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Doctor's Dissertation

A Polarographic Study of the Reduction  
of Unsymmetrical Benzils

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A POLAROGRAPHIC STUDY OF THE REDUCTION  
OF UNSYMMETRICAL BENZILS

A thesis submitted by

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## SUMMARY

This investigation applied the techniques of polarography and controlled potential electrolytic reduction to the study of a series of unsymmetrical benzils. Eleven unsymmetrical benzils were synthesized and studied in 50% ethanol-water (by volume) solvent systems buffered at pH 1, 5, and 13. The results showed that, with unsymmetrical benzils substituted with electron-withdrawing or electron-donating groups, the carbonyl closest to the ring with the least electron-donating power was the preferred reaction site. However, the dicarbonyl system was nevertheless reduced as a unit, and Hammett sigma values of disubstituted symmetrical benzils were approximately additive. This was ascertained by comparing the ease of reduction of eight unsymmetrical benzils to the ease of reduction of the corresponding disubstituted symmetrical benzils. It was proposed that the electrons were added to the oxygen of one carbonyl, and that the second carbonyl was involved in the reduction chiefly through complete polarization of the dicarbonyl system at the electrode.

In general, the reduction of unsymmetrical benzils appeared to follow the same path previously reported for symmetrical benzils. That is, the enediol form of the benzoin was consistently the dropping mercury electrode product. The enediol rearranged to the reducible benzoin faster in basic than in acidic media. In general, this gave rise to the appearance of one polarographic wave at acid pH and two or more polarographic waves at basic pH. However, with benzils substituted with strong electron-withdrawing groups, a suppressed second wave appeared even at low pH, probably due to a rapid rearrangement of the enediol of these compounds.

Controlled potential electrolysis and product isolation showed that the product of the polarographic reduction of unsymmetrical benzils was a mixture of benzoin isomers. The fraction of the electronically less stable benzoin isomer

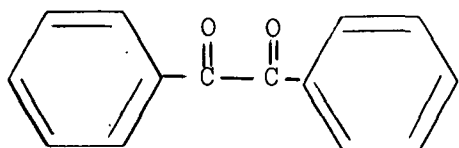
produced was found to be as high as 40%. This percentage decreased with increasing electron-donating or electron-attracting power of the substituents.

Controlled potential electrolysis and a study of the polarographic reduction of benzoin isomer products formed from the reduction of benzils showed that the product of the second wave in the reduction of benzils was a deoxybenzoin derivative. The deoxybenzoin derivative underwent a further reduction to give a third wave, which for most compounds was merged with the second wave to give the appearance of a single wave. More specifically, the initial product of the reduction of benzoin at the dropping mercury electrode was deoxybenzoin, although, in the past, electrolytic reductions at mercury pool electrodes have given the impression that hydrobenzoin is the product formed. Although deoxybenzoin is formed by the conversion of the carbinol group of benzoin to a methylene group, the initial attack of the electrons in the polarographic reduction of benzoin appeared to occur at the carbonyl group.

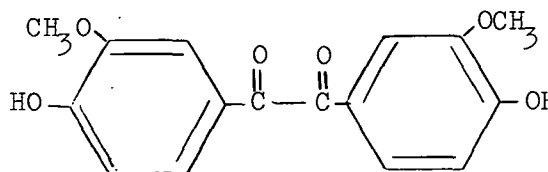
# INTRODUCTION

## DIRECTION OF THE STUDY

Chemical reduction has been used in the past to study the characteristics of a number of lignin-related model compounds such as benzil (I) and vanillil (II) (1). The results from the chemical reduction of these compounds indicate that the type of substituent on the benzene ring influences the reduction of the keto groups. Reducing agents yielding a certain reduction product with benzil may either cause no reduction or give a different reduction product when applied to a substituted compound such as vanillil.



I



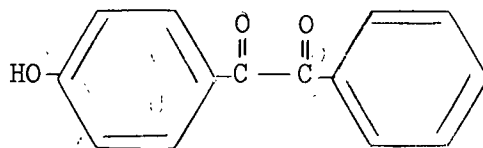
II

For a more complete understanding of the chemistry of these  $\alpha$ -diketone compounds, quantitative knowledge of how various substituents on the ring affect ease of reduction is required. Chemical reduction studies are not a completely suitable source of knowledge due to the complicating effects of specific chemical reducing agents. Electrochemical methods, however, have advantages over the more conventional chemical techniques. The main advantage is that the potential at which a reversible electrochemical reaction occurs is a direct quantitative measure of molecular activity.

A study of the polarographic reduction of symmetrical benzil derivatives has recently been completed by Myers (2). With symmetrical benzil derivatives, electronic resonance and inductive effects due to substituent groups should be felt by each keto group to the same degree. As a result, the carbonyls cannot

be distinguished as to ease of reduction. However, with an unsymmetrically substituted benzil, the electron density about one carbonyl should differ from that about the other. Reduction should occur at the most favorable site.

A natural extension of Myers' work therefore was the study of unsymmetrical benzil derivatives, i.e., 4-hydroxybenzil (III). With this unsymmetrical benzil there are two possible reaction sites, and the sites are not equivalent. Since the hydroxyl group is an electron-donating group, the electron density around the carbonyl neighboring the substituted ring should be greater than the electron density around the carbonyl remote from the substituted ring. The attack of the electrons during reduction would then occur at the carbonyl remote from the substituted ring since electronically this would be the preferred site. The half-wave potential, a measure of the ease of reduction, would then be relatively independent of the electron-donating power of the hydroxyl group on the remote ring. However, if the electron-donating hydroxyl substituent were replaced with an electron-withdrawing substituent, the most favorable site of reduction would be the carbonyl adjacent to the substituted ring and the half-wave potential would exhibit a strong dependency on the electron-withdrawing power of the substituent.



III

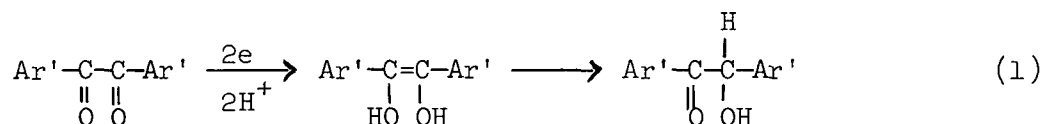
The main objective of this study was to test the hypothesis that the site of reduction will be changed when the substituent on the ring is changed from electron-withdrawing to electron-donating. This investigation of the mechanism of the reduction involved preparation of benzil and benzoin derivatives,



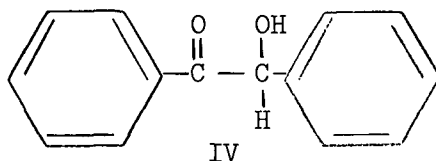
polarographic investigation of the reduction steps of benzil derivatives and product analysis for each of the reduction steps.

# BACKGROUND

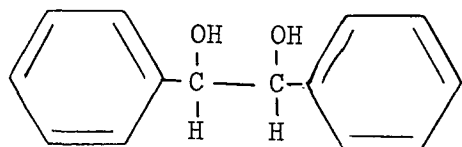
A thorough review of previous polarographic studies of benzil has been given by Myers (3). Along with benzil, Myers studied seven methoxy- and hydroxy-substituted benzil derivatives. He concluded that the overall reaction was the same for all compounds since benzoin (IV) and benzoin derivatives were identified as reaction products. Although the mechanism for hydroxy-substituted compounds was found to be complicated by intermediate, irreversible steps caused by solvent and electric field interactions, the mechanism for nonhydroxy-substituted compounds was found to be similar to that proposed by other investigators. That is, the reductions were dependent on hydrogen ion concentration to about the same degree, and the primary product of the electrode appeared to be the enediol form of the benzoin. In general, the following scheme was applicable.



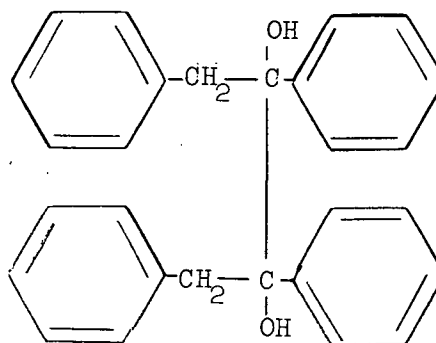
The enediol rearranges rapidly to benzoin in basic media although the rearrangement is slow in acidic media (4). The enediol intermediate is not reducible at the dropping mercury electrode, and only a single wave is observed for the reduction of benzil and benzil derivatives in acidic or neutral media. However, in alkaline media a second wave appears which is due to the reduction of benzoin formed by the base-catalyzed rearrangement of the enediol before it can diffuse away from the mercury cathode.



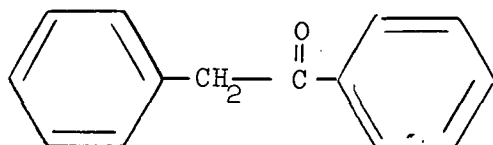
Benzoin, whose reduction is responsible for the second wave in the reduction of benzil, has been reported to give a single two-electron wave at all pH's (5). The product of the reduction of benzoin after controlled potential electrolysis at pH 8.6 has been reported by Pasternak (4) to be hydrobenzoin (V). This would be the expected product from a two-electron reduction of benzoin, indicating simple reduction of the benzoin carbonyl. At pH 1.3 Pasternak isolated a deoxybenzoin pinacol (VI). This result has been interpreted as being due to a reduction of the benzoin to hydrobenzoin followed by an acid-catalyzed dehydration to deoxybenzoin (VII) which on reduction produced the pinacol (5). Lund (6) later stated that it was just as plausible that the secondary alcohol group of the benzoin was directly reduced to a methylene group and that the deoxybenzoin thus formed was then reduced further to the pinacol. Lund based his conclusion on results from the reduction of acetylbenzoin in mineral acid solution. Deoxybenzoin was the product of this reduction. Lund further studied the reduction of deoxybenzoin and isolated the deoxybenzoin pinacol as the main product in both mineral acid and very basic solution.



V



VI



VII

In the reduction of aliphatic ketones, the electron can be pictured as being added to an electroactive carbon atom. However, Leonard, Laitinen, and Mottus (7) proposed a slightly different mechanism in their study of several aliphatic 1,2-diketones which underwent a one-electron and one-proton reduction process. For their system they proposed that the electron was added at one oxygen of the dicarbonyl system as shown in Fig. 1. Electron addition was accompanied by the capture of a proton at the other oxygen. The degree of polarization which can be developed by the dicarbonyl system at the electrode was believed to be responsible for the fact that the diketones were reduced more easily than monoketones at the dropping mercury electrode.

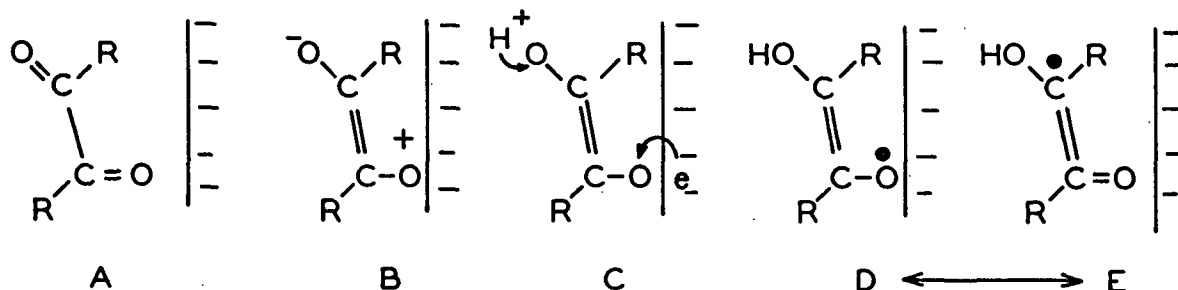


Figure 1. Behavior of a 1,2-Diketone at the Dropping Mercury Electrode (7)

Although no previous polarographic reduction studies have been reported for unsymmetrical benzils, Van Es and Backeberg (8) undertook a study of the chemical reduction of unsymmetrical benzils using sodium dithionite. They reported that the benzil was quantitatively reduced to the benzoin isomer which had the carbinol group next to the ring with the greatest electron-withdrawing power.

## PRINCIPLES OF POLAROGRAPHY

The principles of polarography have been described in detail by Kolthoff and Lingane (9), Delahay (10), and Meites (11). Short discussions may be found in most books on physical methods. It will be remarked briefly here that polarography

is the study of current-potential relationships during the electrolysis of a solution between a dropping mercury electrode and some standard reference electrode. The plot of current versus potential is referred to as a polarogram. As the applied potential is increased from zero the current flowing initially is small. When one of the components of the solution begins to be reduced at the mercury cathode, there is a rapid rise in current which causes a sigmoid-shaped wave. The potential at the midpoint of the wave is characteristic of the substance being reduced and is referred to as the half-wave potential ( $E_{1/2}$ ). If the compound is oxidized or reduced in more than one step at potentials differing by about 0.15 volt or more, a series of two or more sigmoid-shaped curves are obtained as shown in Fig. 2.

As applied potential is increased above the half-wave potential, a maximum value of current is reached which is referred to as the limiting or diffusion current. The diffusion current is limited by the rate at which the reducible substance diffuses to the mercury droplet and can be predicted by the Ilkovic equation.

$$i_d = 708 n D_O^{1/2} C^o m^{2/3} t^{1/6} \quad (2)$$

where

$i_d$  = diffusion current, microamps ( $\mu a.$ )

$n$  = number of electrons involved in the electrode process

$D_O$  = diffusivity of the reducible species,  $cm.^2/sec.$

$C^o$  = concentration of the reducible species, in the bulk of the solution,  $mM/l.$

$m$  = mass flow rate of mercury,  $mg./sec.$

$t$  = length of time that elapses between the instants at which two successive drops fall,  $sec.$

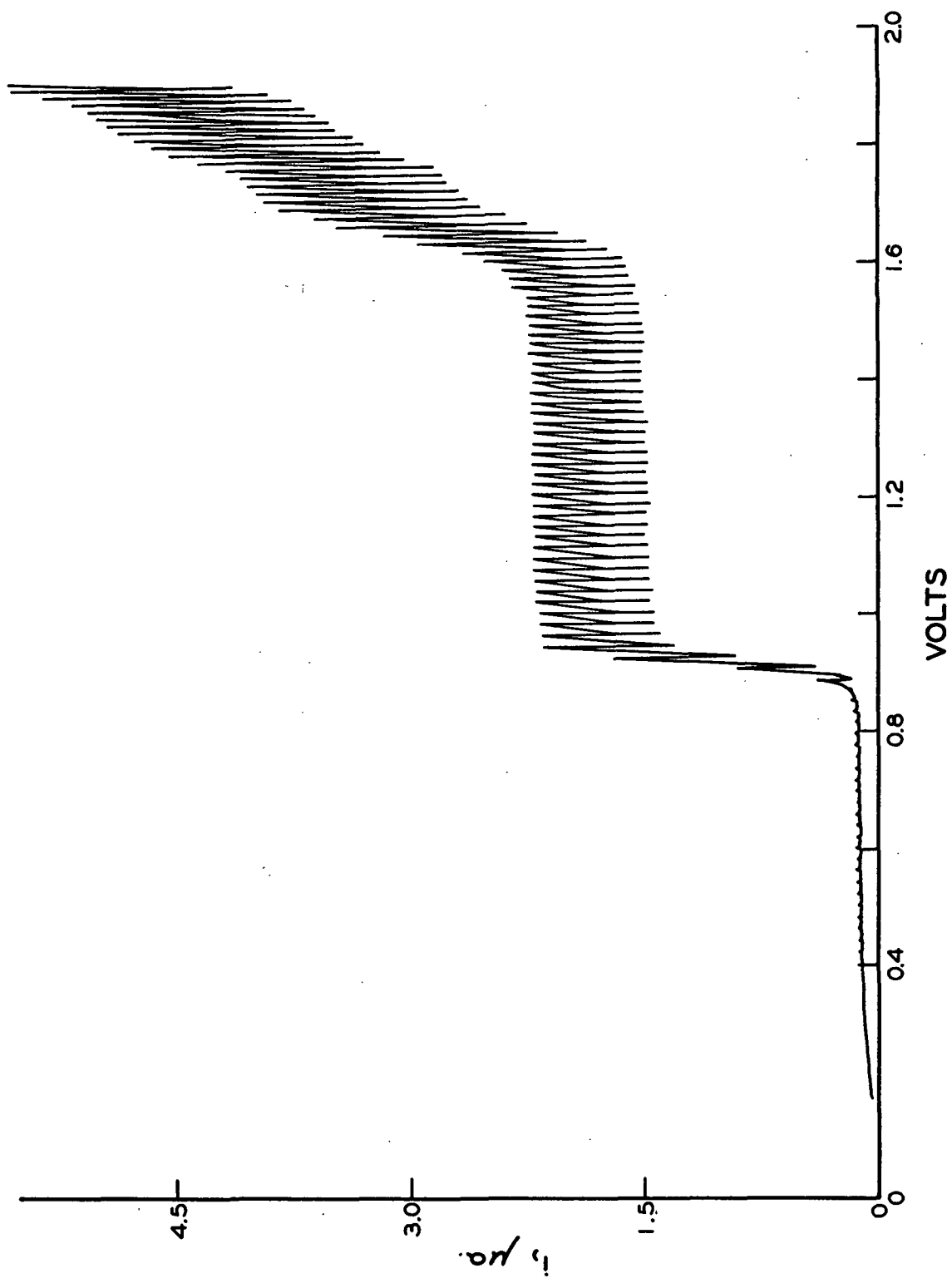


Figure 2. Polarogram of 4,4'-Dimethoxybenzil, pH 13.6

When measuring diffusion current, a correction is made for residual current which is the current obtained for the solvent-electrolyte system in the absence of the reducible species.

An electrode process is said to be reversible if the electrochemical reaction is so rapid that electrochemical equilibrium is achieved at the electrode. The mass transfer of the reacting substance to the electrode is then a controlling factor. The current-potential relationship for a reversible process is

$$E = E_{1/2} + (RT/nF) \ln ((i_d - i)/i) \quad (3).$$

A determination of reversibility may be made from Equation (3) by plotting the potential of the dropping mercury electrode versus  $\log ((i_d - i)/i)$  and analyzing the slope which is equal to  $0.0591/\underline{n}$  at  $25^\circ$  for a reversible system. The half-wave potential for a reversible process can be simply related to the standard potential,  $E^\circ$ , by the following equation

$$E_{1/2} = E^\circ - (RT/nF) \ln (f_R D_O^{1/2} / f_O D_R^{1/2}) \quad (4)$$

where

$\underline{R}$  = gas constant,  $8.315 \text{ joules } (^\circ\text{K})^{-1} (\text{g.-mole})^{-1}$

$\underline{T}$  = absolute temperature,  $^\circ\text{K}$

$\underline{F}$  = Faraday constant, the number of international coulombs which must be passed through a cell to deposit one gram equivalent of any element, 96,500

$\underline{f}_R$  = activity coefficient of the reduced species

$\underline{f}_O$  = activity coefficient of the reducible species

$\underline{D}_O$  = diffusivity of the reducible species,  $\text{cm.}^2/\text{sec.}$

$\underline{D}_R$  = diffusivity of the reduced species

For an irreversible process, the half-wave potential is a more complicated function and is primarily controlled by the rate of the forward electrode reaction

for the organic half-cell:



where  $k_{f,h}$  and  $k_{b,h}$  are the rate constants for the forward and backward reactions, respectively, and  $O$  and  $R$  represent the oxidized and reduced species. The dependence of the half-wave potential is then

$$E_{1/2} = (RT/\alpha nF) \ln (t^{1/2} k_{f,h}^0 \lambda_{1/2} D_0^{1/2}) \quad (6)$$

where

$k_{f,h}^0$  = rate constant for the reduction when  $E$  vs. a normal hydrogen electrode equals zero

$\lambda_{1/2}$  = constant having the value of 0.76

$\alpha$  = transfer coefficient related to the fraction of the potential operating in the direction of the reduction

The current-potential relationship for an irreversible process is

$$E = E_{1/2} + (RT/\alpha nF) \ln ((i_d - i)/i) \quad (7)$$

A plot of the logarithm of the quantity  $(i_d - i)/i$  against potential should yield a straight line whose slope is  $\alpha nF/RT$ .

