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Part I. Correlation of polarographic reduction potentials of organic carbonyl compounds with reactivity. Part II. Reactivity of furans bearing electron-attracting substituents

Frederik Snelling Schultz
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PART I
CORRELATION OF POLAROGRAPHIC REDUCTION
POTENTIALS OF ORGANIC CARBONYL COMPOUNDS WITH REACTIVITY

PART II
REACTIVITY OF FURANS
BEARING ELECTRON-ATTRACTING SUBSTITUENTS

by
Frederik Snelling Schultz

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Physical Organic Chemistry

Approved:

Signature was redacted for privacy.

In Charge of Major Work

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Iowa State College

1950

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PART I

CORRELATION OF POLAROGRAPHIC REDUCTION
POTENTIALS OF ORGANIC CARBONYL COMPOUNDS WITH REACTIVITY

I. INTRODUCTION

Half-wave potentials obtained from polarographic studies have been shown to have thermodynamic significance when reversible systems¹ are being studied.² However, in organic chemistry the reversible systems are limited to a few quinone-hydroquinone types.^{2b,3} In such reversible systems the half-wave potentials determined in well-buffered solutions are equal to the standard reduction potentials of the compounds in question. However, no satisfactory thermodynamic treatment has been developed for the irreversible reduction of organic compounds.

A large number of organic compounds which are irreversibly reduced at the dropping mercury electrode have been studied.^{2a,3} Because early investigators in this field did not realize the significance of hydrogen ions in the electrode reaction and carried out their studies in unbuffered solutions, their work is of doubtful value. Different methods of determining

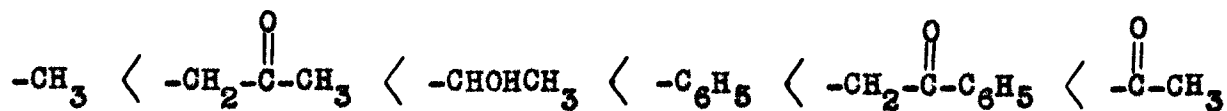
1. A reversible system is defined as one in which the products of reduction (or oxidation) at the dropping mercury electrode are oxidized (or reduced) at the same potential at which they were formed.

2. (a) I. M. Kolthoff and J. J. Lingane, "Polarography," Interscience Publishers, Inc., New York, 1941; (b) O. H. Muller in A. Weissberger, "Physical Methods of Organic Chemistry," Vol. II, Chap. XXIII, Interscience Publishers, Inc., New York, 1946.

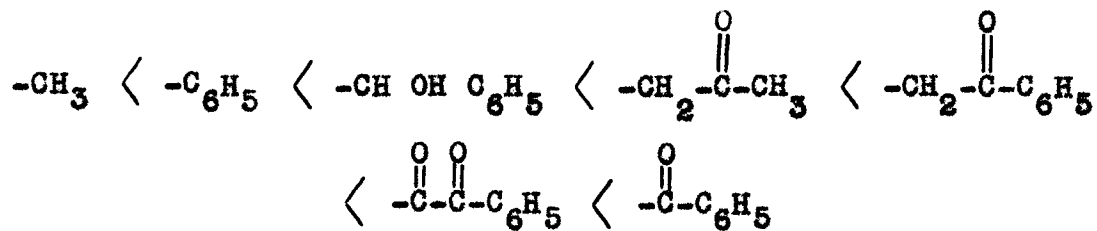
3. S. Wawzonek, Anal. Chem., 21, 61 (1949).

the reduction potential from the polarogram were used by these investigators, making comparisons difficult. The latter difficulty has been met by establishing a standard practice of reporting the half-wave potential.

