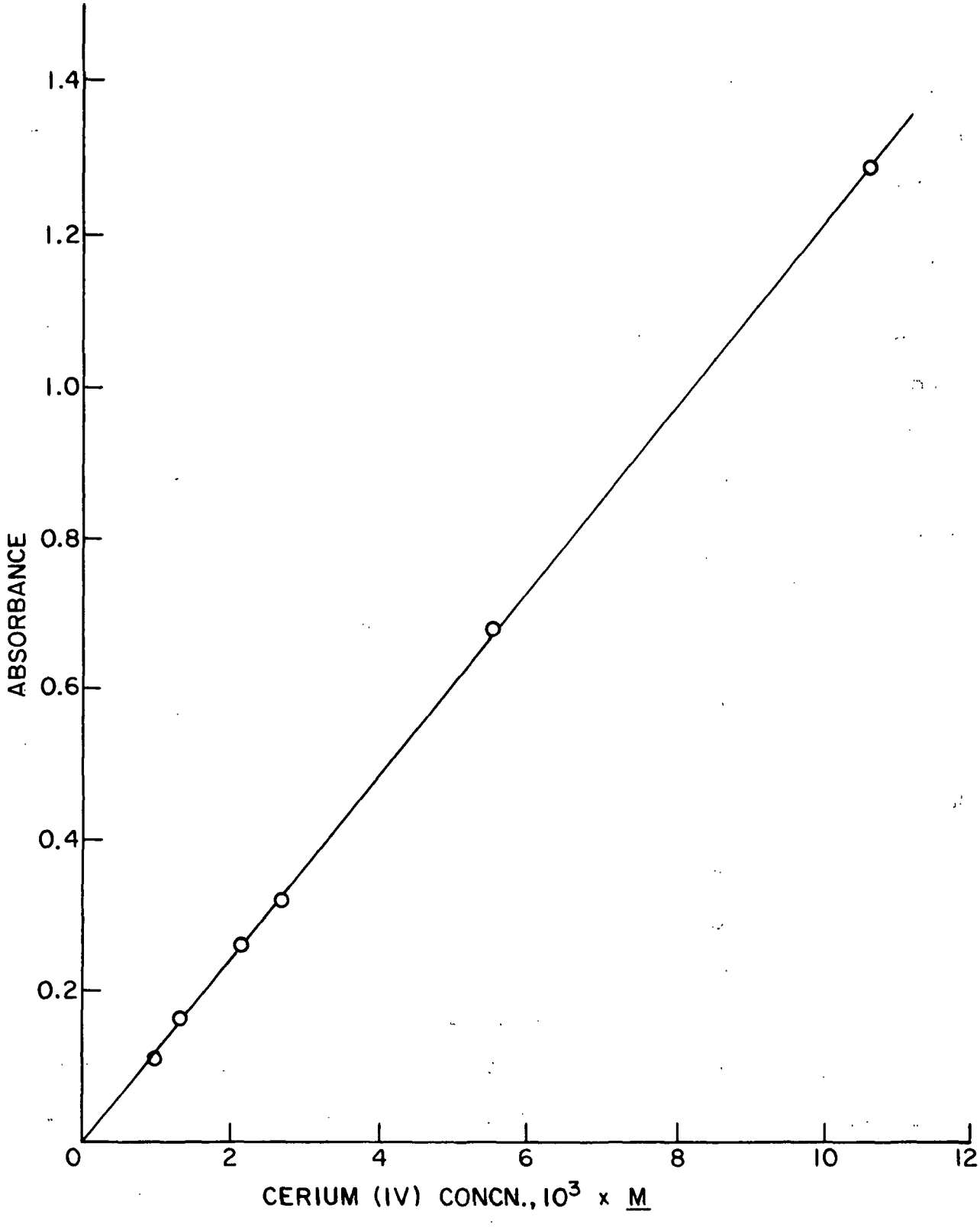


Figure 15. Absorbance Versus Concentration of Cerium(IV) in 1.0M Nitric Acid, Measured at 425 nm and 20°C

A capillary glass tube (1.5 mm inside diameter), bent as shown in Fig. 16, was then placed in the spectrophotometer cell in the cell holder. A syringe (5-ml volume), filled with the desired amount (2.9 ml) of glucose-acid solution, plus an amount equal to the volume of the connecting tubing (Technicon, Acid flex), was connected to the glass capillary via the tubing through the access port on the Cary cell compartment. Reactions were initiated by depressing the syringe plunger with the spectrophotometer in operation (425 nm). Recording of data (absorbance versus reaction time) was thus begun with a time lapse of approximately one second.