If the rate-determining step involves a number of electrons,  $n_a$ , smaller than the total number of electrons consumed in the overall electrode reaction,  $n_a$  should be substituted for  $n$  in Equations (6) and (7).

The distinction between a reversible and irreversible electrode process is somewhat artificial. A reversible system can pass from mass transfer control to electrochemical control when the mass transfer coefficients are increased sufficiently. Therefore, a system can exhibit reversibility at a dropping mercury electrode but irreversibility at electrodes rotating at high speeds.

## EXPERIMENTAL

### PREPARATION AND PURIFICATION OF COMPOUNDS

#### BENZIL DERIVATIVES

All benzil derivatives polarographically reduced during the course of this work are previously reported compounds with the exception of 4-acetylbenzil. Most were synthesized using literature preparations or methods analogous to literature preparations of similar compounds. Several were purchased from chemical supply companies and purified by recrystallization. The remainder were from the library of chemical compounds of the Lignin Group at The Institute of Paper Chemistry.

#### 4-Acetylbenzil

4-Acetylbenzil was prepared by selenium dioxide oxidation of 4-acetyldeoxybenzoin according to a modified general procedure of Hatt, Pilgrim, and Hurran (12). 4-Acetyldeoxybenzoin has two available sites for oxidation. Selenium dioxide would be expected to attack both the methylene group and the activated methyl group of the side chain. The reaction time was shortened in an attempt to minimize oxidation of the side chain.

4-Acetyldeoxybenzoin was obtained by reaction between acetyl chloride and deoxybenzoin according to the method of Borsche and Sinn (13), m.p. 161-162.5°, lit. m.p. 159-160° (13).

4-Acetyldeoxybenzoin (18.6 g., 0.078 mole) was dissolved in 80 ml. of acetic anhydride. When the solution began refluxing on heating, selenium dioxide (12.2 g., 0.11 mole) was added and refluxing was continued for thirty minutes only. After being allowed to cool, the solution was filtered to remove precipitated selenium and unreacted selenium dioxide. The solid material was washed with 10 ml.



of acetic anhydride. After cooling in the freezer, the cloudy filtrate was treated with decolorizing carbon to yield a dark red solution. This solution was concentrated on the rotary evaporator to approximately 40 ml. A heavy precipitate formed which was removed by filtration and saved for further treatment. The filtrate was placed in the refrigerator and a viscous gum precipitated which was removed by filtration. Water was added to the filtrate, and the mixture was heated to initiate hydrolysis of the acetic anhydride. Additional water was then added to the point of cloudiness. The sample was placed in the refrigerator. The crystalline precipitate was collected by filtration and recrystallized twice from ethanol to yield 0.43 g. of 4-acetylbenzil, m.p. 79-81°. The precipitate which had formed on concentration of the original solution yielded 0.15 g. of additional product, obtained through a variety of extractions and fractional crystallizations. Total yield of crude 4-acetylbenzil was 3.1%. Purification of the yellow 4-acetylbenzil crystals was accomplished by several recrystallizations from 95% ethanol, m.p. 80.5-82.0°.

Analysis: Calculated for  $C_{16}H_{12}O_3$ : C, 76.18; H, 4.80. Found: C, 76.34; H, 4.98.

#### Benzil

Benzil, purified by Myers (14), was obtained from the library of chemical compounds of the Lignin Group at The Institute of Paper Chemistry, m.p., 95.0-95.5°, lit. m.p. 95° (15).

#### 4,4'-Bis(dimethylamino)benzil

4,4'-Bis(dimethylamino)benzil was prepared using the method of Tuzon, et al. (16). N,N-Dimethylaniline was reacted with oxalyl chloride in a carbon disulfide solvent with anhydrous aluminum chloride catalyst. The product was purified by recrystallization from 95% ethanol, m.p. 200-201°, lit. m.p. 200-202° (16).

### 3-Chlorobenzil

3-Chlorobenzamide was prepared by the dropwise addition of 3-chlorobenzoyl chloride (Aldrich Company) into ice cold ammonium hydroxide, m.p. 132-134°, lit. m.p. 134-135° (17).

3-Chlorodeoxybenzoin was obtained by reaction between benzyl magnesium chloride and 3-chlorobenzamide. The procedure used was a slightly modified procedure of Jenkins (18) who prepared the identical compound. The modifications were as suggested by Clark, et al. (19). The product was recrystallized from 95% ethanol, m.p. 62-63°, lit. m.p. 62° (18).

3-Chlorobenzil was prepared by the selenium dioxide oxidation of 3-chlorodeoxybenzoin in acetic anhydride according to the method for oxidation of 4-chlorodeoxybenzoin given by Hatt, Pilgrim, and Hurran (12). The 3-chlorobenzil was purified by several recrystallizations from 95% ethanol, m.p. 90.0-90.5°, lit. m.p. 86° (19).

### 4-Chlorobenzil

4-Chlorodeoxybenzoin was obtained by reaction between benzyl magnesium chloride and 4-chlorobenzamide according to the procedure of Jenkins (20). The product was recrystallized from ligroin, m.p. 105-106°, lit. m.p. 107.5° (20).

4-Chlorobenzil was prepared by oxidation of 4-chlorodeoxybenzoin with selenium dioxide in acetic anhydride using the procedure of Hatt, Hurran, and Pilgrim (12). 4-Chlorobenzil was purified by recrystallization from ligroin and alcohol, m.p. 76-76.5°, lit. m.p. 75° (21).

### 3,3'-Dichlorobenzil

3,3'-Dichlorobenzil was prepared by oxidation of crude 3,3'-dichlorobenzoin oil, whose synthesis is described later, in a cupric sulfate-pyridine system.

The method used was the general procedure of Leonard, et al. (22). The product was purified by fractional crystallization from 95% ethanol, m.p. 120-121°, lit. m.p. 121-122° (23).

#### 4,4'-Dichlorobenzil

Crude 4,4'-dichlorobenzoin was prepared through the benzoin condensation reaction using the procedure of Weissberger (24).

4,4'-Dichlorobenzil was prepared by Myers (2) through the cupric sulfate oxidation of the crude 4,4'-dichlorobenzoin using the method of Merz and Plauth (25). The benzil derivative was purified by recrystallization from ligroin, m.p. 197°, lit. m.p. 195° (25).

#### 3,3'-Dihydroxybenzil

3,3'-Dihydroxybenzil, m.p. 149-150°, lit. m.p. 149-149.5° (26), was prepared by Myers (14) by demethylation of 3,3'-dimethoxybenzil.

#### 4,4'-Dihydroxybenzil

4,4'-Dihydroxybenzil, m.p. 246-249°, lit. m.p. 245-247° (26), was prepared by Myers (14) by demethylation of 4,4'-dimethoxybenzil.

#### 3,3'-Dimethoxybenzil

3,3'-Dimethoxybenzil, m.p. 83°, lit. m.p. 83° (27), was prepared by Myers (14) by cupric sulfate oxidation of 3,3'-dimethoxybenzoin.

#### 4,4'-Dimethoxybenzil

4,4'-Dimethoxybenzil, m.p. 246-249°, lit. m.p. 245-247° (28), was prepared by Myers (14) by cupric sulfate oxidation of 4,4'-dimethoxybenzoin.

#### 4,4'-Dimethylbenzil

4,4'-Dimethylbenzil was prepared by cupric sulfate oxidation of 4,4'-dimethylbenzoin, whose synthesis is described later, using the general procedure of

Leonard, et al. (22). The product was purified by recrystallization from 95% ethanol, m.p. 103-104.5°, lit. m.p. 104-105° (29).

#### 4-Dimethylaminobenzil

4-Dimethylaminobenzil was prepared by cupric sulfate oxidation of 4-dimethylaminobenzoin using the procedure of Clarke and Dreger (30). The product was purified by recrystallization from 95% ethanol, m.p. 115.5-116.5°, lit. m.p. 115-116° (31).

#### 4-Dimethylamino-4'-chlorobenzil

4-Dimethylamino-4'-chlorobenzil was prepared by cupric sulfate oxidation of 4-dimethylamino-4'-chlorobenzoin\* using the general method of Clarke and Dreger (30). Melting point of the product after recrystallization from ethanol was 141.5-142.5°, lit. m.p. 143.5-144.0° (21).

#### 3-Hydroxybenzil

3-Hydroxybenzil was prepared by demethylation of 3-methoxybenzil. Demethylation was accomplished by means of hydrobromic acid in acetic acid. The procedure followed was that used by Friedman, et al. (32) in a demethylation of 4-methoxybenzil. The 3-hydroxybenzil was purified by recrystallization from benzene, m.p. 97.5-98.5°, lit. m.p. 97-98° (33).

#### 4-Hydroxybenzil

4-Hydroxybenzil was purchased from K and K Laboratories and purified by recrystallization from aqueous ethanol and benzene, m.p. 129.5-130°, lit. m.p. 129-130° (34).

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\*Primes (') are used to indicate substitution on the ring adjacent to the carbinol carbon atom.

### 3-Methoxybenzil

3-Methoxybenzamide was obtained by refluxing 3-methoxybenzoic acid for two hours with twice the theoretical amount of thionyl chloride. The excess of thionyl chloride was then distilled under reduced pressure, and the crude acid chloride was poured into ice cold ammonium hydroxide solution. The 3-methoxybenzamide was recrystallized from water, m.p. 133-134.5°, lit. m.p. 133° (35).

3-Methoxydeoxybenzoin, m.p. 39-40°, was obtained by condensation of 3-methoxybenzamide and benzyl magnesium chloride using the procedure of Jenkins (18) who prepared similar substituted deoxybenzoin.

3-Methoxybenzil was prepared by selenium dioxide oxidation of 3-methoxydeoxybenzoin in acetic anhydride using the general procedure of Hatt, Pilgrim, and Hurran (12) for the oxidation of phenyl benzyl ketones. The product was purified by recrystallization from 95% ethanol, m.p. 90-91°, lit. m.p. 90-91° (33).

### 4-Methoxybenzil

4-Methoxybenzil was purchased from Aldrich Company and recrystallized from 95% ethanol, m.p. 62.0-63.0°, lit. m.p. 61.5-63.0° (36).

### 4-Methylbenzil

4-Methylbenzil was prepared by selenium dioxide oxidation of 4-methyldeoxybenzoin using the procedure of Hatt, Pilgrim, and Hurran (12). The product was recrystallized from 95% ethanol, m.p. 27-28°, lit. m.p. 31° (12).

### 4-Nitrobenzil

4-Nitrobenzil was prepared according to the method of Chattaway and Coulson (37). This method involved acetylation and nitration of benzoin to form 4'-nitrobenzoin acetate which on oxidative hydrolysis yielded 4-nitrobenzil. The product

was recrystallized twice from acetone and four times from 95% ethanol, m.p. 139.5-141°, lit. m.p. 142° (37).

## BENZOIN DERIVATIVES

### 4'-Acetylbenzoin

4'-Acetylbenzoin was prepared by controlled potential electrolysis of 4-acetylbenzil at 0.45 volt versus a saturated calomel electrode. Electrolysis and isolation procedures are described fully later. The product was recrystallized from 95% ethanol yielding white needles, m.p. 104.5-105.5°.

Analysis: Calculated for  $C_{16}H_{14}O_3$ : C, 75.57; H, 5.55. Found: C, 75.77; H, 5.53.

### Benzoin

Benzoin, purified by Myers (14), m.p. 135-136°, lit. m.p. 134-135° (38), was originally purchased from K and K Laboratories.

### 3-Chlorobenzoin

3-Chlorobenzoin was prepared by bromination of 3-chlorodeoxybenzoin and conversion of the resulting  $\alpha$ -bromo derivative into 3-chlorobenzoin using sodium ethoxide. The experimental procedure was taken from Jenkins (39) who prepared similar unsymmetrical benzoin. Recrystallization of the previously unreported compound from 95% ethanol yielded white needles, m.p. 84.0-84.5°.

Analysis: Calculated for  $C_{14}H_{11}O_2Cl$ : C, 68.12; H, 4.49. Found: C, 67.95; H, 4.58.

### 3'-Chlorobenzoin

3'-Chlorobenzoin was prepared by the isomerization of 3-chlorobenzoin in alkali. 3-Chlorobenzoin (0.5 g., 0.002 mole) was dissolved in 50 ml. of absolute

ethanol. A 0.12N solution of potassium hydroxide in 50 ml. of water was prepared. The two solutions were combined after both were scrubbed with nitrogen to remove oxygen. The mixture was allowed to stand one hour with nitrogen bubbling through it. The mixture was then poured into water and made slightly acidic by the addition of hydrochloric acid. A small yield of material was recovered by filtration. Recrystallization from 95% ethanol yielded white needles, m.p. 94.0-95.0°.

Analysis: Calculated for  $C_{14}H_{11}O_2Cl$ : C, 68.12; H, 4.49. Found: C, 68.00; H, 4.56.

#### 4-Chlorobenzoin

4-Chlorobenzoin was prepared from 4-chlorodeoxybenzoin using the procedure of Jenkins (39) who prepared similar unsymmetrical benzoin. The product was purified by recrystallization from 95% ethanol, m.p. 89-90°, lit. m.p. 90-91° (40).

#### 4'-Chlorobenzoin

4'-Chlorobenzoin was prepared by the isomerization of 4-chlorobenzoin in alkali, using the method described for the preparation of 3'-chlorobenzoin. The melting point after recrystallization from 95% ethanol was 110-112°, lit. m.p. 110-111° (41).

#### 3,3'-Dichlorobenzoin

3,3'-Dichlorobenzoin was prepared by cyanide ion-catalyzed condensation of 3-chlorobenzaldehyde using the procedure of Weissberger (24). The product was recrystallized from ligroin, m.p. 63-66°, lit. m.p. 65-67° (23); 75-76° (24).

#### 3,3'-Dimethoxybenzoin

3,3'-Dimethoxybenzoin, m.p. 83°, lit. m.p. 83° (27), was prepared by Myers (14) through the benzoin condensation reaction.

4,4'-Dimethoxybenzoin

4,4'-Dimethoxybenzoin, purified by Myers (14), m.p. 132-132.5°, lit. m.p. 133° (42), was originally purchased from K and K Laboratories.

4-Dimethylaminobenzoin

4-Dimethylaminobenzoin was purchased from Aldrich Company and recrystallized from 95% ethanol, m.p. 163.5-164.5°, lit. m.p. 163-164° (43).

4-Dimethylamino-4'-chlorobenzoin

4-Dimethylamino-4'-chlorobenzoin was formed by condensation of 4-chlorobenzaldehyde with 4-dimethylaminobenzaldehyde according to conditions given by Jenkins (44). The melting point after recrystallization from alcohol was 128-129°, lit. m.p. 127-128° (44).

3-Methoxybenzoin

3-Methoxybenzoin was prepared from 3-methoxydeoxybenzoin according to the procedure of Jenkins (39) who prepared similar unsymmetrical benzoin. Recrystallization of the previously unreported compound from 95% ethanol yielded white platelets, m.p. 74.5-75.0°.

Analysis: Calculated for  $C_{15}H_{14}O_3$ : C, 74.36; H, 5.83. Found: C, 74.29; H, 5.88.

4-Methoxybenzoin

4-Methoxybenzoin was prepared by the cyanide ion-catalyzed condensation between 4-anisaldehyde and benzaldehyde using the procedure of Jenkins (45). The product was purified by recrystallization from methanol, m.p. 106-106.5°, lit. m.p. 106° (45).



#### 4'-Methylbenzoin

4'-Methylbenzoin was prepared by the condensation of phenylglyoxal with toluene according to the procedure of Ide and Buck (46). The product was purified by recrystallization from methanol, m.p. 116.5-118°, lit. m.p. 116° (47).

#### 4-Methylbenzoin

4-Methylbenzoin was prepared from 4-methyldeoxybenzoin using the procedure of Jenkins (39) who prepared similar unsymmetrical benzoin. The product was purified by recrystallization from 95% ethanol, m.p. 107-108°, lit. m.p. 109-110° (47).

#### 4-Hydroxybenzoin

4-Hydroxybenzoin was prepared by controlled potential electrolysis of 4-hydroxybenzil at 0.64 volt versus a saturated calomel electrode. Electrolysis and isolation procedures are described later. The product was recrystallized from 95% ethanol yielding white needles, m.p. 178-179.5°.

Analysis: Calculated for  $C_{14}H_{12}O_3$ : C, 73.67; H, 5.30. Found: C, 73.84; H, 5.33.

### MISCELLANEOUS ORGANIC REACTANTS AND PRODUCTS

#### Deoxybenzoin

Deoxybenzoin was purchased from Aldrich Company, m.p. 54-56°, lit. m.p. 58-60° (38).

#### $\alpha$ -Deoxybenzoin Pinacol

$\alpha$ -Deoxybenzoin pinacol was prepared by exposure of deoxybenzoin in isopropyl alcohol to sunlight for three days. The procedure was that used for the preparation of  $\beta$ -deoxybenzoin pinacol according to Crawford, Saeger, and Warneke (48).

In this case, however, the only product which could be found was the  $\alpha$  isomer, isolated in 2.0% yield. A possible explanation for the difference could be the reaction temperature. In this case the reaction temperature was low since the reaction vessel was taped to an exposed window in midwinter. The product was recrystallized from 95% ethanol, m.p. 214-215°, lit. m.p. 212° (6).

#### 4,4'-Dimethoxydeoxybenzoin

4,4'-Dimethoxydeoxybenzoin, m.p. 108-110°, lit. m.p. 108-111° (49), was prepared by Myers by the reduction of 4,4'-dimethoxybenzoin using the method of Carter and Craig (49).

#### Hydrobenzoin

Hydrobenzoin, m.p. 134-136°, lit. m.p. 135° (38), was prepared by Myers by the reduction of benzil using the method of Pearl and Dehn (38).