Investigators,⁴ by observing the change in reduction potential of an analogous series of compounds, have been able to formulate electronegativity series for various groups attached to the same reducible function. Such series, however, turn out to be a function not only of the substituent groups but also of the nature of the parent functional group. For example, if $\text{CH}_3-\overset{\text{O}}{\parallel}{\text{C}}-$ is taken as the parent group the reduction potential is shifted to more positive values by the introduction of various groups, the effect increasing in the following order:



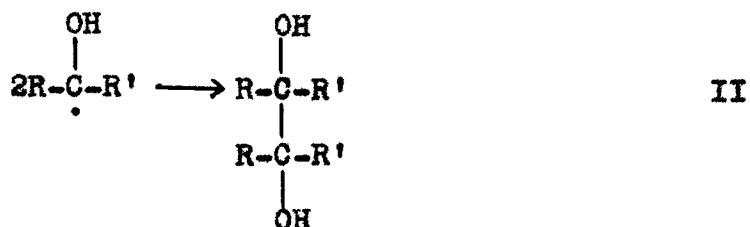
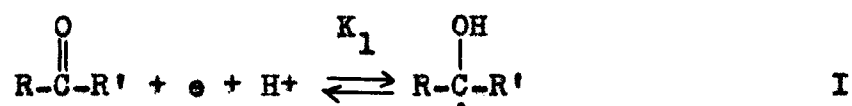
However, if $\text{C}_6\text{H}_5-\overset{\text{O}}{\parallel}{\text{C}}-$ is taken as the parent the following order is observed:



Strong evidence has been advanced to show that the first product in the polarographic reduction of a carbonyl compound

4. M. Shikata and I. Tachi, Coll. Czech. Chem. Commun., 10, 368, (1938).

is a radical which subsequently dimerizes⁵ as follows:

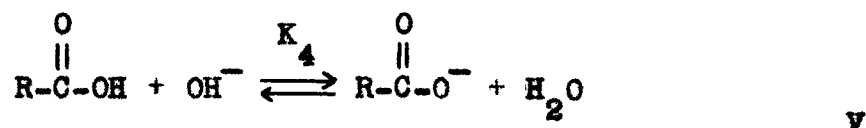
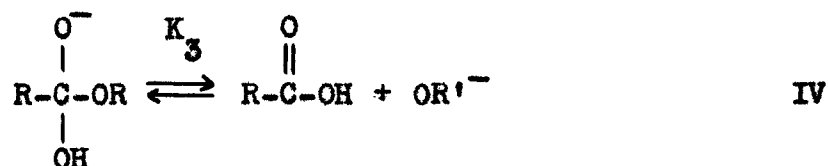
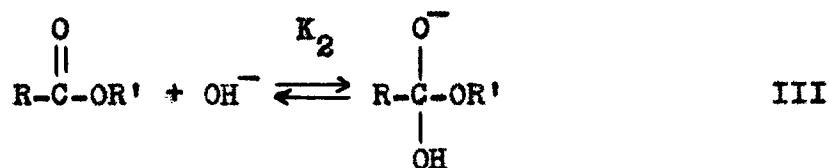


The first step is probably reversible and the second irreversible. The potential, then, at which an electron is added to the carbonyl group would be dependent on the free energy change for reaction I and the rate of dimerization of the free radical. The former depends strongly on such factors as the polar (dipole) interaction between the substituent groups and the carbonyl group and the relative amounts of resonance energy in the carbonyl compound and the free radical. Therefore it should be informative to discuss variations in half-wave potentials for a series of compounds in terms of these variables.

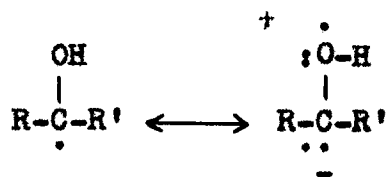
These changes in intramolecular interactions should be somewhat analogous to those observed in many reactions of carbonyl compounds. This change can be shown in the alkaline hydrolysis of esters which is believed to proceed by the

5. R. Pasternack, Helv. Chim. Acta, 31, 753 (1948).

following mechanism:



The reaction is rendered essentially irreversible by the magnitude of K_4 and it is believed that most of the variation in rates of saponification arise from variations in K_2 . As shown by equations I and III the resonance energy of the carbonyl group is lost in both cases. The free radical, however, still retains resonance energy of its own through contributions of the following types of structures:



and additional forms if R is conjugated.