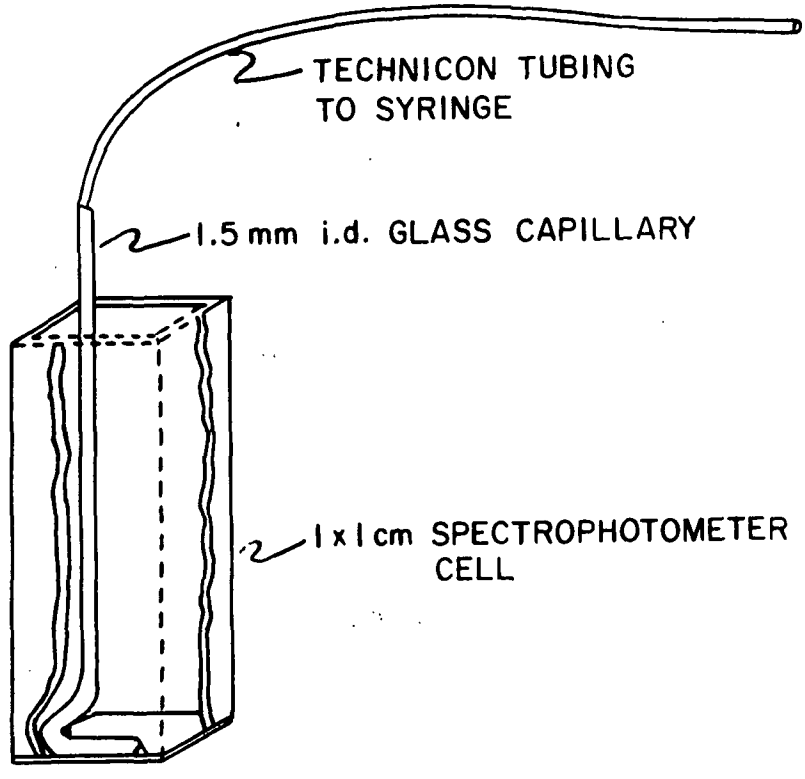


Figure 16. Schematic View of Mixing Tube Used for Kinetic Studies of Rapid Reactions in the Cary Recording Spectrophotometer

The glucose-acid solutions were prepared to correspond to the desired reaction conditions. These conditions (Appendix III) varied depending upon the parameter or effect (e.g., acid concentration, ionic strength, etc.) being studied, and were adjusted using where necessary the proper amounts of nitric

acid, perchloric acid, sodium nitrate, and sodium perchlorate. The stability of glucose in the nitric acid solutions required for these oxidations was demonstrated by quantitative GLC.

At least three kinetic runs were made at each reaction condition. The results of the individual kinetic experiments are tabulated in Tables XVI to XXI, Appendix III. The principal limitations of this technique are the length of time required for mixing (ca. 1 sec for a 3-ml sample) and the maximum chart speed (5 sec/division) which prevents accurate determination of rates greater than about 0.2 sec^{-1}.

TREATMENT OF KINETIC DATA

Pseudo-First-Order Rate Constants

For cerium(IV) oxidation reactions in which all reactants except cerium(IV) are present in large excess the rate expression becomes pseudo-first-order:

$$-dCe(IV)/dt = k'Ce(IV) \qquad (24)$$

where $Ce(IV)$ = total cerium(IV) concentration

k' = pseudo-first-order rate constant.

Integration of the rate expression gives

$$Ce(IV) = Ce(IV)_o \exp(-k't) \qquad (25)$$

where $Ce(IV)_o$ = initial cerium(IV) concentration

or

$$\ln Ce(IV)/Ce(IV)_o = -k't. \qquad (26)$$

Since the integrated rate expression for a first-order reaction involves a ratio of concentrations, any linear function of the cerium(IV) concentration may

be used in place of the concentrations. In the present work the spectrometric absorbance of the reaction solutions was used directly in the calculation of k'.

$$\ln (A/A_o) = -k't \qquad (27)$$

where A_o = initial absorbance.