### CHARACTERIZATION OF UNREPORTED COMPOUNDS

Previously unreported benzoin s were characterized by periodate oxidation with splitting of the molecule to form known benzoic acids and benzaldehydes. The aromatic acid is formed from the carbonyl group and the corresponding benzaldehyde is derived from the alcoholic portion. The procedure used was that of Van Es and Backeberg (8). One modification in the procedure was a reduction in the reaction time from twenty-four to two hours since thin-layer chromatography showed the reaction to be completed in two hours or less. Another modification was that the sample size was very small. The reactions were run with a hundredfold reduction in scale. The identity of the benzoic acid and benzaldehyde produced were established using thin-layer chromatography. A derivative of the benzaldehyde was then formed and the benzoic acid and benzaldehyde derivative were isolated for a melting point determination. In general, due to limited quantities of material, no attempt could be made at purification of the isolated oxidation products.

Oxidation of 3-chlorobenzoin yielded 3-chlorobenzoic acid, m.p. 155-156°, lit. m.p. 158° (50), and benzaldehyde which was isolated as the semicarbazone, m.p. 207-212°, lit. m.p. 214° (51).

Oxidation of 3'-chlorobenzoin yielded benzoic acid, m.p. 119.5-121°, lit. m.p. 122.4° (52), and 3-chlorobenzaldehyde which was isolated as the semicarbazone, m.p. 227-229°, lit. m.p. 228° (53).

Oxidation of 3-methoxybenzoin yielded 3-methoxybenzoic acid, m.p. 105.5-106.5°, lit. m.p. 107-108° (52), and benzaldehyde which was isolated as the semicarbazone, m.p. 214-216°.

Oxidation of 4'-acetylbenzoin yielded benzoic acid, m.p. 121.5-122.5° and 4-acetylbenzaldehyde which was isolated as the bis-phenylhydrazone, m.p. 184-189°, lit. m.p. 189.6-190.8° (54), and also as the bis-oxime, m.p. 177-179.5°, lit. m.p. 180.6-181.2° (54).

Oxidation of 4-hydroxybenzoin yielded 4-hydroxybenzoic acid and benzaldehyde. Isolation of the oxidation products was not attempted due to the very small amount of pure starting material available. The oxidation products were identified with thin-layer chromatography. Benzoic acid and 4-hydroxybenzaldehyde were not present in the reaction mixture. Good separation of these four compounds was achieved when the thin-layer plates were developed in either butanol saturated with 2% aqueous ammonia or in benzene saturated with formic acid.

#### PREPARATIONS OF SOLVENTS AND BUFFERS

The solvent system used in this investigation was 50% ethanol-water (by volume). The solvent system was polarographically pure. Absolute ethanol was purified by distillation in a packed column 22 mm. in diameter and 75 cm. long. The column was packed with glass tubing 6 mm. in diameter and 50 mm. in length.

Water was purified by distilling from sodium hydroxide and potassium permanganate according to Weissberger (55).

Buffer systems were prepared at three pH's in 50% ethanol-water. All compounds used for preparing buffer systems were Analytical Reagent grade. The buffer systems were prepared at a constant ionic strength of 0.4. The least concentrated component of any buffer system was at least 120 times the concentration of the reducible species during a polarographic run.

The apparent pH of each system was measured with a Beckman Model M pH meter. The first buffer system, 0.2N sodium acetate in 0.4N hydrochloric acid, possessed an apparent pH of 1.33. The second buffer system, 0.4N sodium acetate in 0.4N glacial acetic acid, had an apparent pH of 5.56. The basic buffer, 0.12N potassium hydroxide in 0.28N potassium chloride, had an apparent pH of 13.69.

#### APPARATUS

Current-potential curves in the present study were obtained with a Sargent Model XV recording polarograph.

The polarographic cell used in this study has been described by O'Connor (56). It was originally patterned after the general description given by Kolthoff and Coetzee (57). The cell had been slightly modified by Myers to accommodate a second calomel electrode associated with a Sargent Model A Internal Resistance Compensator which was not used in the present study since it seemed to limit the reproducibility of the waves. The cell consisted of a cathode compartment of 40-ml. capacity with a saturated calomel reference electrode as an anode. Both the cathode compartment and the saturated calomel reference electrode were water-jacketed and maintained at  $25.0 \pm 0.05^{\circ}\text{C}$ . with water from a constant temperature bath.

The saturated calomel reference electrode was prepared by Myers (2) as suggested by Meites (58). In order to preserve the agar bridge, the open end was kept immersed in saturated potassium chloride solution between runs.

Prepurified nitrogen was used for deaeration of the test solution. The nitrogen gas was presaturated with solvent by bubbling it through three tubes of 50% ethanol-water connected in series and kept in the constant temperature bath. The nitrogen could be directed by means of a two-way stopcock either into a dispersion tube immersed in the test solution or over the surface of the test solution while recording polarograms.

A Sargent (S-29417) 21-cm. capillary was used as the dropping mercury electrode. With an open circuit and a mercury height of 2.5 cm., the drop time was 5.9 sec., and the mercury flow rate was 1.638 mg./sec. The effect of potential on capillary characteristics was determined in the pH 5.5 buffer solution and is shown in Fig. 3.

A Potentiostat manufactured by Analytical Instruments Inc. was used for controlled potential electrolyses. A Sargent Recording Potentiometer (S-72150) on a suitable current range was used to record current-time curves which could be integrated for coulometric data. Potentials were checked periodically during the course of controlled potential electrolyses by means of a Leeds and Northrup Student Potentiometer. It was necessary to make occasional adjustments of the gain control in the amplifier chassis to get a close degree of potential control during the electrolyses.

The cell used for controlled potential electrolyses was manufactured by Analytical Instruments Inc. (catalog number C3) and was recommended for use with the above Potentiostat. This double-diaphragm cell had a cylindrical working

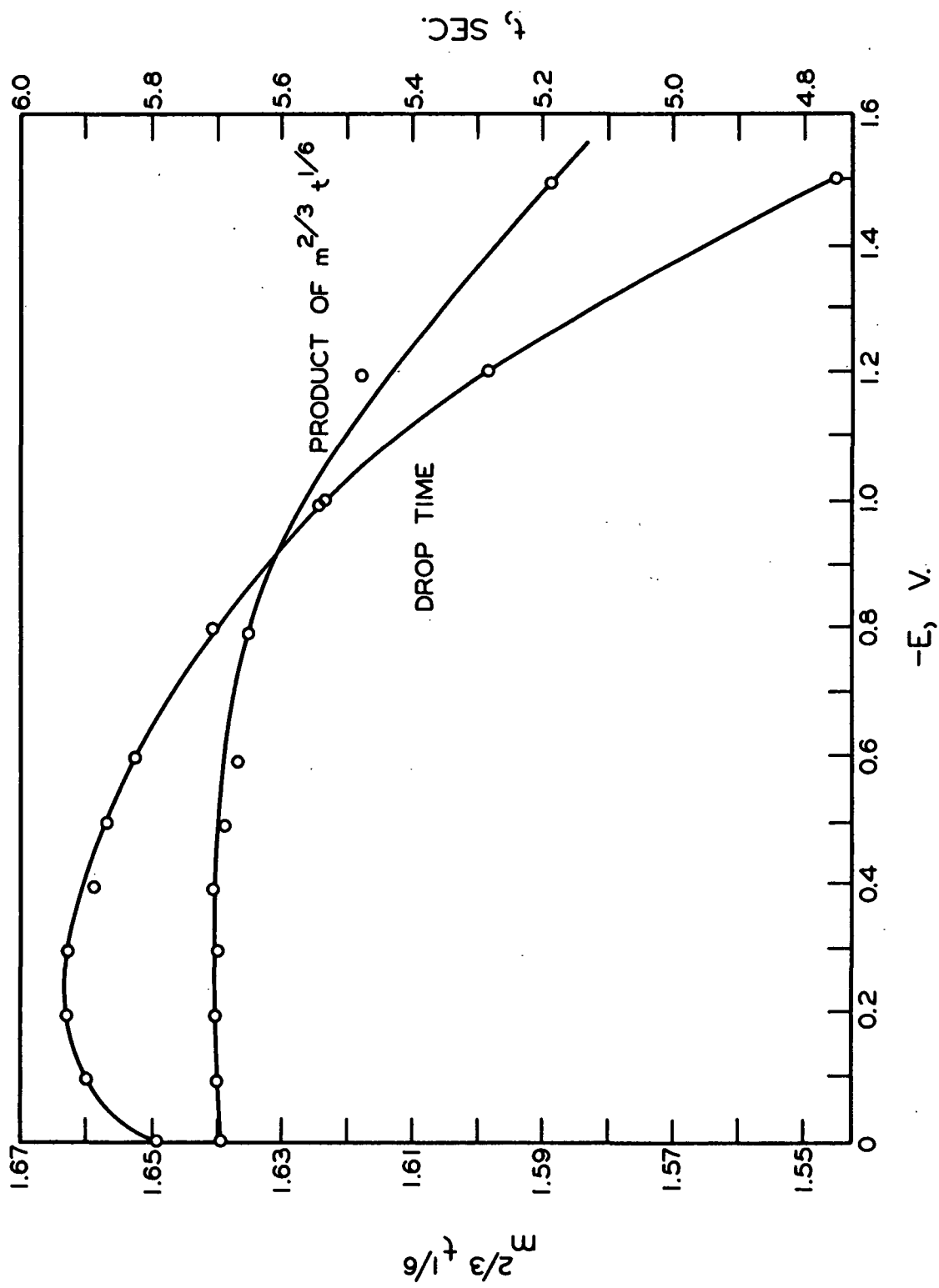


Figure 3. Capillary Characteristics Curves

electrode compartment of 200-ml. capacity. The working electrode compartment was fitted with a Teflon cap containing one hole for accommodation of a glass stirring rod. A stirred mercury pool with an area of  $38.5 \text{ cm.}^2$  was the working electrode. The pool was stirred by means of a 600 r.p.m. Sargent synchronous motor. The reference electrode was a Beckman 5-inch fiber junction saturated calomel electrode. A one-eighth inch carbon rod served as the auxiliary electrode.

Cell resistance measurements were made with a General Radio Type 650-A Impedance Bridge containing a 1000 cycle/sec. a.c. current source. An oscilloscope served as null detector.

#### POLAROGRAPHIC PROCEDURE

The final test solution for polarographic studies usually consisted of a 20-ml. aliquot of stock solution containing the compound under investigation mixed with a 20-ml. aliquot of the buffer-supporting electrolyte solution. Both the stock solutions and the buffer-supporting electrolyte system were prepared in 50% ethanol-water. Stock solutions were used within 24 hours of preparation.

Except where solubility difficulties were encountered, stock solutions were made up in 100-ml. volumetric flasks and made  $1 \times 10^{-3} \text{ M}$  in the compound under investigation. This gave a concentration of reducible species in the final test solution of  $5 \times 10^{-4} \text{ M}$ .

In the cases of 4-nitrobenzil and 3,3'-dichlorobenzil, which were soluble at  $5 \times 10^{-4} \text{ M}$  but not at  $1 \times 10^{-3} \text{ M}$ , the stock solutions were prepared in absolute ethanol at  $2 \times 10^{-3} \text{ M}$ . The test solution was then prepared by pipetting 20 ml. of buffer solution, 10 ml. of the stock solution, 10 ml. of water, and 0.7 ml. of 50% ethanol-water into the cell.

In specified cases of more serious solubility difficulties, the concentration of the reducible species in the final test solution was made  $1 \times 10^{-4}$  M. These cases were handled by preparing  $2 \times 10^{-3}$  M stock solutions in absolute ethanol. The final test solution was then prepared by pipetting into the cell 20 ml. of buffer solution, 2 ml. of the stock solution, 2 ml. of water, and 16.1 ml. of 50% ethanol-water.

The test solution was always deaerated for twenty minutes with nitrogen before running polarograms. In the study of benzoin, the basic buffer solution and the stock solution were deaerated separately before mixing in the cathode compartment. This prevented the rapid decomposition of the benzoin which occurred in basic solution in the presence of oxygen.

Polarograms were recorded at a polarization rate of 0.1 volt per minute. The voltage range was usually 0 to -1 volt for the more easily reduced compounds and -1 to -2 volts for the less easily reduced compounds. The current sensitivity setting for any single wave was generally the maximum allowable value, dictated by the width of the recorder chart. At the higher current sensitivity it was necessary to correct for the fixed internal resistance in the recorder as specified in the manual. A correction was also made for cell resistance which averaged 500 ohms for the aqueous-ethanol system.

All polarograms were recorded without damping. The top oscillatory traces of the waves were used to measure the current. Four duplicate polarograms were recorded for each of the benzil derivatives at the three pH levels. For all compounds other than benzil derivatives only two duplicate polarograms were recorded. Reported half-wave potential data are averages of the duplicate polarograms.



## ELECTROLYSIS AND PRODUCT ANALYSIS PROCEDURE

The concentration of reducible species was  $5 \times 10^{-4}$  M for controlled potential electrolysis except when it was increased to  $5 \times 10^{-3}$  M for 4-acetylbenzil and 4-hydroxybenzil. All controlled potential electrolyses were carried out at pH 5.5. The procedure for filling the working electrode compartment was to add 35 ml. of cleaned mercury, 100 ml. of buffer solution, 80 ml. of 50% ethanol-water and 10 ml. of water. The auxiliary electrode compartment and the middle section of the cell were filled with 50 and 30 ml., respectively, of buffer solution diluted with an equal volume of 50% ethanol-water. Stirring of the mercury pool was begun, and the working electrode compartment was deaerated for 30 minutes with nitrogen. Although there was no evidence of reducible impurities, the solution was preelectrolyzed for a short period in order to establish the residual current at the potential chosen for electrolysis. Ten milliliters of an absolute ethanol solution, 0.01M in the compound under investigation, were introduced into the working electrode compartment. A few minutes were allowed for deaeration, and the electrolysis was begun. Electrolysis was continued until a fairly constant current was obtained, usually about 1% of the initial current. This required from 2-1/2 to 3 hours.

The reduction products were isolated by extracting the electrolyses solutions four to six times with benzene. The benzene layer was then dried over anhydrous magnesium sulfate and reduced to dryness under vacuum on the rotary evaporator. This procedure usually left a relatively pure crystalline organic residue which could be used for infrared and mixed melting point determinations. Extraction with ether was also attempted but it gave less satisfactory results than benzene extraction. The benzoin products appeared to be readily oxidized to the original benzil derivatives during isolation using an ether extraction. This was particularly true with 4-hydroxybenzoin which appeared to be susceptible to oxidation

even during the benzene extraction procedure. It was noted that an ether extraction removed acetic acid which benzene did not extract. However, neutralization of the acetic acid with sodium hydroxide did not appear to substantially improve the extraction procedure.

Extensive use was made of thin-layer chromatography, especially for preliminary product identification. The plates most frequently used were Eastman Chromagram Sheets Type K301R. For plates sprayed with sulfuric acid or potassium permanganate, glass backed plates were prepared with Silica Gel G. The plates were usually developed in either pure chloroform or pure benzene. Both of these solvents would generally separate benzoin derivatives from benzil derivatives. Benzene had the added advantage of separating deoxybenzoin from benzil. For separation of 4-hydroxy compounds it was necessary to use the chloroform developer with a trace of ethyl acetate. The fluorescent dye in the manufactured sheets served as an adequate indicator for all compounds containing carbonyl groups. 2,4-Dinitrophenylhydrazine was also a convenient spray. Qualitative identification of spots was made by comparison with knowns run on the same sheet.

## RESULTS AND DISCUSSION

### GENERAL CHARACTERISTICS OF THE POLAROGRAMS

#### DESCRIPTION OF THE POLAROGRAMS

With other factors in the Ilkovic equation (2) held constant, the diffusion current of a polarographic wave is proportional to the number of electrons involved in the reduction. The diffusion currents from the first reduction step of all unsymmetrical benzil derivatives, with the exception of 4-nitrobenzil, were similar to that of benzil. The polarographic wave of benzil is known to represent a two-electron reduction to benzoin (5). The fact that other benzil derivatives had diffusion currents similar to that of benzil indicates that their reductions are also two-electron reductions.

The diffusion current of the first wave of 4-nitrobenzil was approximately twice as great as for the other benzil derivatives. This was felt to be an indication of either reduction of the side group or an unique mechanism of reduction of the dicarbonyl system. Since 4-nitrobenzil differed from the normal benzil series, further work was not done with this compound. However, future studies could be interesting since a new reduction mechanism of the dicarbonyl system might be demonstrated.

In general, only one wave was observed in the reduction of all benzil derivatives at pH 1 and 5. However, at least two waves were observed at pH 13. This behavior is similar to that reported previously for benzil by Philp, Flurry, and Day (59) and for certain benzil derivatives by Myers (60). The explanation of this behavior has been that a nonreducible enediol intermediate is formed at the electrode. This intermediate is slow to rearrange in acidic solution. However, in basic solution, rearrangement to a reducible benzoin is rapid and occurs

before the enediol has a chance to diffuse away from the electrode. The reduction of the benzoin which is formed by rearrangement at the electrode is responsible for a second wave at high pH. The appearance of a second wave at high pH in this work supports the conclusion that an enediol intermediate is formed in the reduction of unsymmetrical benzil derivatives.

Disubstituted compounds consistently gave polarographic waves with lower diffusion currents than the corresponding monosubstituted compounds. This indicates that diffusion is the current controlling process, since compounds with a larger molecular size would be expected to diffuse slower.

One characteristic of a diffusion controlled process is that the quantity  $i_d/C$  is independent of concentration. Limited experimental data taken on the variation of  $i_d/C$  with concentration are given in Table I. Slight variations of  $i_d/C$  with concentration can be attributed to inaccuracies in measuring diffusion currents at low concentrations of the reducible species.

TABLE I  
EFFECT OF CONCENTRATION ON DIFFUSION CURRENT AT 25°

Compound	Concentration, mM	$i_d/C$ , $\mu a./mM$		
		pH 1.3	pH 5.5	pH 13.6
Benzil	0.5	4.4	4.3	4.3
	0.1	4.5	4.5	4.2
4-Chlorobenzil	0.5	4.5	4.2	4.0
	0.1	4.9	4.5	4.4

#### REVERSIBILITY OF THE ELECTRODE PROCESS

One criterion of reversibility of an electrode reaction is that a plot of the potential of the dropping mercury electrode versus  $\log (i_d - i)/i$  is a straight line of slope  $0.0591/n$  at 25°. Significant deviation of the slope is fairly conclusive proof of some degree of irreversibility. The slope of the line representing

an irreversible reaction is equal to  $0.0591/\alpha n$ . The transfer coefficient ( $\alpha$ ) is used to indicate the fraction of the applied electrode potential which favors the reaction in the forward direction. The value is used as an indication of the degree of irreversibility of the reduction.

The  $\alpha n$  values have been calculated for selected polarograms of benzil derivatives, and these values are presented in Table II. In all cases,  $n$  has been determined by controlled potential electrolysis to be two. Therefore, the  $\alpha n$  value for a reversible electrode process equals two. The most significant point of interest of the  $\alpha n$  data is that reductions of unsymmetrical benzil derivatives at pH 13.6 are reversible, with the exclusion of 4-hydroxybenzil. All compounds show some degree of irreversibility at lower pH's.