Hammett⁶ has shown that for many reactions on side chains of meta and para substituted benzene derivatives the rate or

6. L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Company, Inc., New York, 1940, p. 186.

ionization constants can be represented by the following equation:

$$\log k - \log k^{\circ} = \rho \underline{g} \quad (1)$$

where k° and k are the rate or ionization constants for the unsubstituted and substituted derivatives respectively, ρ , a constant for the particular reaction, and \underline{g} , a constant for the substituent. He also has shown that the failure of the method when applied to ortho substituted benzene derivatives and aliphatic compounds can be correlated with the intrusion of entropy effects of a considerable magnitude.

Since the hydrolysis is somewhat analogous to the polarographic reduction of carbonyl compounds it should be possible to correlate \underline{g} with the half-wave potential.

It is of particular interest in light of the proposed mechanism of polarographic reduction that Walling et al.⁷ have successfully applied the Hammett equation to the rates at which growing polystyrene free radicals add to meta and para substituted styrenes in copolymerization experiments.



This reaction bears a considerable similarity to reaction I for the polarographic reduction of carbonyl compounds. One

7. C. Walling, E. R. Briggs, K. B. Wolfstirn and F. R. Mayo, J. Am. Chem. Soc., 70, 1937 (1948).

might expect that the rate of dimerization of the radicals would vary very little from one compound to another since it is likely to be diffusion controlled. Therefore, some support for the mechanism might be gained if, as is actually the case, the Hammett equation can be shown to apply to the apparent reduction potentials of a series of suitably substituted benzaldehydes and phenyl ketones.

Hixon and Johns⁸ have developed a theory in which groups are assigned a finite value called the "electron-sharing ability" which is calculated from the basic dissociation constants of amines by the equation

$$\log_{10} K = -20(e^{0.05x} - 0.75) \quad (2)$$

where x is the electron-sharing ability.

Hixon et al.^{8,9} have further shown that when these

8. R. M. Hixon and I. B. Johns, J. Am. Chem. Soc., 49, 1786 (1927).

9. (a) J. B. Allison and R. M. Hixon, J. Am. Chem. Soc., 50, 168 (1928); (b) I. B. Johns, W. D. Peterson and R. M. Hixon, J. Phys. Chem., 34, 2218 (1930); (c) I. B. Johns and R. M. Hixon, Ibid., 34, 2226 (1930); (d) L. C. Craig and R. M. Hixon, J. Am. Chem. Soc., 53, 4367 (1931); (e) D. F. Starr, H. Bulbrook and R. M. Hixon, ibid., 54, 3971 (1932); (f) L. D. Goodhue and R. M. Hixon, ibid., 56, 1329 (1934); (g) I. B. Johns and R. M. Hixon, ibid., 56, 1333 (1934); (h) L. D. Goodhue and R. M. Hixon, ibid., 57, 1688 (1935); (i) E. L. Carr, I. B. Johns and R. M. Hixon, ibid., 60, 891 (1938); (j) F. E. Ware and R. M. Hixon, ibid., 60, 1262 (1938); (k) F. A. Landee, "Relationship Between the Electron-Sharing Ability of Radicals and the Association of Organic Compounds." Unpublished Doctoral Dissertation, Ames, Iowa, Iowa State College Library, (1938); (l) F. S. Martin, "Some Factors Affecting the Raman Frequencies of the Carbon-Mercury Bond." Unpublished Doctoral Dissertation, Ames, Iowa, Iowa State College Library, (1938).

values of x are plotted against acid dissociation constants, stability of organomercurial nitrates, and other physical and chemical properties a smooth curve results. Over the range which Hammett's $\rho\sigma$ treatment is valid a correlation will be made between his treatment and that of Hixon and Johns.

At the outset of this study it was thought that the same type of correlation as mentioned above might be made by the polarographic reduction of organomercuric iodides. In this work large maxima which could not be suppressed were obtained. Because of these maxima the polarograms could not be interpreted.