The pseudo-first-order rate constant, k', can be evaluated from the slope of a plot of $\ln (A/A_o)$ versus time (Fig. 5). Use was made, however, of a multiple regression least squares computer program to calculate the values of k'. Regression coefficients of 1.0 were obtained in calculating all the reported rate constants, indicating the plots of $\ln (A/A_o)$ versus time were indeed linear, and that pseudo-first-order kinetics were followed for all the cerium(IV) oxidations studied.

Complex Formation Constants

The equilibrium constant for complex formation was evaluated in this work by the kinetic method (see Introduction, Theory of Oxidations involving intermediate complexes, for a discussion of the theory involved). The equilibrium constant was calculated from the slope and intercept of the reciprocal plot in which the slope and intercept were calculated by a least squares linear regression analysis.

In determining equilibrium constants from reciprocal plots it is necessary to use the concentration of uncoordinated substrate in the reaction mixture. This concentration differs from the initial substrate concentration by the amount of substrate involved in the coordination complex and was calculated by a method of successive approximations with the aid of a computer program. The initial substrate concentration was used to obtain a first estimate of the

equilibrium constant. The substrate concentration was then corrected using the first estimate of the equilibrium constant and the following equations, based on a 1:1 substrate-cerium(IV) complex (31,32):

$$[S] = S_o - C \tag{28}$$

and

$$C = K[S]Ce(IV)_o/(1-K[S]) \tag{29}$$

where $[S]$ = equilibrium substrate concentration

S_o = initial substrate concentration

C = complex concentration

K = equilibrium constant

$Ce(IV)_o$ = initial total cerium(IV) concentration.

Then a second estimate of the equilibrium constant was obtained using the corrected substrate concentration and the process was repeated successively until the value of the equilibrium constant converged to a constant value.

NOMENCLATURE

A	spectrometric absorbance
AF	4-*O*-formyl-D-arabinopyranose
CAN	ceric ammonium nitrate
Ce(IV)	cerium(IV)
CHG	cyclohexyl β-D-glucopyranoside
DSS	sodium 2,2-dimethyl-2-silapentane-5-sulfonate
ESR	electron spin resonance
FA	formic acid
GA	3-*O*-(β-D-glucopyranosyl)-arabinose
GE	2-*O*-(β-D-glucopyranosyl)-erythrose
GLC	gas liquid chromatography
IR	infrared
K	equilibrium constant for complex formation
k	disproportionation rate constant
k'	pseudo-first-order rate constant
Lit.	literature
MG	methyl β-D-glucopyranoside
mM	millimole
nm	nanometer(s), 10^{-9}m
NMR	nuclear magnetic resonance
P.R.	programmed rate
R_t	retention time, min
[*S*]	equilibrium substrate concentration
S_o	initial substrate concentration
t	time
TLC	thin-layer chromatography

TMS	trimethyl silyl
μ	ionic strength
UV	ultraviolet

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APPENDIX I

RETENTION TIMES AND RESPONSE FACTORS REQUIRED FOR PRODUCT ANALYSIS WORK

This appendix contains the retention times and response factors for the reactants and products of the cerium(IV) oxidations of glucose and cellobiose which were required for quantitative product analysis. All response factors were determined relative to the appropriate internal standard using alditol acetate derivatives, as described in the Experimental section, Determination of Response Factors and Mass Balances. They were calculated from Equation (30) where the terms have been previously defined in Equation (23).

$$f_{s/x} = (M_x/M_s)\ (\text{Area Standard/Area x}). \qquad (30)$$

Also included in this appendix are the relative retention times of the compounds referred to above and of some corresponding aldonic acids and lactones as TMS derivatives, which were necessary for qualitative product investigations.

TABLE IX

RETENTION TIMES AND RESPONSE FACTORS OF COMPOUNDS FOR THE GLUCOSE SYSTEM

Compound	Time, min	Response Factor $(f_{s/x})^a$
Erythrose	5.5-5.6	2.25
Arabinose	9.0	1.51
Glucose	12.5	1.21
CHG	16.0	1.0

[a] Response factors of the alditol acetate derivatives relative to CHG.

TABLE X

RETENTION TIMES OF TMS DERIVATIVES FOR THE GLUCOSE SYSTEM

Compound		Relative Retention Time[a]	
Erythronic lactone		0.13	
Erythronic acid		0.22	(0.21)[b]
Arabinose		0.31	(0.28)
		0.34	
		0.39	
		0.43	
Arabinono lactone	(1,4)	0.31	
	(1,5)	0.36	
Arabinonic acid		0.63	(0.62)
Glucono lactone	(1,5)	0.91	(0.87)
	(1,4)	0.96	
Glucose	(α)	1.0	(1.0)
	(β)	1.52	(1.58)
Gluconic acid		1.63	(1.68)

[a]Times relative to α-glucose.