TABLE II

THE EFFECT OF HYDROGEN ION CONCENTRATION ON  $\alpha n$

pH	3-Chlorobenzil	Benzil	4-Dimethyl-aminobenzil	4-Hydroxybenzil
1.3	1.06	0.98		0.95
5.5	1.51	1.08		0.80
13.6	2.02	2.14	2.10	1.60

Another criterion of polarographic reversibility is that the half-wave potential should be independent of concentration of the reducible species. The half-wave potentials of irreversible waves vary with concentration and usually become more negative as the concentration increases. The data in Table III show that benzil derivatives satisfy this criterion of polarographic reversibility at pH 13.6, while they show evidence of irreversibility at pH 1.3. The data at pH 5.5 is inconclusive.

TABLE III  
EFFECT OF CONCENTRATION ON HALF-WAVE POTENTIAL

Compound	Concentration, mM	$E_{1/2}$ , v.		
		pH 1.3	pH 5.5	pH 13.6
Benzil	0.5	0.238	0.494	0.830
	0.1	0.224	0.491	0.830
4-Chlorobenzil	0.5	0.210	0.456	0.805
	0.1	0.193	0.452	0.803

#### INFLUENCE OF SOLVENT ON THE ELECTRODE PROCESS

Limited exploratory work was done with the polarographic reduction of benzil derivatives in solvents other than aqueous ethanol. Concentration of the reducible species was kept at 0.001M in these investigations.

Benzil was reduced in dimethylformamide using both 0.3M lithium chloride and 0.3M tetraethylammonium bromide (TEAB) as supporting electrolytes. In dimethylformamide no hydrogen ions are available for protonation. The waves recorded in dimethylformamide seemed to resemble those reported by Philp, Flurry, and Day (59). That is, benzil underwent two one-electron reductions in dimethylformamide when tetraethylammonium bromide was used as a supporting electrolyte. When lithium chloride was used as a supporting electrolyte the reduction yielded a single two-electron wave. Philp, Flurry, and Day felt that through chelation the lithium ion delocalized the charge of the first electron over the diketo reduction site thereby allowing a second electron transfer and the appearance of a single two-electron wave.

In this work, benzil was also reduced using an absolute ethanol solvent with 0.3M lithium chloride as supporting electrolyte. The initial electrode reaction in this solvent was believed to be a two-electron reduction. However, there was an increase in diffusion current over what was expected from studies in ethanol-water.

This increase in diffusion current is probably due to decreased viscosity of the absolute ethanol solvent (61).

Both benzil and vanillil were also reduced in a 50% benzene-methanol solvent using 0.3M lithium chloride as supporting electrolyte. Benzil appeared to give a normal two-electron wave while vanillil gave two one-electron waves. No further work was done with this solvent but it would be interesting to extend these studies. A study of a series of benzil derivatives to determine which undergo a two-electron process and which undergo two one-electron processes might reveal the cause of the mechanism change. It should also be possible to isolate the one-electron reduction products after controlled potential electrolysis.

Half-wave potential and diffusion current data obtained in solvents other than aqueous ethanol are given in Table IV.

TABLE IV  
HALF-WAVE POTENTIALS AND DIFFUSION CURRENTS  
IN NONAQUEOUS SOLVENTS

Compound	Solvent	Supporting Electrolyte	$-E_{1/2}$ , v.	$i_d$ , $\mu$ a.
Benzil	Benzene-methanol	LiCl	0.820	5.8
Benzil	Dimethyl-formamide	LiCl	0.555	3.8
Benzil	Dimethyl-formamide	TEAB	0.620	2.2
Benzil	Absolute ethanol	LiCl	0.900	4.6
Vanillil	Benzene-methanol	LiCl	0.987	2.0
1st Wave			1.295	1.8
2nd Wave				

# STUDY OF FIRST WAVE

## EFFECT OF HYDROGEN ION CONCENTRATION

### Effect on Half-Wave Potential

The half-wave potentials of benzil and all benzil derivatives were dependent upon pH. The half-wave potential data obtained at the three pH's studied for benzil derivatives are given in Table V. The reproducibility of the half-wave potential is estimated to be  $\pm 0.002$  volt.

TABLE V

THE EFFECT OF HYDROGEN ION CONCENTRATION ON  
HALF-WAVE POTENTIAL AT 25°

	$\sigma^a$	$-E_{1/2}$ , v.		
		pH 1.3	pH 5.5	pH 13.6
4-Acetylbenzil	+0.502	0.174	0.410	0.764
3-Chlorobenzil	+0.373	0.200	0.443	0.793
4-Chlorobenzil	+0.227	0.210	0.456	0.805
3-Methoxybenzil	+0.115	0.229	0.480	0.822
Benzil	0.000	0.238	0.494	0.830
4-Methylbenzil	-0.170	0.266	0.507	0.847
4-Methoxybenzil	-0.268	0.271	0.532	0.863
4-Dimethylaminobenzil	-0.83	0.223	0.566	0.916
3-Hydroxybenzil	-0.055 <sup>b</sup>	0.238	0.500	--
(ionized)	-0.708 <sup>c</sup>	--	--	0.900
4-Hydroxybenzil	-0.335 <sup>b</sup>	0.278	0.593	--
(ionized)	-1.00 <sup>c</sup>	--	--	1.045
4'-Chloro-p-dimethylaminobenzil		0.201	0.539	0.891
4,4'-Dihydroxybenzil		0.362	0.744	1.372
4,4'-Bis (dimethylamino)benzil		--	0.642	1.017
4,4'-Dimethoxybenzil		0.304	0.571	0.899
3,3'-Dihydroxybenzil		0.238	0.514	1.055
4,4'-Dimethylbenzil		0.278	0.523	0.866
3,3'-Dimethoxybenzil		0.223	0.471	0.817
3,3'-Dichlorobenzil		0.163	0.401	0.766
4,4'-Dichlorobenzil ( $1.0 \times 10^{-4} M$ )		0.165	0.422	0.785

<sup>a</sup> Sigma values are reported by Hine (63) based on the ionization of benzoic acids in water except as noted.

<sup>b</sup> Value reported by Bright and Briscoe (64) based on ionization of benzoic acids in 50% ethanol-water.

<sup>c</sup> Based on some reaction other than ionization of benzoic acids (63).



All unsymmetrical benzil derivatives, with the exception of the hydroxybenzils and 4-dimethylaminobenzil, appeared to have an identical dependency on pH. This dependency is shown in Fig. 4. As expected from the data of Myers (62), the reductions are more pH dependent in acid media than in basic media. The pH at which the change in slope of the half-wave potential versus pH plot actually occurs cannot be determined here due to insufficient data. However, Myers (62) reported that the change in slope for benzil occurred at pH 7.2.

The pH dependency of 3-hydroxybenzil and 4-hydroxybenzil is shown in Fig. 5. Data from these compounds are plotted together with that of benzil which is used as a reference. Some change in the slope of the lines relative to benzil may arise from changes in the relative degree of irreversibility of the reductions. However, most of the change in slope is due to ionization of the hydroxyl group. This ionization increases the electron-donating power of the substituent, and the reductions occur at potentials greater than would be expected for nonionized groups.

Figure 6 is a graph of half-wave potential versus pH for 4-dimethylaminobenzil with benzil as a reference. Ordinarily the 4-dimethylamino group is a strong electron-donating group. However, at low pH, the half-wave potential of 4-dimethylaminobenzil is more positive than that of benzil. The side chain is apparently protonated in acid, and the group changes from an electron-donating to an electron-withdrawing group.

#### Effect of Diffusion Current

The diffusion current values for benzil and benzil derivatives at the three pH's studied are given in Table VI. These data were corrected for variation of the product  $\underline{m}^{2/3} \underline{t}^{1/6}$  with potential, which is shown in Fig. 3. The reproducibility of the diffusion current is estimated to be  $\pm 0.1 \mu\text{a}$ .

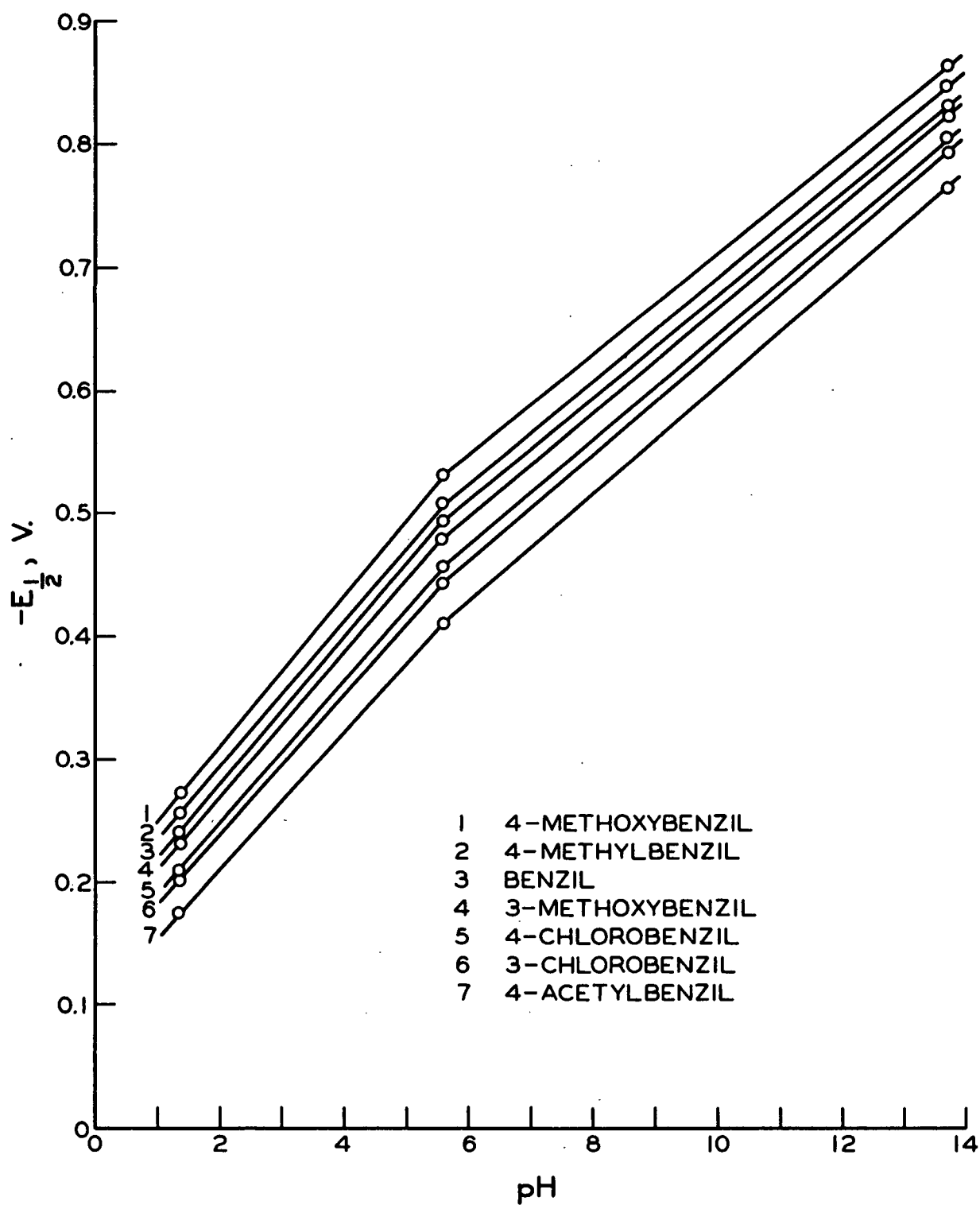


Figure 4.  $E_{1/2}$ , vs. pH in 50% Ethanol-Water

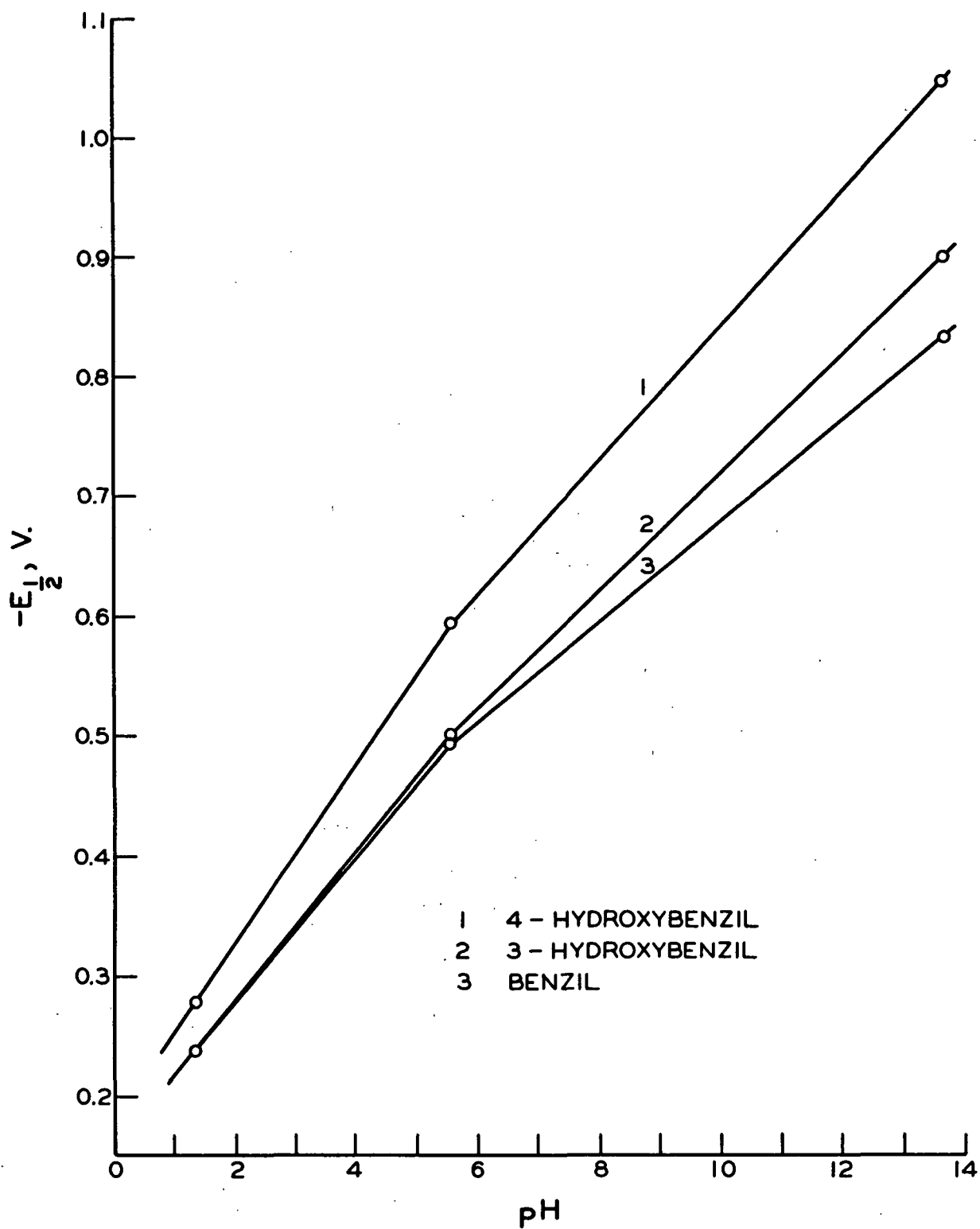


Figure 5.  $E_{1/2}$  vs. pH in 50% Ethanol-Water

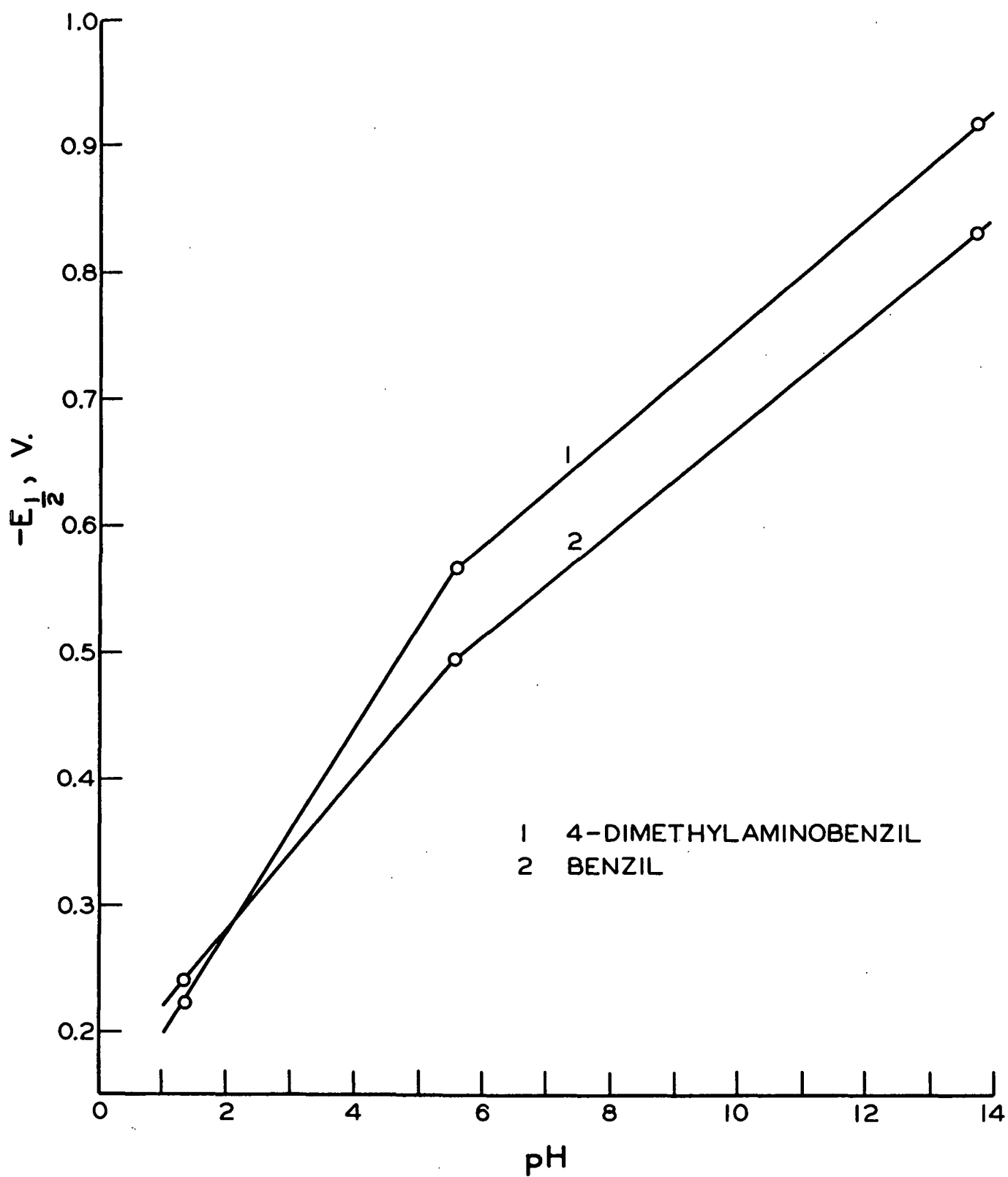


Figure 6.  $E_{1/2}$  vs. pH in 50% Ethanol-Water

TABLE VI

THE EFFECT OF HYDROGEN ION CONCENTRATION ON  
DIFFUSION CURRENT AT 25°

	$\frac{i}{d}$ , $\mu$ a.		
	pH 1.3	pH 5.5	pH 13.6
4-Acetylbenzil	2.05	1.92	--
3-Chlorobenzil	2.15	2.10	2.01
4-Chlorobenzil	2.25	2.10	2.01
3-Methoxybenzil	2.08	2.08	2.05
Benzil	2.22	2.14	2.13
4-Methylbenzil	2.21	2.18	2.16
4-Methoxybenzil	2.22	2.13	2.17
4-Dimethylaminobenzil	2.07	2.06	2.03
3-Hydroxybenzil	2.08	2.02	1.92
4-Hydroxybenzil	2.09	2.00	1.90
4'-Chloro-4-dimethylaminobenzil	2.05	1.94	1.99
4,4'-Dihydroxybenzil	1.84	1.84	1.74
4,4'-Bis(dimethylamino)benzil	1.95	1.89	1.87
4,4'-Dimethoxybenzil	2.12	2.07	2.08
3,3'-Dihydroxybenzil	1.93	1.93	1.71
4,4'-Dimethylbenzil	2.14	2.14	2.10
3,3'-Dimethoxybenzil	1.93	1.90	1.86
3,3'-Dichlorobenzil	2.04	1.94	2.01
4,4'-Dichlorobenzil ( $1.0 \times 10^{-4} M$ )	2.12	1.95	2.01

Diffusion current decreases slightly as the pH is increased. No simple relationship between diffusion current and molecular weight or size could be found with the unsymmetrical benzil derivatives although the monosubstituted benzil derivatives always gave higher diffusion currents than the corresponding disubstituted symmetrical benzil derivatives. As expected, benzil was one of the fastest diffusing compounds. Hydroxy-substituted compounds were among the slowest diffusing compounds. Myers (65) found similar results and attributed this to hydrogen bonding or other interaction with the solvent which would slow down the diffusion of hydroxy-substituted compounds.