II. POLAROGRAPHY OF CARBONYL COMPOUNDS

A. Historical

In the last 20 years polarography has enjoyed phenomenal growth and wide acceptance in the scientific field. This is indicated by the large number of papers that have been published.¹⁰ These papers include theory, instrumentation and application in a wide variety of fields. A large number of review papers have also appeared in the literature.

The technique of polarography is well described in Kolthoff and Lingane's book, "Polarography"² and also in the review by Muller.¹¹ The fundamental circuit and the method of measuring the small current change is also discussed by these same authors. Lingane¹² has reviewed the various commercial instruments now available on the market as well as the different types of cells which have been constructed for special purposes.

The study of organic compounds is complicated by the fact that very few are soluble in water and other solvents

10. "Leeds and Northrup Bibliography of Polarographic Literature," Leeds and Northrup Company, Philadelphia, 1950.

11. O. H. Muller, J. Chem. Education, 18, 65, 111, 172, 227, 320 (1940).

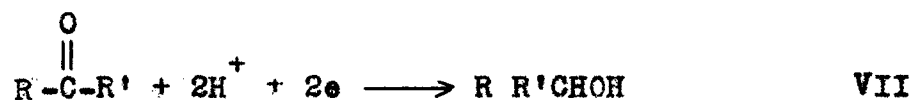
12. J. J. Lingane, Anal. Chem., 21, 45 (1949).

must be used. Mixtures of water and organic solvents such as alcohol, acetic acid, dioxane, glycerol, and ethylene glycol have been used. The shape of the wave, the wave height and the half-wave potential changes with changes in solvent. The nature of the supporting electrolyte, the hydrogen-ion concentration, and temperature also cause changes in the data obtained. In many cases the shape, height and position of the wave are changed if other reducible species are present in the solution. All these variations are adequately discussed in the various review articles available.^{2,13}

During the early work on reduction of organic compounds it was thought that in acid solution the reduction was brought about by atomic hydrogen and in basic solution by the atomic metal formed from the cation in solution. It has been shown that in the intermediate acid range (pH 2.5 to 5) many carbonyl compounds give two waves of equal height; at higher pH values these two waves coalesce giving one wave. The height of this wave is equal to the combined height of the two waves at lower pH values. This indicates that the diffusion current is independent of the hydrogen-ion concentration. Therefore the reduction could not be by atomic hydrogen. Further, it could not be by atomic alkali metal in basic solutions since the same type of wave with approximately the same height was obtained with ammonium ions.

13. (a) O. H. Muller, Chem. Review, 24, 95 (1939); (b) S. Wawzonek, Anal. Chem., 21, 61 (1949); (c) S. Wawzonek, ibid., 22, 30 (1950).

It was further shown that each wave in the acid range required one Faraday per mole. For the first wave the reactions given in equations I and II were postulated. In the second wave since a total of two Faradays are required the following process has been postulated:



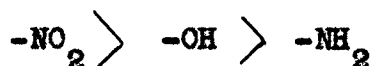
Pasternak,⁵ by controlled electrolytic reductions has given strong evidence to support the mechanism given in equations I and II and the process in equation VII. At a pH of 1.3, benzaldehyde gave a half-wave potential of -0.98 volts against a normal calomel electrode. At a pH of 8.6 the half-wave potential of the one wave was -1.45 volts. With a benzaldehyde solution of pH 1.3 electrolyzed employing a rapidly stirred mercury electrode with a potential of 1.2 volts, hydrobenzoin was the only product isolated. With a pH of 8.6 and a potential of 1.5 volts, both hydrobenzoin and benzylalcohol were isolated.

Earlier Tokuoka¹⁴ had arrived at similar conclusions by studying the reduction of benzaldehyde over the pH range of 1 to 14. From the wave heights and the diffusion constants, Tokuoka showed that two Faradays were required for the reduction of each mole of benzaldehyde. From these data he

14. M. Tokuoka, Coll. Czech. Chem. Commun., 7, 392 (1935).

concluded that the first wave in the acid range was due to a one electron reduction to hydrobenzoin and the second wave, reduction to benzylalcohol.