[b]The numbers in parentheses represent the relative retention times (to α-glucose) reported by McCloskey (82).

TABLE XI

RETENTION TIMES AND RESPONSE FACTORS FOR THE CELLOBIOSE SYSTEM

Compound	Time, min	Response Factor $(f_{s/x})$[a]
MG	5.1	1.0
GE	14.8	--
GA[b]	16.6	0.585
Cellobiose	18.6	0.582

[a]Response factors of the alditol acetate derivatives relative to MG.

[b]The response factor for GA was calculated (indirectly) from the amount of arabinose formed after hydrolysis of the disaccharide GA.

TABLE XII

RETENTION TIMES AND RESPONSE FACTORS FOR THE CELLOBIOSE ACID HYDROLYSIS SYSTEM

Compound	Time, min	Response Factor $(f_{s/x})^a$
1,5-Anhydro-xylitol	7.0	1.0
Erythrose	7.8	--
Arabinose	11.8	0.710
Glucose	15.6	0.702

[a]Response factors of the alditol acetate derivatives relative to 1,5-anhydro-xylitol.

TABLE XIII

RETENTION TIMES OF DISACCHARIDE TMS DERIVATIVES

Compound		Relative Retention Time[a]
Cellobiose	(α)	1.0
	(β)	1.46
Cellobiono lactone		1.23
Cellobionic acid		1.68

[a]Time relative to α-cellobiose.

APPENDIX II

PRODUCT ANALYSIS DATA

This appendix contains the results of quantitative product analyses made on the cerium(IV) oxidations of glucose (Table XIV) and cellobiose (Table XV). The oxidations are identified by reaction numbers which refer to The Institute of Paper Chemistry Research Notebook number, page number, and run identification number. All data have been expressed on a mmole basis. These data have been averaged (for replicate runs), summarized, and reported in Tables II and III of the Results and Discussion section.

TABLE XIV

PRODUCT ANALYSIS DATA FOR THE CERIUM(IV) OXIDATION OF GLUCOSE IN NITRIC AND PERCHLORIC ACID AT 20°C

Reaction	Reaction Media	Initial Glucose	Ce(IV) Consumed	Initial Glucose/Ce(IV)	Glucose Consumed	Arabinose Formed	Erythrose Formed	Oxidation[a] Time, sec
2910-61-6	1.0M HNO_3	0.2753	0.1543	2.04	0.0576	0.0462	0.009	120
2910-62-7	1.0M HNO_3	0.2855	0.1343	2.11	0.0583	0.0441	0.008	120
2910-68-9	1.0M HNO_3	0.2828	0.1343	2.13	0.0567	0.0446	0.009	120
2910-73-11	1.0M HNO_3	0.2752	0.1250	2.20	0.0528	0.0432	0.010	120
2910-103-12	1.0M HNO_3	0.2538	0.1250	2.03	0.0523	0.0421	0.009	120
2910-123-1R	1.0M HNO_3	0.1251	0.1250	1.0	0.0490	0.0351	0.0138	--
2910-98-1A	1.5M HNO_3	0.2609	0.1238	2.1	0.0473	0.0421	0.008	170
2910-101-2A	0.5M HNO_3	0.2694	0.1347	2.0	0.0547	0.0455	0.009	--
2910-147-3A	2.0M HNO_3	0.2574	0.1285	2.0	0.0484	0.0417	0.007	180
2910-153-4A	1.5M HNO_3	0.2483	0.1238	2.02	0.0487	0.0428	0.007	170
2965-5-5A	0.1M HNO_3	0.2525	0.1263	2.0	0.0535	0.0444	0.008	110
2910-145-3S	1.0M HNO_3+ 1.0M NH_4NO_3	0.2502	0.1250	2.0	0.0520	0.0427	0.009	180
2910-125-1P	1.0M $HClO_4$	0.2498	0.1250	2.0	0.0518	0.0401	0.011	36

[a]Time required for the disappearance of the color of the ceric solution.