An accurate diffusion current could not be recorded for 4-acetylbenzil at pH 13.6 since this compound decomposed in base with time.

#### CORRELATION OF SUBSTITUENTS WITH THE REDUCTION

It was stated earlier that the main objective of this thesis was to test the hypothesis that the site of reduction would be changed when the substituent on the ring is changed from electron-withdrawing to electron-donating. As evidence for the shift in site of reduction, it was felt that the half-wave potentials would exhibit a strong dependency on the power of electron-withdrawing substituents while half-wave potentials would be relatively independent of the power of electron-donating substituents.

The Hammett equation is used to correlate reactivity with electron-donating or -withdrawing power of substituents (63). Through a relatively simple derivation, the Hammett equation can be incorporated in the following expression involving the half-wave potential of a reversible electrode reaction at 25° (66).

$$E_{1/2} - E_{1/2}^0 = (0.0591/n)\rho\sigma$$

where

$E_{1/2}^0$  = half-wave potential of the unsubstituted compound, benzil

$E_{1/2}$  = half-wave potential of a compound substituted at the meta or para position

$\sigma$  = Hammett substituent constant

$\rho$  = Hammett reaction constant

The slope of the line formed in a Hammett plot of half-wave potential versus sigma would be an indication of the sensitivity of the half-wave potential to the electron-withdrawing or -donating power of the substituent. If the half-wave potential was more sensitive to electron-withdrawing than to electron-donating

substituents, a change in the slope of the Hammett plot would occur at a sigma value of zero.

In preparing Hammett correlations, nonionized hydroxyl sigma values for a 50% ethanol-water solvent were used as reported by Bright and Briscoe (64). All other values were taken from Hine (63). Sigma values are reported in Table V.

The Hammett correlation obtained at pH 13.6, where the most reversible reductions are obtained, is shown in Fig. 7. The proposal that a change in the slope of the line would occur is not easily supported since the correlation with a straight line is quite good. The slope of the straight line determined by least squares calculations was -0.107 volt and the correlation coefficient was 0.994. A slope of -0.107 volt gives a rho value of 3.6.

The ionized hydroxyl group is well above the line and was not included in the least squares calculations. The sigma value of the ionized hydroxyl group may be particularly solvent-dependent. No sigma value is available for an ionized hydroxyl group in 50% ethanol-water. This could be the primary reason for the deviation of the 4-hydroxybenzil point from the line. Some part of the deviation may also be caused by irreversibility which seems to be associated with hydroxy-substituted benzils.

The expression relating the Hammett equation to half-wave potential was derived for reversible electrode reactions. However, the relation can be used for a series of irreversible electrode reactions provided that the effects of irreversibility are about the same for the entire series of compounds. Figures 8 and 9 show the Hammett correlations obtained at pH 1.3 and 5.5, respectively. Again the correlations with a straight line are quite good. At pH 1.3 the slope of the line obtained was -0.117 volt with a correlation coefficient of 0.993.

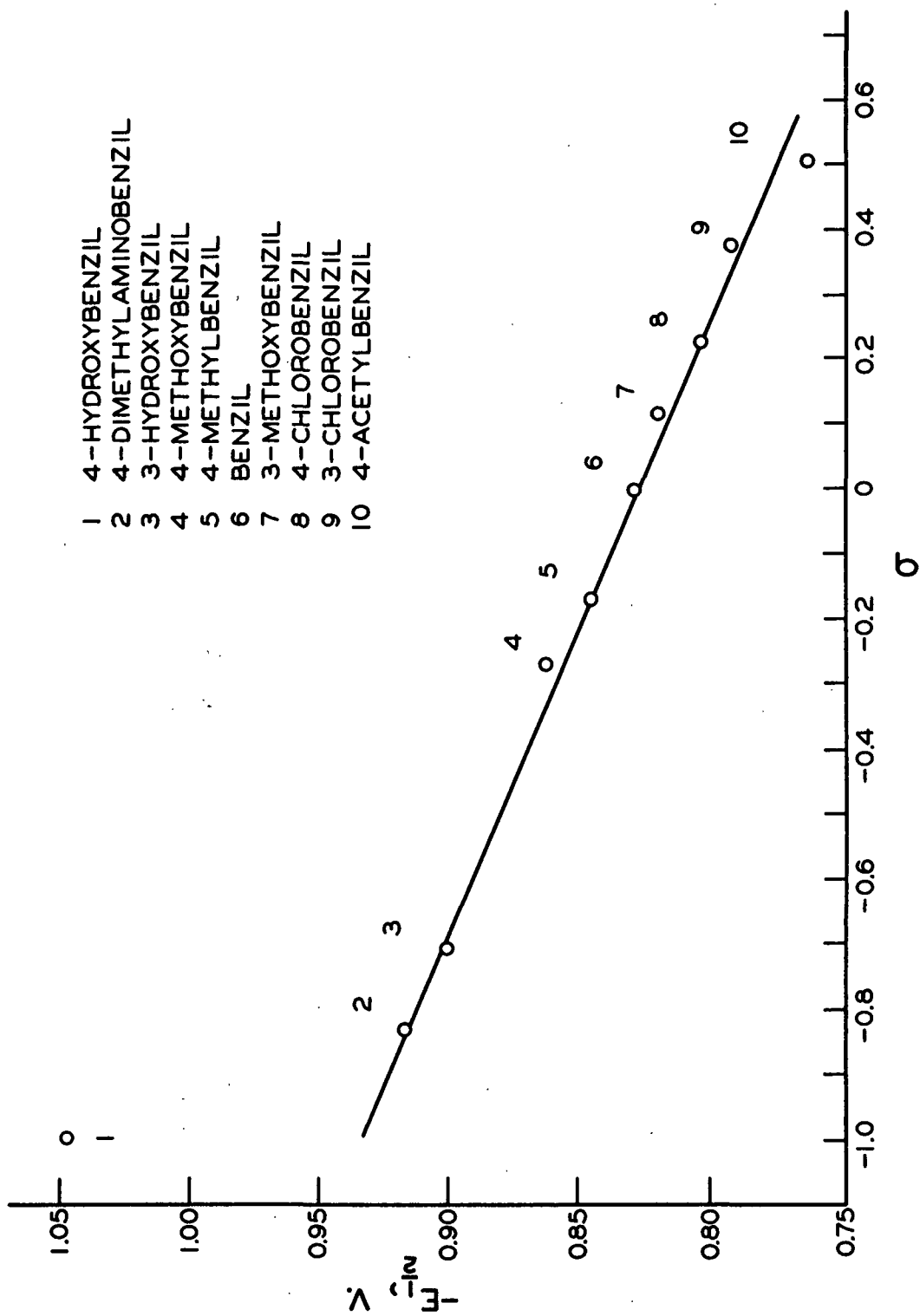


Figure 7. Hammett Correlation for Unsymmetrical Benzils, pH 13.6



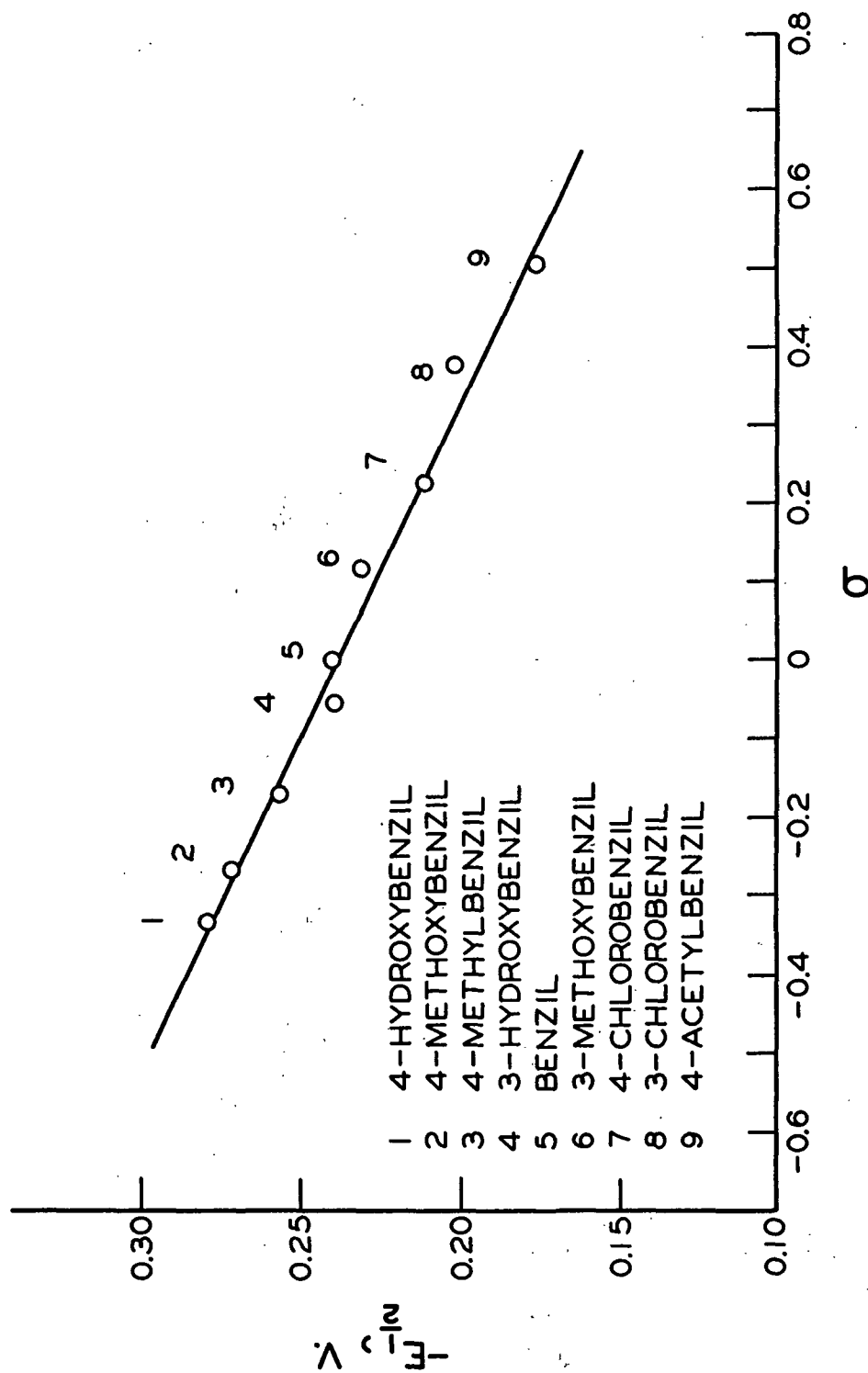


Figure 8. Hammett Correlation of Unsymmetrical Benzils, pH 1.3

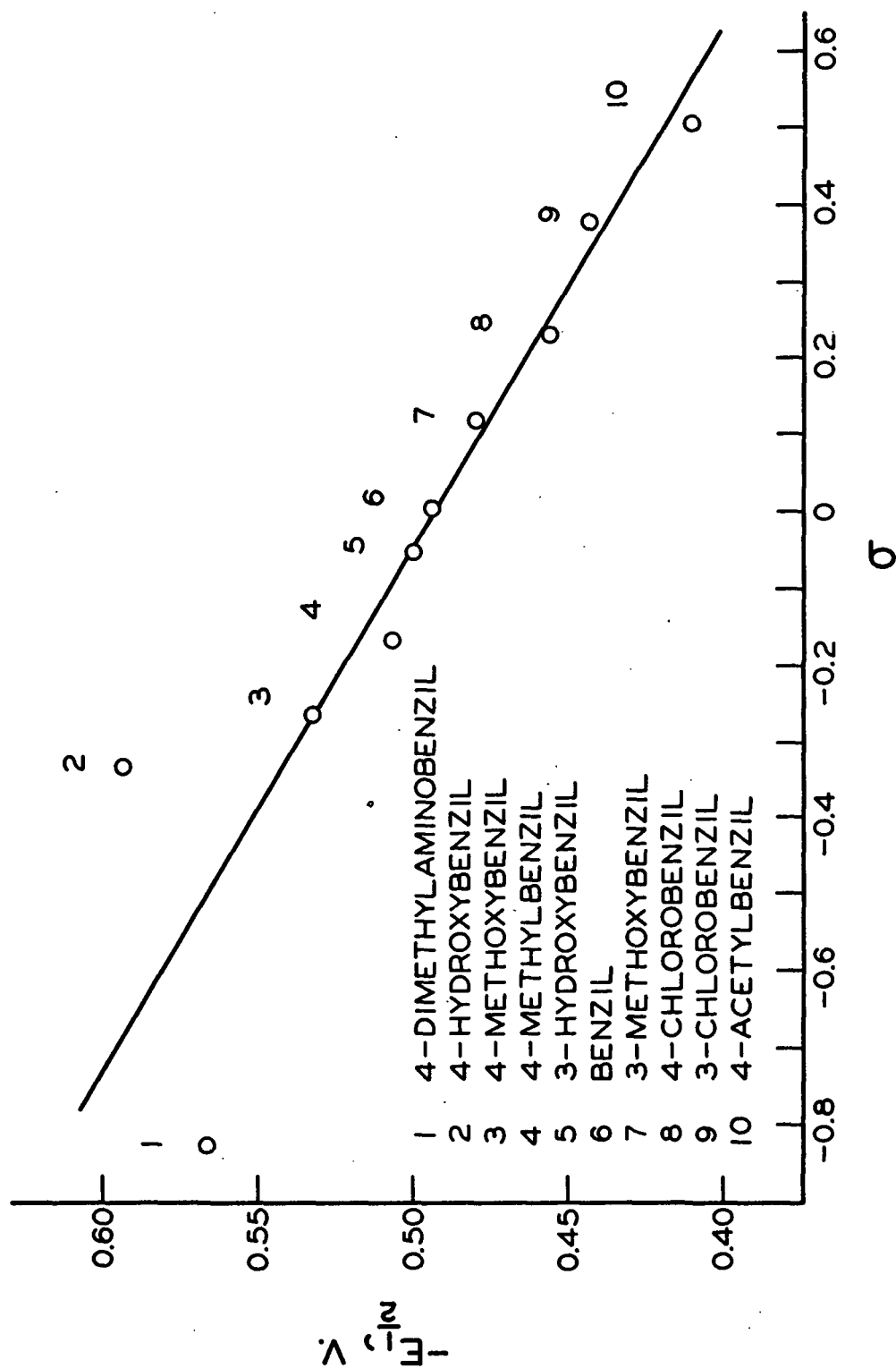


Figure 9. Hammett Correlation of Unsymmetrical Benzils, pH 5.5

At pH 5.5, the slope of the line obtained was 0.131 volt with a correlation coefficient of 0.913. These slopes at pH 1.3 and 5.5 correspond to rho values of 4.0 and 4.4, respectively. The slopes of the lines obtained in Hammett correlations at all three pH's are quite similar. Differences probably arise from the effects of irreversibility.

Since there is no obvious change in slope in Hammett correlations when going from electron-attracting to electron-donating substituents, it would appear that the carbonyls in unsymmetrical benzils do not operate independently, and it would be difficult to distinguish the carbonyls as to ease of reduction. This means the sigma values of benzil derivatives which are substituted on both rings should be additive.

In order to reveal the extent that sigma values are additive, the direct comparison of symmetrical and unsymmetrical benzils was made. If the sigma values were perfectly additive, then the reduction of a disubstituted symmetrical compound would be twice as difficult or, depending on sigma, twice as easy as the corresponding monosubstituted compound. This may be seen from the equation of the straight line obtained in a Hammett correlation which would be

$$E_{1/2} - E_{1/2}^0 = (0.0591/n) \rho (\sigma_1 + \sigma_2)$$

where  $\sigma_1$  and  $\sigma_2$  are the Hammett substituent constants for the first and second phenyl rings, respectively.

However, if the sigma values are not completely additive and if it is assumed that the initial reduction site occurs adjacent to the phenyl ring with the least electron-donating power, then only a fraction ( $\underline{x}$ ) of the electron-donating power of the substituent on the distant ring will be felt. The appropriate equation of the line obtained in a Hammett plot would then be

$$E_{1/2} - E_{1/2}^{\circ} = (0.0591/n) \rho (\sigma_1 + x \sigma_2)$$

where  $\sigma_1$  is the Hammett substituent constant for the substituent on the phenyl ring adjacent to the initial reduction site and  $\sigma_2$  is for the phenyl ring remote from the initial reduction site.

In the case of benzil derivatives substituted with electron-withdrawing groups, it can easily be shown that

$$x = \left[ (E_{1/2}'' - E_{1/2}^{\circ}) / (E_{1/2}' - E_{1/2}^{\circ}) \right] - 1$$

where  $E_{1/2}'$  refers to a monosubstituted unsymmetrical benzil and  $E_{1/2}''$  refers to the corresponding disubstituted symmetrical benzil. If the difference between the half-wave potentials of the symmetrical benzil and benzil is twice the difference between the half-wave potentials of the corresponding unsymmetrical benzil and benzil, then the fraction  $x$  equals one and the sigma values would be additive.