Shikata, the first to reduce an organic compound polarographically,¹⁵ was also the first to formally state that the reduction potentials of carbonyl compounds depended on the electronegativity of the groups combined with the carbonyl group.¹⁶ In compounds of the type $R-\overset{\overset{O}{\parallel}}{C}-R'$, the R' group could be varied and when these were reduced polarographically he found that as the electron withdrawal by R' increased the reduction potential was shifted to a more positive potential. Shikata¹⁶ extended this study to the reduction of substituted nitrobenzenes and found qualitatively that the reduction potential of the nitro group was dependent on the substituent in the benzene ring. From this study the following order of electronegativity was observed:



Shikata summarized these results by saying:¹⁶

. . . the electrolytic reduction potential closely depends on the electronegativity of the groups combined with the reducible group of the organic compound and that the more electronegative the substituted group, the more reducible is the compound group.

15. M. Shikata, Trans. Faraday Soc., 21, 42 (1925).

16. M. Shikata and I. Tachi, Coll. Czech. Chem. Commun., 10, 368 (1938); J. Chem. Soc. Japan, 53, 834 (1932); C. A., 27, 220 (1933).

Semerano and Chisini¹⁷ studied the reduction of benzaldehyde and substituted benzaldehydes in 50% ethanol solutions 0.1 N in ammonium chloride. Semerano and his students employed the applied E. M. F. at the point of maximum curvature¹⁸ of the current voltage curve (tangent at 35° 16') as the reduction potential. The observed reduction potential for a selected few of their polarographic determinations taken from their paper¹⁷ is shown in Table 1.

Winkel and Proske¹⁹ studied the reduction potential of a large number of ketones and aldehydes in 0.1 N ammonium chloride, lithium chloride, and potassium chloride. Their reduction potential, which they later called depolarization potential,²⁰ was taken as the potential where a line drawn through the residual current and a line through the steepest portion of the rising current intersect. Table 2 is a compilation of their data. These were all run using 0.1 N ammonium chloride as the supporting electrolyte.

They found that saturated aliphatic ketones were not reducible at the dropping mercury electrode using 0.1 N potassium chloride or 0.1 N lithium chloride as a supporting

17. G. Semerano and A. Chisini, Gazz. chim. ital., 63, 802 (1933).

18. G. Semerano, Gazz. chim. ital., 62, 518 (1932).

19. (a) A. Winkel and G. Proske, Ber., 69B, 693 (1936);
(b) A. Winkel and G. Proske, ibid., 69B, 1917 (1936).

20. A. Winkel and G. Proske, ibid., 71B, 1785 (1938).

Table 1

Reduction Potentials of Substituted Benzaldehydes
in 50% Ethanol with 0.1 N Ammonium Chloride
as the Supporting Electrolyte

(Semerano and Chisini¹⁷)

Compound	Concentration	Observed reduction potential*
o-Chlorobenzaldehyde	1.05×10^{-3}	-1.111
m-Chlorobenzaldehyde	1.09×10^{-3}	-1.161
p-Chlorobenzaldehyde	1.09×10^{-3}	-1.198
o-Methylbenzaldehyde	1.61×10^{-3}	-1.237
Benzaldehyde	1.50×10^{-3}	-1.251
m-Methylbenzaldehyde	1.64×10^{-3}	-1.255
p-Methylbenzaldehyde	1.34×10^{-3}	-1.285
o-Hydroxybenzaldehyde	1.63×10^{-3}	-1.305
p-Methoxybenzaldehyde	0.92×10^{-3}	-1.357

* Measured against a normal calomel electrode.