TABLE XV

PRODUCT ANALYSIS DATA FOR THE CERIUM(IV) OXIDATION OF CELLOBIOSE

Reaction	Reaction Media	Temp., °C	Initial Cellobiose	Initial Ce(IV)	Initial Cellobiose/Ce(IV)	Cellobiose[a] Consumed	GA[a] Formed	Oxidation[b] Time, min
2965-43-1C	1.0M HNO_3	20	0.1006	0.0499	2.01	0.0223	0.0198	5
2965-50-2C	1.0M HNO_3	20	0.1016	0.0499	2.04	0.0215	0.0192	5
2965-69-3CO	1.0M HNO_3	0	0.1003	0.0499	2.0	0.0214	0.0193	75
2965-78-4CPO	0.5M $HClO_4$	0	0.0496	0.0485	1.04	0.0192	0.0155	20
2965-80-5CRO	0.5M HNO_3	0	0.0552	0.0500	1.1	0.0208	0.0174	90

[a]The amount of cellobiose consumed was determined from analysis of the disaccharide system (Fig. 13). The yield of the major product GA was determined from the amount of arabinose formed after hydrolysis of the disaccharide GA for the oxidations at 20°C (Fig. 14). At 0°C the yield of GA was determined directly from the disaccharide analysis employing a calculated response factor for this product based on the amount of arabinose formed in the previous oxidations at 20°C. The difference between the amount of cellobiose consumed and GA formed was assumed to be the yield of the minor product GE (Table III).

[b]This is the time required for the disappearance of color of the reaction solution.

APPENDIX III

RESULTS OF KINETIC EXPERIMENTS

This appendix contains the original kinetic data (time and absorbance values) for all the cerium(IV) oxidations of glucose conducted. The calculated rate constant for each set of data has also been reported. These rate constants have been averaged for replicate runs (normally 3) and reported in Tables IV to VII of the Results and Discussion section. As in the Product Analysis Oxidations, the kinetic reactions are identified by numbers which refer to The Institute of Paper Chemistry Research Notebook number, page number, and identification number.

Table XXII of this appendix contains the data which were obtained in confirming the adherence to Beer's Law for the concentrations of cerium(IV) solutions used in the kinetic work.

TABLE XVI

REACTIONS OF 0.040M GLUCOSE WITH 0.00209M CERIUM(IV) IN PERCHLORIC ACID AT 20°C

Reaction 2965-118-1P, 1.0M $HClO_4$

Time, sec	Absorbance		
5	0.244	0.296	0.220
10	0.100	0.121	0.095
15	0.048	0.059	0.044
k', sec^{-1}	0.162	0.161	0.161

Reaction 2965-119-3P, 0.5M $HClO_4$

Time, sec	A	A	A
5	0.169	0.143	0.140
10	0.075	0.062	0.063
15	0.040	0.031	0.032
k', sec^{-1}	0.144	0.152	0.147

Reaction 2965-119-4P, 0.25M $HClO_4$

Time, sec	A	A
5	0.235	0.158
10	0.108	0.073
15	0.057	0.038
k', sec^{-1}	0.141	0.142

TABLE XVII

REACTIONS OF 0.040M GLUCOSE WITH 0.00209M CERIUM(IV) IN NITRIC ACID AT 20°C

Reaction 2965-122-2HN, 0.5M HNO_3

Time, sec	A	A	A
10	0.377	0.389	0.333
20	0.221	0.223	0.186
30	0.130	0.133	0.109
40	0.080	0.083	0.065
50	0.052	0.052	0.041
k', sec^{-1}	0.0498	0.0501	0.0524

Reaction 2965-122-3HN, 1.0M HNO_3

Time, sec	A	A	A
10	0.316	0.341	0.373
20	0.183	0.205	0.226
30	0.110	0.127	0.137
40	0.068	0.079	0.086
50	0.044	0.050	0.056
k', sec^{-1}	0.0477	0.0479	0.0475

Reaction 2965-123-4HN, 2.0M HNO_3

Time, sec	A	A	A
10	0.616	0.496	0.303
20	0.445	0.341	0.210
30	0.314	0.238	0.147
40	0.225	0.170	0.104
50	0.157	0.118	0.077
60	0.111	0.085	--
k', sec^{-1}	0.0343	0.0352	0.0344

TABLE XVIII

REACTIONS OF 0.040M GLUCOSE WITH 0.00209M CERIUM(IV)
IN 1.0M NITRIC ACID AT 20°C
AND VARYING IONIC STRENGTH

Reaction 2965-126-3μ, μ = 1.5

Time, sec	A	A	A
10	0.395	0.388	0.415
20	0.221	0.213	0.222
30	0.127	0.120	0.121
40	0.080	0.069	0.069
k', sec^{-1}	0.0564	0.0575	0.0569