The same reasoning applies in the case of benzil derivatives substituted with electron-donating groups where it can be shown that

$$1/x = \left[ (E_{1/2}'' - E_{1/2}^{\circ}) / (E_{1/2}' - E_{1/2}^{\circ}) \right] - 1$$

Values of  $x$ , expressed as percentages, were determined from available half-wave potential data and are given in Table VII. If the Hammett sigma values were perfectly additive the percentages would be 100%. However, the values are less than 100%. For example, with 3,3'-dichlorobenzil at pH 13.6, only 71% of the electron-withdrawing power of the second ring is effective in regulating the reduction. Correspondingly, only 84% of the electron-donating power of the second 4-methyl group in 4,4'-dimethylbenzil is effective in regulating the reduction.

TABLE VII

## ADDITIVITY OF HAMMETT SIGMA VALUES

Compound	Sigma Value from Remote Ring Influencing Reaction Site, %		
	pH 1.3	pH 5.5	pH 13.6
3,3'-Dichlorobenzil	97	82	71
4,4'-Dichlorobenzil	90	77	67
3,3'-Dimethoxybenzil	67	64	62
4,4'-Dimethylbenzil	82	81	84
4,4'-Dimethoxybenzil	100	97	92
4,4'-Bis(dimethylamino)benzil	--	94	85

From these data it appears that the phenyl group with the greatest electron-withdrawing power has the strongest influence on the reduction. Therefore, it appears that the electrons preferentially enter the carbonyl adjacent to the ring with the greatest electron-withdrawing power. However, the dicarbonyl system is still reduced essentially as a single unit. This conclusion is supported by the work of Leonard, Laitinen, and Mottus (7) who suggested that half-wave potential values for various cyclic 1,2-diketones were influenced by the degree of coplanarity of the dicarbonyl system allowed by the ring size.

The involvement of the second carbonyl in the reduction of benzil derivatives probably arises due to polarization of the dicarbonyl system as shown in Fig. 10. This diagram is a simple extension of the one-electron, one-proton process suggested by Leonard, Laitinen, and Mottus (7) for the reduction of aliphatic dicarbonyl compounds. In the extreme case of polarization, a double bond is formed between the carbonyls. Hydrogen ion aids in the process by protonating the oxygen of the remote carbonyl. The molecule is then prepared for the addition of two electrons after which a hydrogen ion is added to form the enediol intermediate.

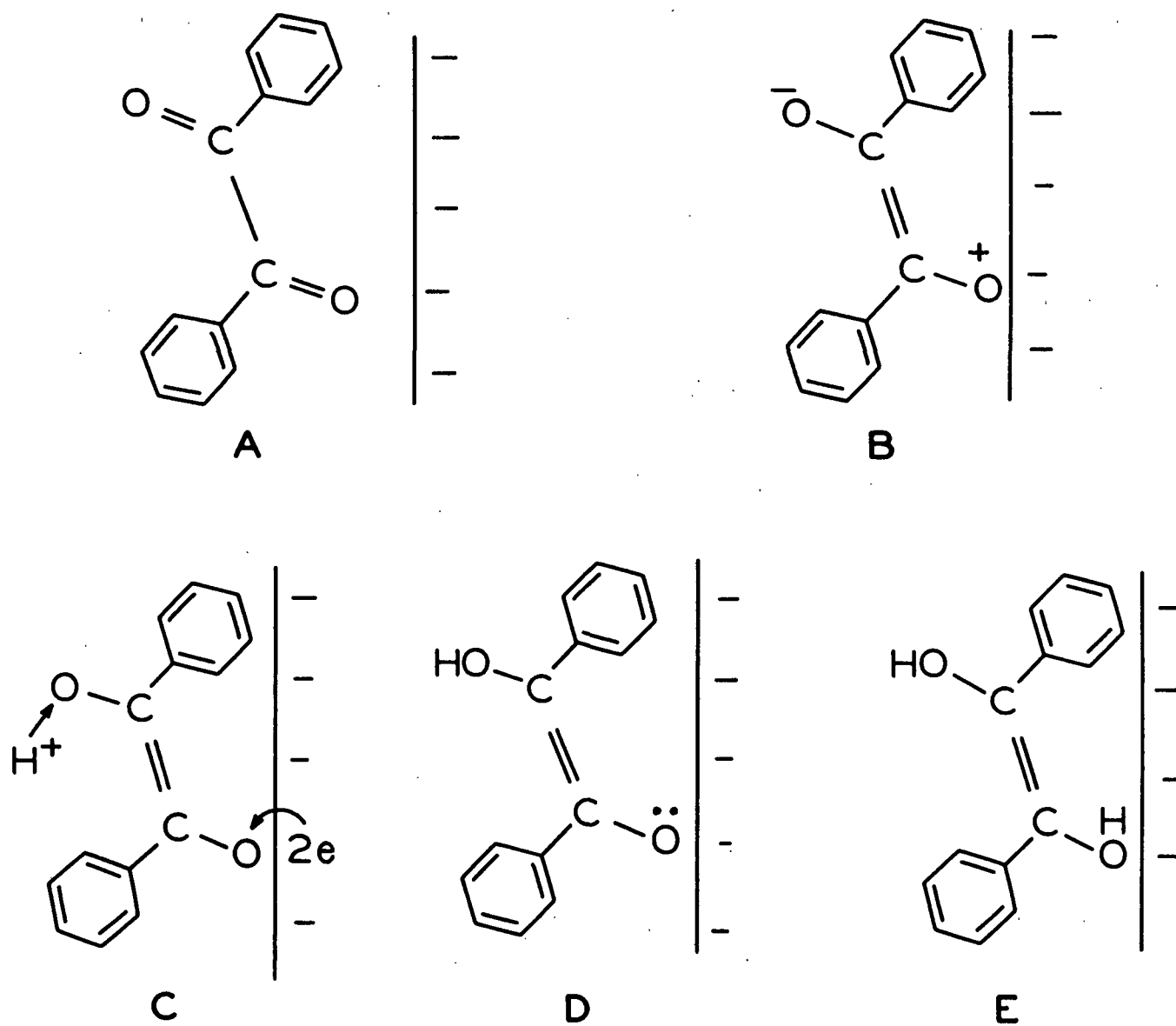


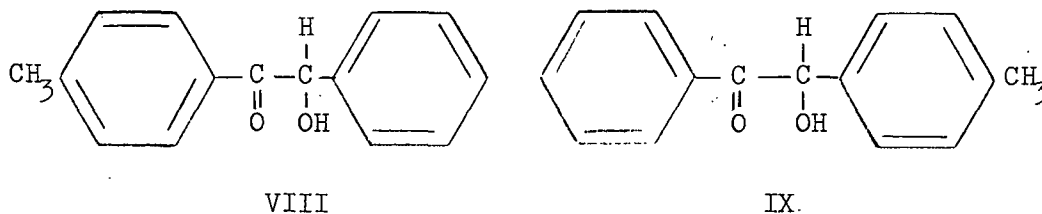
Figure 10. Behavior of Benzil Derivative at the Electrode

The data indicate that the assumption that the carbonyls are reduced as a unit and that the sigma values are approximately additive is essentially valid. If the sigma values are to be considered additive it should be permissible to plot disubstituted symmetrical benzils on the same Hammett plots shown earlier for the unsymmetrical compounds. Figure 11 is such a Hammett plot obtained at pH 13.6. Hydroxy-disubstituted benzil derivatives have not been included. All the symmetrical compounds plotted seem to correlate reasonably well with the straight line whose slope has been determined in Fig. 7.

Figure 12 is the Hammett plot at pH 1.3 with disubstituted symmetrical compounds included. Hydroxy-disubstituted compounds have also been included since 4-hydroxybenzil did not deviate from the straight line determined in Fig. 8. Again the correlation of the symmetrical compounds with the straight line is good.

#### PRODUCTS OF THE REDUCTION

In every case, reduction of a benzil derivative gave a benzoin derivative. However, two benzoin isomers may be formed from a single unsymmetrical benzil derivative. For example, 4-methylbenzil might be expected to give either 4-methylbenzoin (VIII) or 4'-methylbenzoin (IX). Primes (') are used to indicate substitution on the ring adjacent to the carbinol carbon atom. The higher melting, more stable isomer is found to be the isomer where the phenyl ring with the greater electron-donating power is adjacent to the carbonyl group.



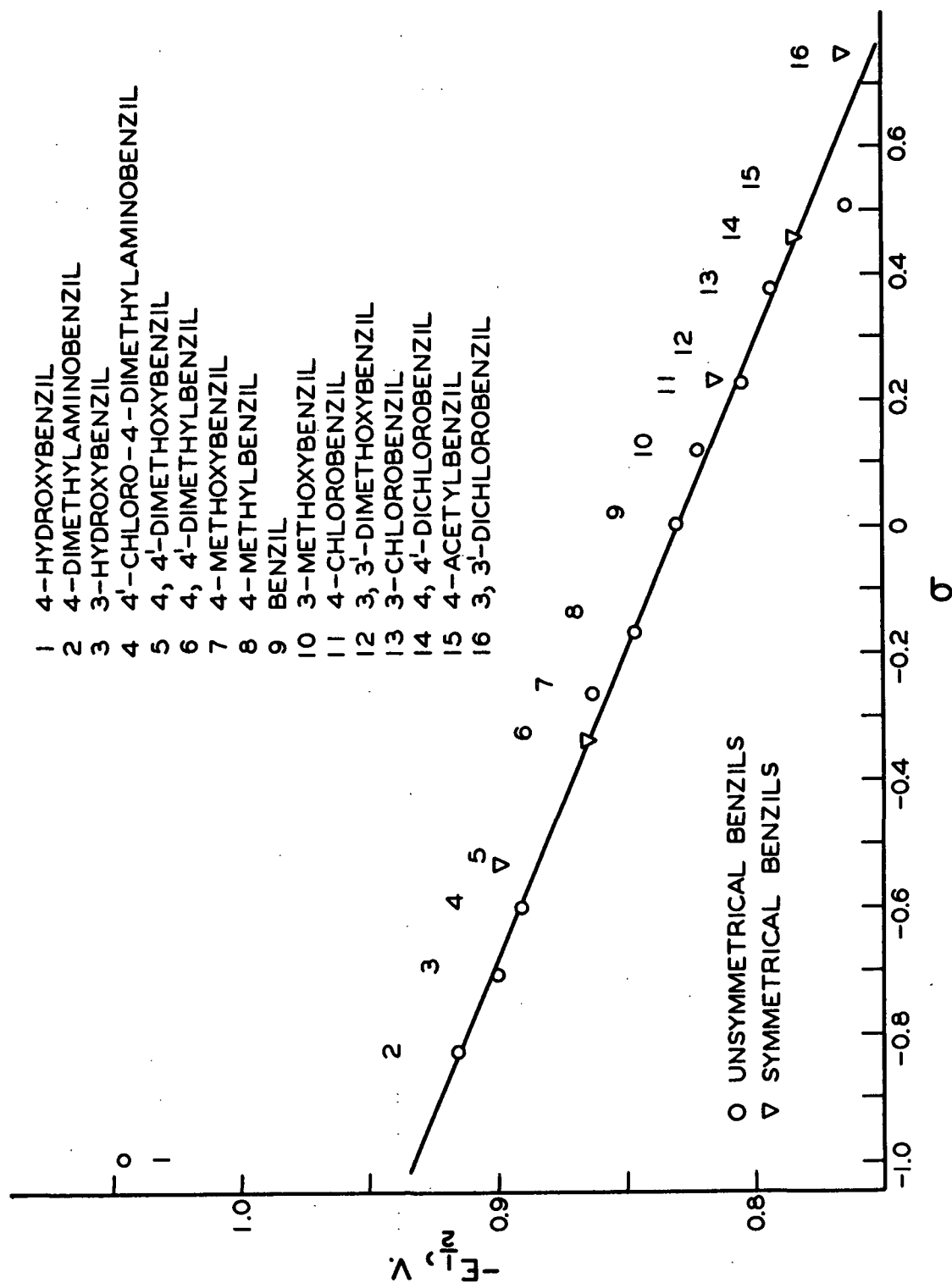


Figure 11. Hammett Correlation for Benzil Derivatives, pH 13.6



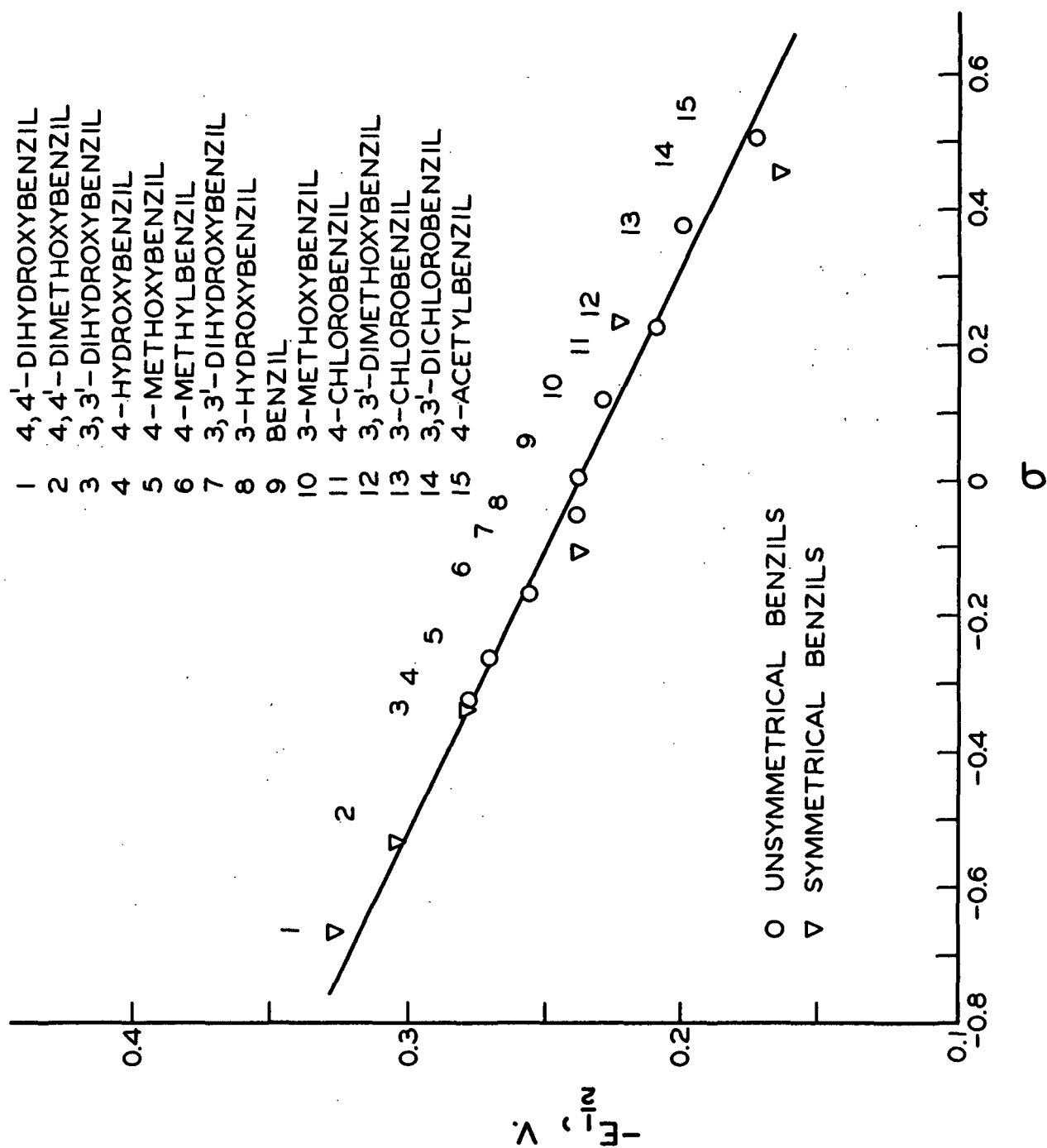


Figure 12. Hammett Correlation for Benzil Derivatives, pH 1.3

A controlled potential electrolysis of 4-methylbenzil was conducted at pH 5.5. The product was isolated in 95% yield. The homogeneous product was submitted for infrared analysis. Comparison with infrared spectra of known mixtures demonstrated that the product was 60% 4-methylbenzoin, the more stable isomer, and 40% 4'-methylbenzoin, the less stable isomer. These benzoin products are formed as a result of the rearrangement of the enediol at the electrode. The fact that such a high percentage of the less stable isomer was formed is an indication that the difference in stability of the two isomers is not very great. The 4-methyl group is a weak electron-donating group which could account for the small difference in stability between the two isomers.

In the reduction of 3-chlorobenzil it is likely that the more stable isomer, 3'-chlorobenzoin, would be the predominant product. The 3-chloro group is a strong electron-withdrawing group, and the difference in stability between the isomers should be large. A controlled potential electrolysis of 3-chlorobenzil was conducted at pH 5.5. The solution was concentrated, spotted on a thin-layer chromatogram, and developed in benzene. Only 3'-chlorobenzoin could be detected. However, small amounts of 3-chlorobenzoin would not be detectable since the known 3-chlorobenzoin spot trails just behind 3'-chlorobenzoin.

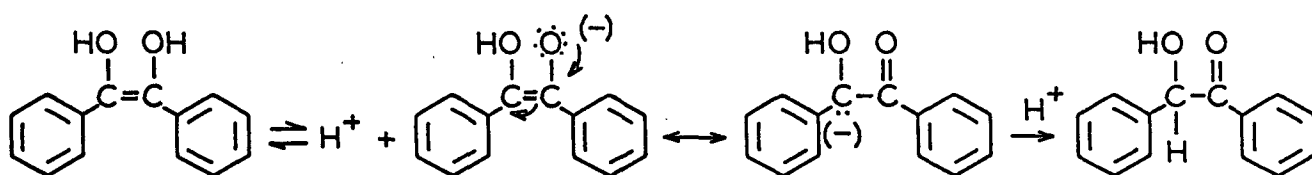
A controlled potential electrolysis of 4-acetylbenzil was conducted at pH 5.5. The product was isolated in 78% yield. As expected, the product appeared to be predominantly the more stable isomer, 4'-acetylbenzoin. The melting point of the crude product was 100-102.5°. This melting point was over a relatively narrow range and was close to the melting point of purified 4'-acetylbenzoin, 104.5-105.5°.

## STUDY OF SECOND AND THIRD WAVES

### EFFECT OF HYDROGEN ION CONCENTRATION

#### Effect on Appearance of a Second Wave

A suppressed second wave was observed at pH 1.3 and pH 5.5 for 3-chlorobenzil and 3,3'-dichlorobenzil. At pH 13.6, a second wave appeared for all compounds. The appearance of a second wave at the basic pH has already been explained in terms of rapid base-catalyzed rearrangement of the enediol to produce a reducible benzoin at the electrode. The appearance of a second wave at low pH for certain compounds indicates that a portion of the enediol of these compounds is rearranged at the electrode even at the low hydrogen ion concentration. The limiting currents of these suppressed second waves are low and may be controlled by the rate at which the enediol rearranges to the reducible benzoin. The observation of these second waves at low pH is not surprising in view of the mechanism proposed by Philp, Flurry, and Day (59) for the rearrangement of enediol to benzoin. Their mechanism, which was to account for the effect of acidity on the rearrangement, was as follows.