Reaction 2965-126-4μ, μ = 2.0

Time, sec	A	A	A
10	0.394	0.400	0.395
20	0.207	0.212	0.200
30	0.114	0.116	0.108
k', sec^{-1}	0.0620	0.0619	0.0648

TABLE XIX

REACTIONS OF 0.040M GLUCOSE WITH 0.00209M CERIUM(IV)
IN 1.0M NITRIC ACID AT 20°C
AND VARYING NITRATE ION CONCENTRATIONS

Reaction 2965-128-1N, 0.5M [$NO_3^{\ominus}$]

Time, sec	A	A	A
10	0.277	0.250	0.268
15	0.175	0.161	0.168
20	0.114	0.107	0.107
25	0.076	0.076	0.068
30	0.052	0.057	0.046
k', sec^{-1}	0.0836	0.0771	0.0886

Reaction 2965-128-2N, 1.0M [$NO_3^{\ominus}$]

Time, sec	A	A
10	0.338	0.331
20	0.163	0.167
30	0.086	0.089
40	0.047	0.049
k', sec^{-1}	0.0656	0.0636

Reaction 2965-128-3N, 2.0M [$NO_3^{\ominus}$]

Time, sec	A	A
10	0.402	0.422
20	0.248	0.258
30	0.151	0.161
40	0.099	0.100
50	0.064	0.065
k', sec^{-1}	0.0460	0.0469

TABLE XX

REACTION OF 0.040M GLUCOSE WITH 0.00420M CERIUM(IV) IN 1.0M NITRIC ACID AT 20°C

Reaction 2965-124-2C

Time, sec	A	A
10	0.807	0.621
20	0.492	0.369
30	0.293	0.229
40	0.181	0.142
50	0.115	0.091
k', sec^{-1}	0.0490	0.0480

TABLE XXI

REACTIONS OF GLUCOSE WITH 0.00209M CERIUM(IV) IN 1.0M NITRIC ACID AT 20°C

Reaction	2965-129-1G	2965-125-1μ	2965-122-1HN	2965-123-1C, 0.040M Glucose
Time, sec	A	A	A	A
10	0.314	0.297	0.609	0.372
20	0.190	0.174	0.365	0.206
30	0.117	0.104	0.228	0.120
40	0.073	0.064	0.144	0.076
50	--	0.043	0.091	0.048
k', sec^{-1}	0.0486	0.0486	0.0473	0.0501

Reaction 2965-130-2G, 0.030M Glucose

Time, sec	A	A	A
10	0.316	0.330	0.324
20	0.198	0.210	0.207
30	0.130	0.137	0.131
40	0.087	0.091	0.085
50	0.060	0.060	0.058
k', sec^{-1}	0.0414	0.0424	0.0433

TABLE XXI (Continued)

REACTIONS OF GLUCOSE WITH 0.00209M CERIUM(IV) IN 1.0M NITRIC ACID AT 20°C

Reaction 2965-130-3G, 0.020M Glucose

Time, sec	A	A	A
10	0.223	0.271	0.251
20	0.158	0.209	0.177
30	0.115	0.148	0.123
40	0.085	0.107	0.088
50	0.063	0.077	0.062
k', sec^{-1}	0.0315	0.0318	0.0349

Reaction 2965-130-4G, 0.015M Glucose

Time, sec	A	A	A
10	0.161	0.190	0.172
20	0.120	0.147	0.123
30	0.092	0.112	0.098
40	0.070	0.086	0.076
50	0.056	0.066	0.059
k', sec^{-1}	0.0265	0.0265	0.0262

Reaction 2965-131-5G, 0.010M Glucose

Time, sec	A	A	A
15	0.037	0.115	0.072
30	0.028	0.085	0.054
45	0.022	0.062	0.041
60	0.016	0.046	0.030
k', sec^{-1}	0.0184	0.0204	0.0193

TABLE XXII

BEER'S LAW VERIFICATION FOR CERIUM(IV) NITRIC ACID (1.0M) SOLUTIONS AT 425 NM[a]

Cerium(IV) Concn., M	Absorbance
0.01060	1.287
0.00530	0.690
0.00265	0.320
0.00212	0.267
0.00133	0.167
0.00106	0.109

[a]Data are plotted in Fig. 15.