This mechanism would require that the ease of rearrangement depend upon the acidity of the enediol. An enediol substituted with strong electron-withdrawing groups would have a relatively high acid strength. Consequently, appreciable concentrations of the anion could be expected to form even at low pH, and hence a second wave could be observed.

Half-wave potentials and approximate limiting currents for second waves at pH 1.3 and pH 5.5 are given in Table VIII.

TABLE VIII  
HALF-WAVE POTENTIALS AND LIMITING CURRENTS  
OF SECOND WAVE AT LOW pH

Compound	pH 1.3		pH 5.5	
	$-E_{1/2}$ , v.	$i_d$ , $\mu$ a.	$-E_{1/2}$ , v.	$i_d$ , $\mu$ a.
3-Chlorobenzil	0.85	0.04	1.23	0.22
3,3'-Dichlorobenzil	0.80	0.15	1.19	0.40

#### Effect of Half-Wave Potential

The potential which coincides with the appearance of the second wave from the reduction of benzil derivatives at pH 13.6 is approximately the potential at which the corresponding benzoin derivatives are reduced. Half-wave potentials for second waves of benzil derivatives at pH 13.6 and half-wave potentials for the corresponding benzoin derivatives at pH 13.6 are given in Table IX. A single column is given for benzoin derivatives since half-wave potentials of benzoin isomer pairs are identical. The logical explanation for this is that at a high pH there is a rapid transformation from the original solution of a pure isomer to an equilibrium mixture of both isomers. Thus, when recording a polarographic curve on one of the members of a benzoin isomer pair, the wave obtained actually represents an equilibrium mixture of both isomers.

The formation of the equilibrium mixture at pH 13.6 is not instantaneous. With 3-chlorobenzoin, where the first polarographic wave was recorded within two minutes after start of addition of the solution to the basic buffer, a shift in half-wave potential of 0.018 volt was observed between the first wave which was recorded and a second wave recorded ten minutes later. This change in half-wave potential represents the change in composition of the solution as 3-chlorobenzoin

was being transformed to 3'-chlorobenzoin. The shift in half-wave potential is not representative of the total change in composition of the solution since a substantial portion of the 3-chlorobenzoin probably had already been transformed to 3'-chlorobenzoin during the two-minute interval before the first wave could be recorded.

TABLE IX

HALF-WAVE POTENTIALS OF THE SECOND WAVE OF BENZIL  
DERIVATIVES AND HALF-WAVE POTENTIALS OF  
BENZOIN DERIVATIVES

Compounds	$-E_{1/2}$ , v.		Difference, v.
	Second Wave	Corresponding Benzoin Derivative	
3-Chlorobenzil	1.533	1.516	+0.017
4-Chlorobenzil	1.532	1.517	+0.015
3-Methoxybenzil	1.552	1.546	+0.006
Benzil	1.564	1.558	+0.006
4-Methylbenzil	1.599	1.589	+0.010
4-Methoxybenzil	1.616	1.606	+0.010
4-Dimethylaminobenzil	1.685	1.689	-0.004
4'-Chloro-4'-dimethyl- aminobenzil	1.670	1.664	+0.006
3,3'-Dichlorobenzil	1.438	1.422	+0.016
4,4'-Dimethylbenzil	1.620	1.610	+0.010
4,4'-Dimethoxybenzil	1.623	1.621	+0.002

A number of benzoin derivatives were studied at all three pH's. It was felt that such a study of the reduction of benzoin derivatives would give direct insight into the path of the reduction represented by the second wave of benzil derivatives. By studying the benzoin derivatives directly, waves can be obtained which are free from the complicating effects of the reduction occurring in the

first wave. The half-wave potential data obtained from benzoin derivatives is given in Table X.

TABLE X  
HALF-WAVE POTENTIALS OF BENZOIN  
DERIVATIVES AT 25°

	$-E_{1/2}$ , v.		
	pH 1.3	pH 5.5	pH 13.6
3-Chlorobenzoin	0.751	1.160	1.516
3'-Chlorobenzoin	0.802	1.219	1.516
4-Chlorobenzoin	0.777	1.194	1.517
4'-Chlorobenzoin	0.801	1.221	1.517
3-Methoxybenzoin	0.791	1.211	1.546
Benzoin	0.814	1.247	1.558
4-Methylbenzoin	0.824	1.262	1.589
4'-Methylbenzoin	0.802	1.238	1.589
4-Methoxybenzoin	0.855	1.300	1.606, 1.704
4-Dimethylaminobenzoin	0.783	--	1.689
4'-Chloro-4-dimethyl- aminobenzoin	0.783	--	1.664
3,3'-Dichlorobenzoin	0.752	1.136	1.422, 1.70
4,4'-Dimethylbenzoin	0.814	1.251	1.610
4,4'-Dimethoxybenzoin	0.848	1.279	1.621, 1.75

Two distinct waves were observed at pH 13.6 for 4-methoxybenzoin and 4,4'-dimethoxybenzoin, and separate half-wave potentials for these waves are given in Table IX. Two distinct waves were also believed to be present for 4-dimethylaminobenzoin and 4'-chloro-4-dimethylaminobenzoin, but the second wave was masked by decomposition current; half-wave potentials for these compounds are reported for the first reduction step only. A small irreversible second wave, with a half-wave potential of approximately 1.70, was observed for 3,3'-dichlorobenzoin at pH 13.6. All other benzoin derivatives at pH 13.6 exhibited only one distinct wave. This wave was assigned a single half-wave potential even though it was felt that the wave was actually a combination of two waves with similar half-wave potentials. No half-wave potentials have been reported at pH 5.5 for 4-dimethylaminobenzoin and

4'-chloro-4-dimethylaminobenzil since these compounds did not give distinct waves at this pH under the conditions employed.

The dependency of half-wave potential on pH for the unsymmetrical benzoin is shown in Fig. 13. As with the benzil derivatives, the reductions are less pH dependent in basic media than in acidic media. However, in acidic media the dependency on pH is slightly greater for the benzoin derivatives than it was for the benzil derivatives.

#### Effect on Diffusion Current

The diffusion current values for benzoin and benzoin derivatives at the three pH's studied are given in Table XI. Values of the diffusion current at pH 1.3 are slightly less than the diffusion current for the corresponding benzil derivatives at pH 1.3. Assuming two-electron reductions, this means that benzoin derivatives diffuse slower in ethanol-water than the corresponding benzil derivatives. A slight reduction in diffusion rate can be attributed to the aliphatic hydroxyl which is likely to have some interaction with the solvent and slow down the diffusion of the molecule.

Diffusion currents for benzil derivatives decreased slightly with increase in pH. The same behavior might be expected for benzoin derivatives. However, the data in Table XI show that the diffusion current at pH 5.5 is approximately 40% greater than the diffusion current at pH 1.3. This increase in diffusion current would correspond to a change from a two-electron reduction at pH 1.3 to a three-electron reduction at pH 5.5.

The diffusion currents at pH 13.6 are somewhat difficult to interpret. For the 4-methylbenzoin there is a slight increase in diffusion current from pH 5.5 to pH 13.6. However, for most other benzoin derivatives there is a decrease in

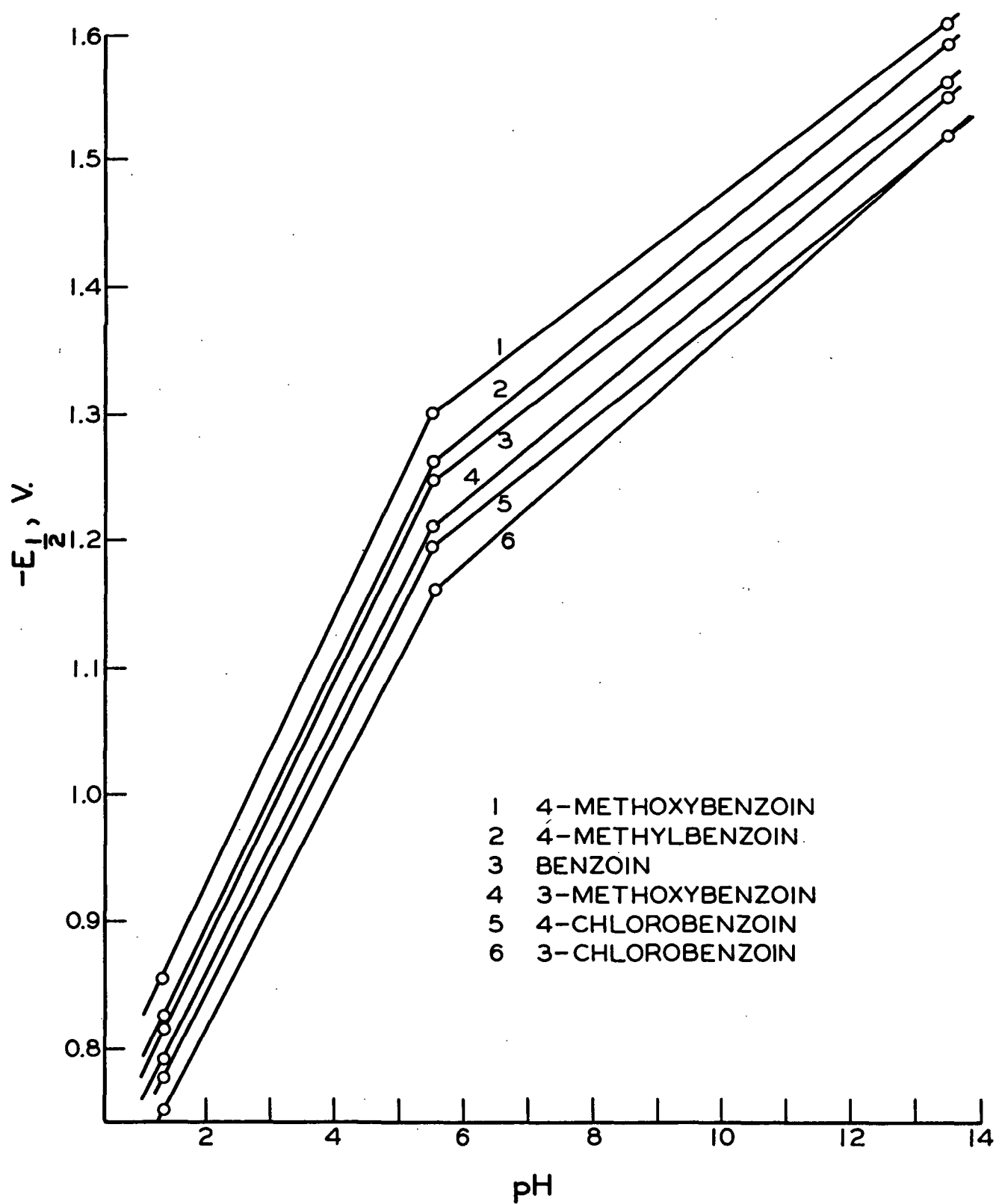


Figure 13.  $E_{1/2}$  vs. pH for Unsymmetrical Benzoin



diffusion current from pH 5.5 to pH 13.6. This is because diffusion currents at pH 13.6 for benzoin derivatives show a definite decrease with increasing sigma value of the substituents. The drop in diffusion current with increase in sigma is shown in Fig. 14.

TABLE XI

DIFFUSION CURRENT FOR BENZOIN DERIVATIVES AT 25°

	$\frac{i}{d}$ , $\mu$ a.		
	pH 1.3	pH 5.5	pH 13.6
3-Chlorobenzoin	2.00	2.86	2.08
3'-Chlorobenzoin	2.02	2.88	2.08
4-Chlorobenzoin	2.05	2.91	2.20
4'-Chlorobenzoin	2.07	2.80	2.22
3-Methoxybenzoin	2.08	2.86	2.52
Benzoin	2.15	2.79	2.74
4-Methylbenzoin	2.08	2.77	2.91
4'-Methylbenzoin	2.11	2.64	2.84
4-Methoxybenzoin	2.02	2.82	1.95, 0.094
4-Dimethylaminobenzoin	1.98	--	1.80
4'-Chloro-4-dimethyl-aminobenzoin	1.90	--	1.80
3,3'-Dichlorobenzoin	1.96	2.79	0.72, 0.046
4,4'-Dimethylbenzoin	1.88	2.52	2.64
4,4'-Dimethoxybenzoin	1.96	2.70	1.97, 0.098

The most logical explanation for this decrease in diffusion current is a decrease in the effective concentration of reducible species. At pH 13.6, this decrease is most likely to be due to transformation of a large portion of the enediol form of the benzoin to an ionized form. Concentration of the nonreducible ionized form would increase with increasing acidity of the enediol. Therefore, diffusion current of benzoin derivatives at pH 13.6 decreases with increasing electron-withdrawing power of the substituents.

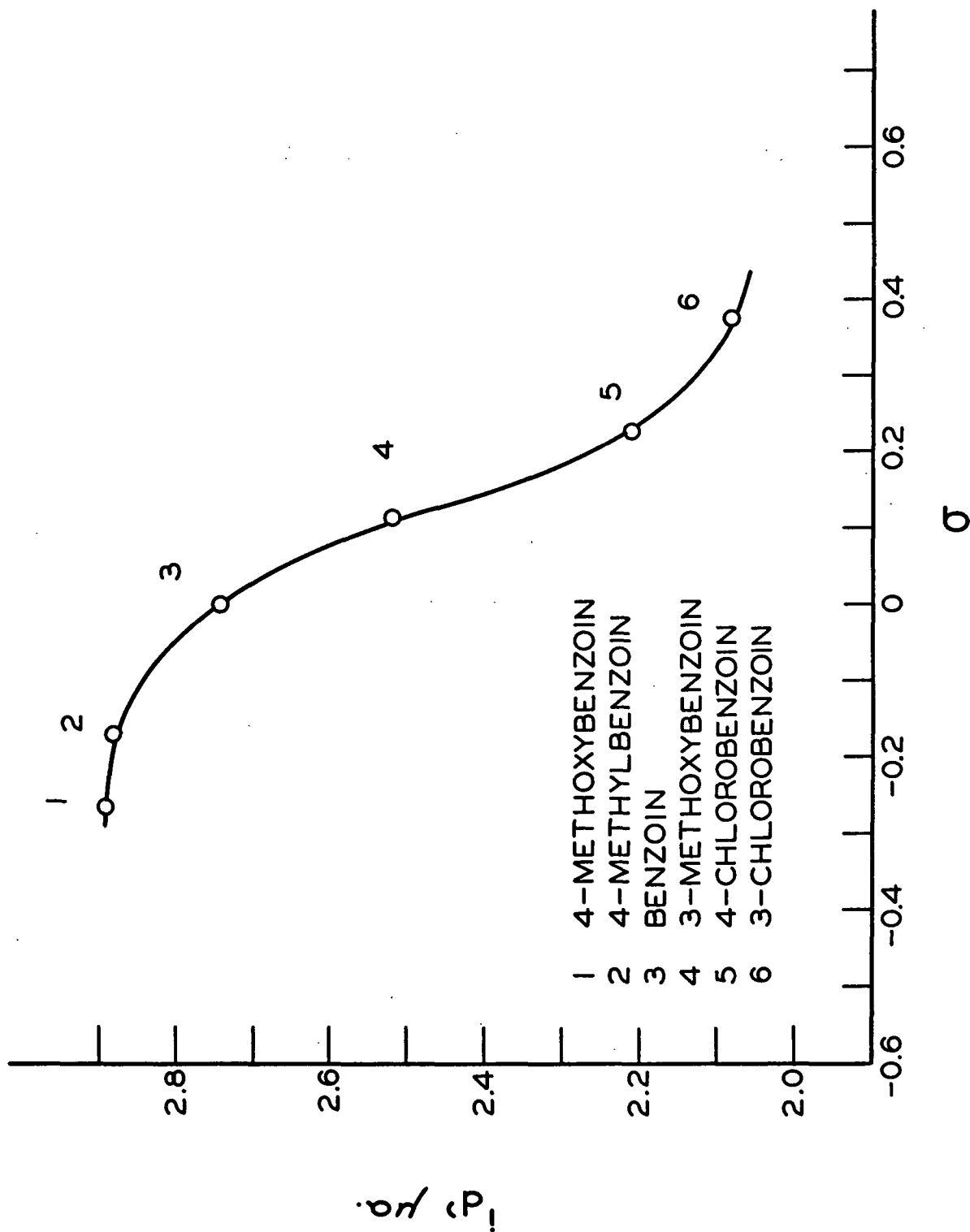


Figure 14. Diffusion Current vs.  $\sigma$  for Unsymmetrical Benzoin, pH 13.6

## CORRELATION OF SUBSTITUENTS WITH THE REDUCTION

The half-wave potential of an unsymmetrical benzoin substituted in the ring adjacent to the carbonyl group is quite sensitive to electron-withdrawing or -donating character of the substituent. Figure 15 is a plot of half-wave potential versus sigma values for these benzoin at pH 1.3. A similar plot is shown in Fig. 16 for pH 5.5. The slopes of the straight lines formed in these plots are -0.150 volt at pH 1.3 and -0.207 volt at pH 5.5. These slopes correspond to rho values of 5.1 and 7.0, which are slightly greater than the values obtained for benzil derivatives.

The reduction of an unsymmetrical benzoin substituted in the ring adjacent to the carbinol group is not as sensitive to the electron-withdrawing or -donating powers of the substituent. The half-wave potential values for these compounds do not fall on the lines in Fig. 15 and 16. They would be expected to fall on the lines only if the half-wave potentials of benzoin isomers were approximately the same. This is not the case as can be seen from an examination of half-wave potential values reported in Table X. For example, the half-wave potentials of benzoin, 4'-chlorobenzoin, and 4-chlorobenzoin at pH 5.5 are 1.247, 1.221, and 1.194, respectively. In this case, 4-chlorobenzoin, with the electron-attracting chloro group located adjacent to the carbonyl, is the most easily reduced compound.

In another example, the half-wave potential values at pH 5.5 for benzoin, 4'-methylbenzoin, and 4-methylbenzoin are 1.247, 1.238, and 1.262, respectively. 4-Methylbenzoin, which has the electron-donating methyl group situated in the ring adjacent to the carbonyl, is harder to reduce than 4'-methylbenzoin. It may be noted that 4'-methylbenzoin is actually somewhat easier to reduce than benzoin in spite of the fact that the methyl group is an electron donator. The half-wave potential difference under discussion is small and it would be difficult to give

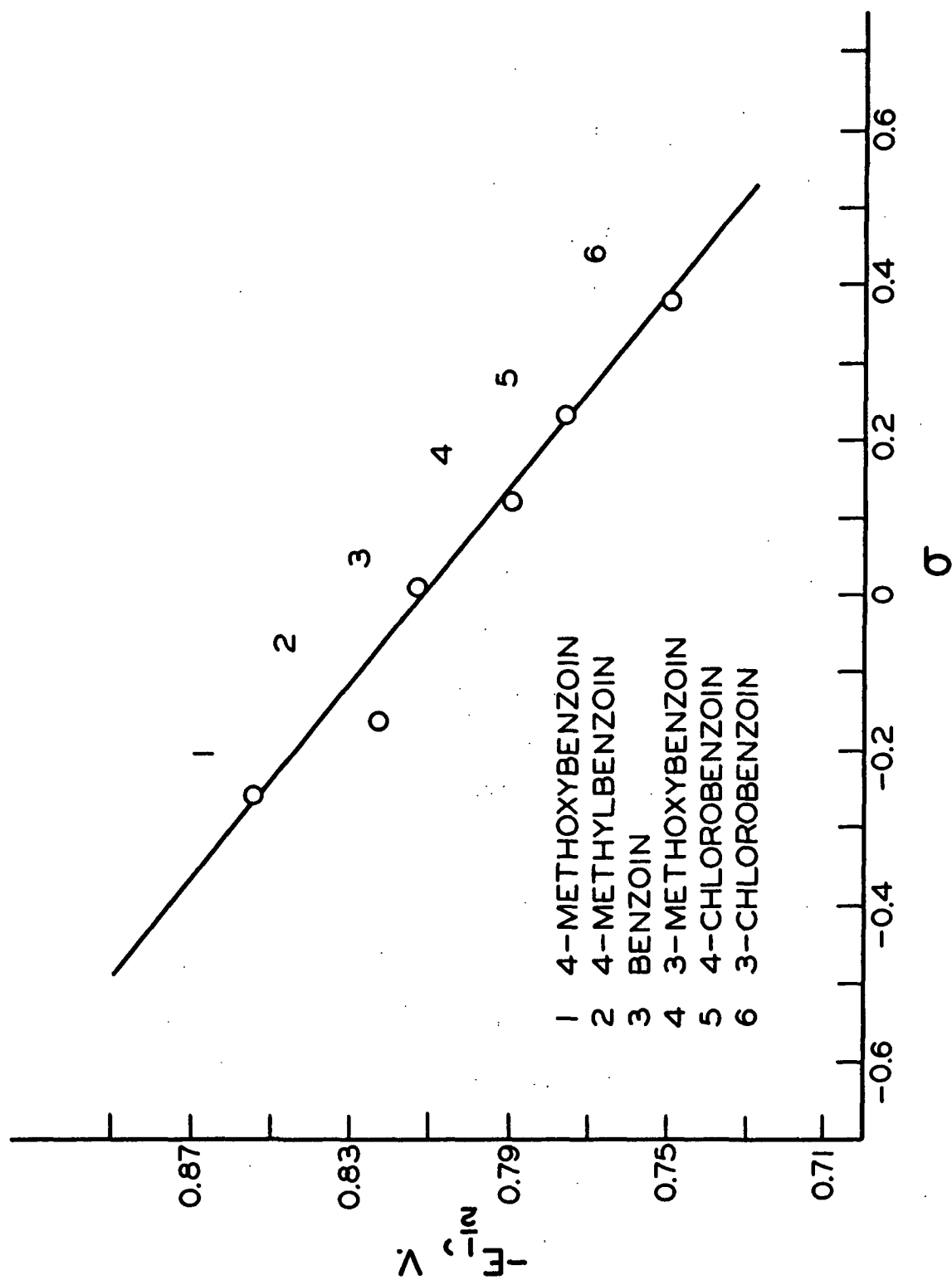


Figure 15. Hammett Correlation for Unsymmetrical Benzoin, pH 1.3

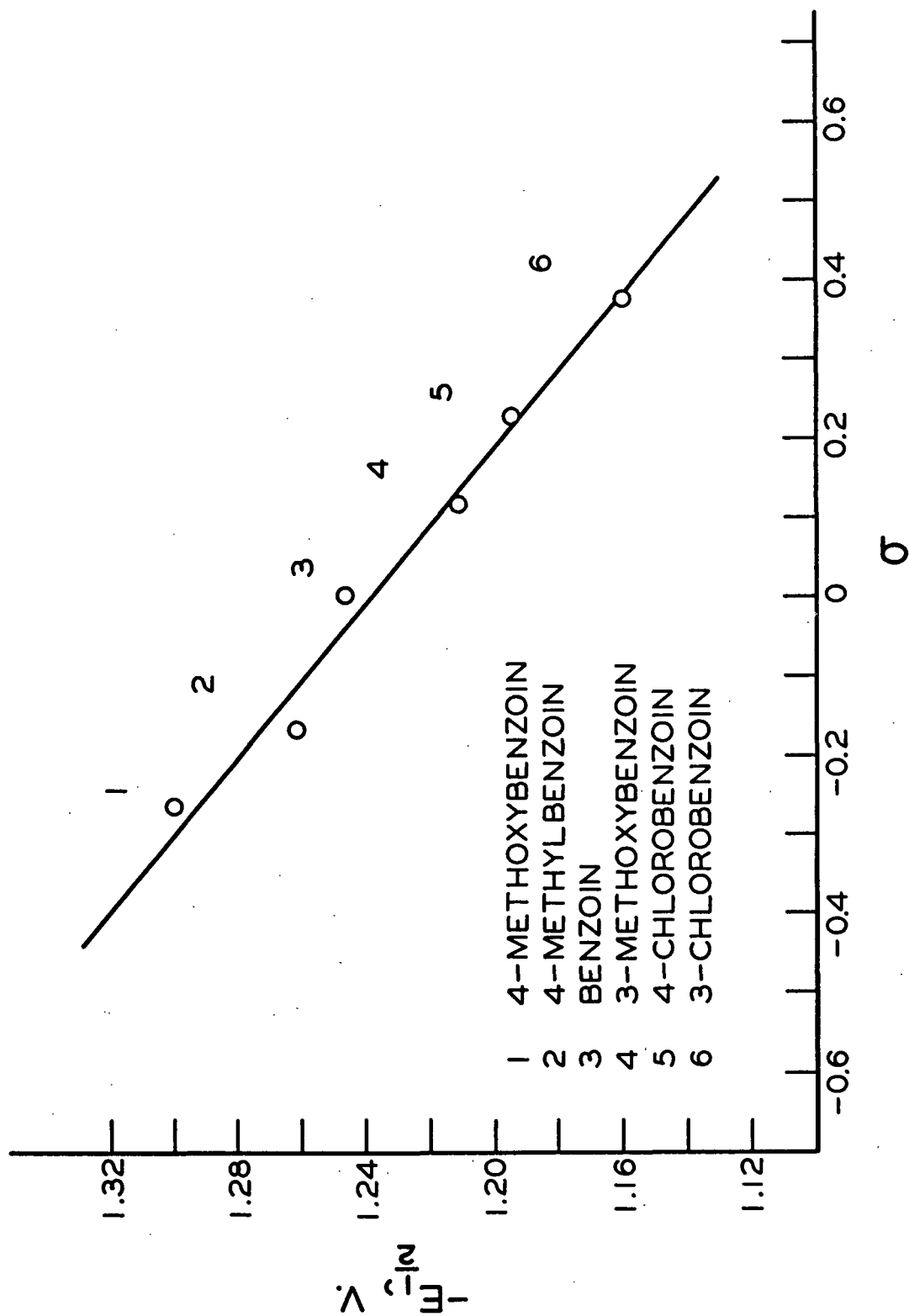


Figure 16. Hammett Correlation for Unsymmetrical Benzoin Condensation, pH 5.5

the data any meaningful interpretation. However, it also appears that 4'-methoxybenzoin, which was not available, would be easier to reduce than benzoin. This is because 4,4'-dimethoxybenzoin had a lower half-wave potential than 4-methoxybenzoin at low pH indicating that the methoxy group substituted on the ring adjacent to the carbinol group aids in the reduction.

In basic media, the half-wave potentials for benzoin isomer pairs are identical since the actual composition of the solution is an equilibrium mixture of isomers. The actual percentage of isomers at equilibrium is unknown so that half-wave potential values obtained at basic pH have limited significance.

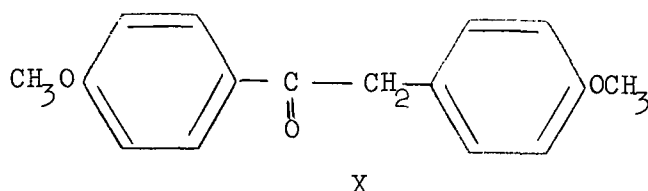
The most significant conclusion which can be drawn from the benzoin half-wave potential data is that the attack of the electron during reduction of benzoin isomers occurs at the carbonyl group. Electron-donating substituents on the ring adjacent to the carbonyl group hinder the reduction while electron-attracting groups aid in the reduction. This generalization cannot be made for substituents substituted in the ring remote from the carbonyl. The effect of substituents in this ring is small.

#### PRODUCTS AND MECHANISM OF THE REDUCTION

Evidence has been presented that, in the reduction of benzil derivatives, the second wave obtained represents a three-electron reduction of the benzoin product of the first wave. A three-electron wave could be accounted for by postulating an initial two-electron reduction of the benzoin to form a deoxybenzoin, followed by a one-electron reduction of the deoxybenzoin to form a deoxybenzoin pinacol.

In the reduction of 4,4'-dimethoxybenzoin at pH 13.6, the two-electron and one-electron processes are separated sufficiently to allow two separate waves

to be observed. If the first wave represents reduction to the deoxybenzoin derivative, then the second wave should occur at the same potential as a wave for authentic 4,4'-dimethoxydeoxybenzoin (X). The half-wave potential recorded for authentic 4,4'-dimethoxydeoxybenzoin was 1.749 at pH 13.6. This was almost identical to the value of 1.750 recorded for the second wave in the reduction of 4,4'-dimethoxybenzoin.



No wave was obtained for authentic 4,4'-dimethoxydeoxybenzoin at pH 1.3 because of the low decomposition potential. This would explain why only a two-electron wave is obtained for benzoin at pH 1.3 while a three-electron wave is obtained at the other pH's.

Reduction of benzoin has previously been reported to yield hydrobenzoin (V, see page 6) at all pH's (4). This would be the expected product of the reduction of benzoin, especially in view of the fact that half-wave potential data show that electron attack occurs at the carbonyl group. The reduction of benzoin to hydrobenzoin requires only two electrons. However, it has been seen that the reduction of benzoin is apparently a three-electron reduction at pH 5.5 and pH 13.6. Since hydrobenzoin was found to be stable to further reduction at the dropping mercury electrode, it would seem that hydrobenzoin is not formed during the reduction of benzoin at the dropping mercury electrode.

A controlled potential electrolysis at a mercury pool electrode was performed at 1.15 volts on benzoin at pH 5.5. The product was isolated and identified chromatographically as hydrobenzoin. No deoxybenzoin could be detected. This result is not in accord with polarographic data.

An extended controlled potential electrolysis of benzoin at pH 5.5 at the dropping mercury electrode was then made. The electrolysis was allowed to continue for six days at 1.260 volts. The voltage chosen was the voltage at which the current was two-thirds the diffusion current for the benzoin wave. This potential was chosen so that the product would represent no more than a two-electron reduction. After electrolysis the solution was extracted with benzene. The concentrated benzene extract was spotted on a thin-layer chromatogram. Only deoxybenzoin and the benzoin starting material could be detected.

To test whether the deoxybenzoin could have occurred from dehydration of hydrobenzoin during the long electrolysis, a blank was prepared containing hydrobenzoin at pH 5.5. After five days the solution was extracted, concentrated, and spotted. No deoxybenzoin could be detected. Therefore, deoxybenzoin is the product of the extended controlled potential electrolysis of benzoin at pH 5.5 at a dropping mercury electrode.

In view of the difference in products obtained at the mercury pool electrode and the dropping mercury electrode, another controlled potential electrolysis of benzoin was run at pH 5.5 at the mercury pool electrode. The applied potential was reduced to 0.8 volt. This potential was the lowest applied potential at which appreciable current would still flow. Analysis of the electrolyzed solution on the polarograph produced a wave which was identical to a wave obtained from a  $7.5 \times 10^{-5} \text{ M}$  solution of deoxybenzoin. This is good evidence that the concentration of deoxybenzoin which existed in the electrolyzed solution as product was  $7.5 \times 10^{-5} \text{ M}$ . This concentration represents 15% of the expected total product.

The electrolyzed solution was extracted with benzene and the benzene extract was concentrated and spotted on a thin-layer chromatogram. Deoxybenzoin was



identified as one of the products with the aid of 2,4-dinitrophenylhydrazine spray reagent. An unknown material was also present which did not move from the starting line on the chromatogram.

Some deoxybenzoin pinacol might be expected to be present, since the deoxybenzoin which is formed at the electrode is readily reducible at a slightly higher potential. Although the product of the reduction of deoxybenzoin over the entire pH range has not been well established, it appears to be a one-electron process. Lund (6) found that reduction of deoxybenzoin gave deoxybenzoin pinacol in both acid and basic solution. In this work, controlled potential electrolysis of authentic deoxybenzoin at pH 5.5 yielded deoxybenzoin pinacol, identified as a product by thin-layer chromatography.

From the above discussion, it appears that products obtained from controlled potential electrolysis of benzoin at a mercury pool electrode can be a function of applied potential. These results show that conclusions drawn from isolation of products after reduction of benzoin at a mercury pool electrode are not necessarily valid for a dropping mercury electrode. While either deoxybenzoin or hydrobenzoin could be obtained at the mercury pool electrode, deoxybenzoin was the initial product of reduction at the dropping mercury electrode. Deoxybenzoin pinacol is then formed by a secondary one-electron reduction of the deoxybenzoin formed at the electrode.

If deoxybenzoin is formed from the reduction of benzoin, then the carbinol group of the benzoin has been reduced to a methylene group. The carbonyl group remains intact. Yet the attack of the electrons is at the carbonyl group. The reduction mechanism which is proposed to explain these findings is diagrammed in Fig. 17.

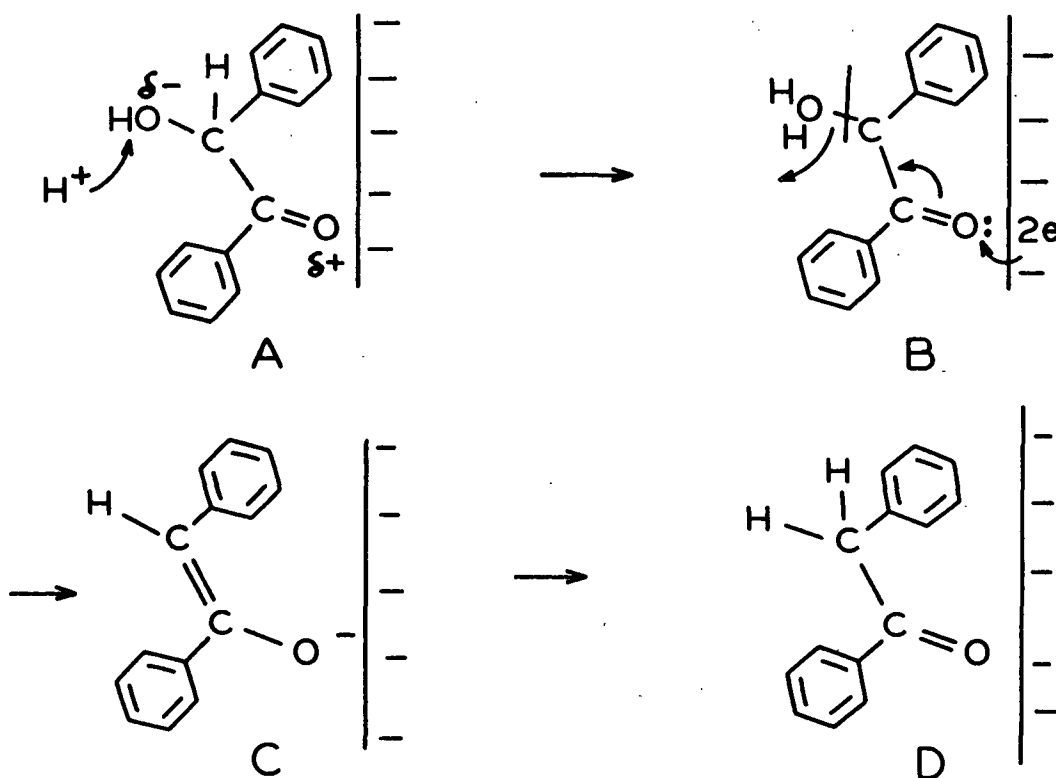


Figure 17. Behavior of Benzoin Derivative at the Electrode

The molecule approaches the electrode and becomes partially polarized. Partial polarization at the electrode encourages capture of a proton at the distant hydroxyl and prepares the oxygen for the addition of two electrons. In the next step, two electrons are added and there is a simultaneous elimination of water to form an enolate anion. This anion is then free to pick up a hydrogen and be converted to deoxybenzoin.

This mechanism is quite similar to the one proposed for the reduction of benzils where the initial electrons are added to the oxygen of the carbonyl group adjacent to the ring with the greatest electron-withdrawing power, and there is capture of a proton at the opposite end of the dicarbonyl system.

An important difference with benzil derivatives is that almost complete polarization of the dicarbonyl system is possible so that there is a very strong influence of the distant ring. In the reduction of benzoin, the substituted ring remote from the carbonyl does not have a well-defined influence.

## CONCLUSIONS

The reduction of unsymmetrical benzil derivatives proceeds through essentially the same path followed in the reduction of benzil and symmetrical benzil derivatives. That is, the reduction proceeds through an enediol which rearranges to form a benzoin product. With unsymmetrical benzil derivatives, the data suggest that the electrons are added to the carbonyl remote from the electron-donating ring. However, the dicarbonyl system is still reduced essentially as a single unit. The involvement of the second carbonyl group probably arises due to polarization of the dicarbonyl system. Since both carbonyls are involved in the reduction, Hammett sigma values for disubstituted benzils such as 4'-chloro-4-dimethylaminobenzil are approximately additive.

The products of reduction of unsymmetrical benzil derivatives are benzoin isomers. The fraction of the electronically less stable benzoin isomer which is formed can be as high as 40%. This percentage decreases with increasing electron-donating or electron-withdrawing power of the substituents.

The second polarographic wave in the reduction of benzil derivatives is due to the reduction of benzoin derivatives. The initial products of the reduction of benzoin derivatives are deoxybenzoin derivatives. At pH 5.5 and 13.6 these deoxybenzoin derivatives are in turn reduced in a one-electron step to form a deoxybenzoin pinacol.

The proposed mechanism for the reduction of benzoin derivatives is similar to that proposed for benzil derivatives. Half-wave potential data indicate that the attack of the electrons is at the carbonyl. It is further suggested that the molecule is partially polarized at the electrode and a proton is captured at the distant hydroxyl. This is followed by simultaneous elimination of water and

the addition of two electrons to the carbonyl. Hydrogen ion is then added and the deoxybenzoin product is formed.

It should be emphasized that the reaction schemes proposed here are only attempts to suggest possible logical mechanisms consistent with the limited amount of experimental data.

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