Table 2

Depolarization Potentials of Benzaldehyde and Acetophenone
and Their Mono-Substituted Derivatives in 0.1 N Ammonium Chloride

(Winkel and Proske¹⁹)

Compound	Anode potential	Depolarization potential vs. S. C. E.	Step height ($\cdot 10^{-5}$ amp.)	% alcohol
Acetophenone	0.067 v	-1.44 v	5.3	1.0
p-Methylacetophenone	0.060	-1.48	5.5	1.0
p-Chloroacetophenone	0.064	-1.39	5.5	2.0
o-Chlorobenzaldehyde	0.077	-1.07	3.9	2.5
m-Chlorobenzaldehyde	0.080	-1.12	4.7	2.5
p-Chlorobenzaldehyde	0.076	-1.18	4.8	2.5
m-Bromobenzaldehyde	0.070	-1.19	5.5	3.4
p-Bromobenzaldehyde	0.065	-1.21	5.5	3.4
Benzaldehyde	0.076	-1.27	5.2	2.5
o-Hydroxybenzaldehyde	0.075	-1.28	5.3	2.5
m-Hydroxybenzaldehyde	0.079	-1.21	5.7	2.5
p-Hydroxybenzaldehyde	0.073	-1.38	5.2	2.5
p-Methoxybenzaldehyde	0.077	-1.33	5.6	2.5

electrolyte. This is in disagreement with previous workers in the field.^{4,21} They found, however, that alpha halogenated ketones could be reduced. The depolarization potential becomes more positive as the electronegativity of the halogen decreased, i. e., from chlorine to iodine. These waves were probably due to the reduction of the halogen rather than the reduction of the carbonyl groups since benzyl bromide and benzyl chloride give well defined waves.²² Also it has been found that dichloro- and trichloro-acetic acids are reduced at the dropping mercury electrode giving one and two waves respectively while monochloroacetic acid and acetic acid are not reduced at -2.0 volts.²³ It was found also that two electrons were required for each wave and these waves were independent of the pH.

Winkel and Proske¹⁹ give evidence that there is a relation between reduction potential and the Raman and ultraviolet absorption spectra. They show that as the reduction potential of a carbonyl group becomes more positive its absorption maxima move in the direction of longer wave lengths and its Raman frequencies become smaller.

In their study it was shown also that the depolarization potential of organic compounds is influenced by the concentration

21. G. Semerano, Gazz. chim. ital., 62, 959 (1932).

22. R. Pasternak and H. Halban, Helv. Chim. Acta, 29, 190 (1946).

23. P. Elving and C. Tang, J. Am. Chem. Soc., 72, 3244 (1950).

of the reducible substance, the concentration and type of supporting electrolyte, temperature, and the hydrogen-ion concentration. The effect of the first three is small but the pH effect is quite large.

Adkins and Cox²⁴ studied a large number of aldehydes and ketones at the dropping mercury electrode. In this work the measured potential is the half-wave potential of Heyrovsky²⁵ which is the presently accepted practice. These studies were made using as a supporting electrolyte 0.1 N potassium chloride and 0.2 N tetramethylammonium hydroxide. A selected few of the compounds studied by them is shown in Table 3.

The first semiquantitative study of the effects of substitution on the reduction of benzaldehyde was that of Baker, Davies and Hemming.²⁶ They reduced para substituted benzaldehydes in MacIlvaine's buffer solutions, 0.1 N tetramethylammonium bromide and 0.1 N potassium chloride. They employed the method of Winkel and Proske²⁰ to determine the depolarization potential. This method was chosen because of its simplicity and because they encountered maxima which

24. H. Adkins and F. Cox, J. Am. Chem. Soc., 60, 1151 (1938).

25. J. Heyrovsky and D. Ilkovic, Coll. Czech. Chem. Commun., 7, 198 (1935).

26. J. Baker, W. Davies, and M. Hemming, J. Chem. Soc., 1940, 692.

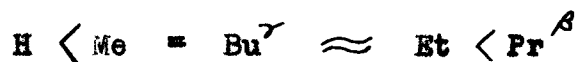
Table 3

Half-wave Potentials of Aldehydes
in 0.2 N Tetramethylammonium Hydroxide, 50% Ethanol
(Adkins and Cox²⁴)

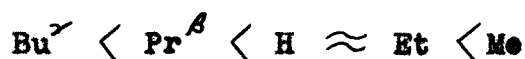
Compound	$E_{\frac{1}{2}}$ vs. Hg pool
Acetaldehyde	-1.87
n-Butyraldehyde	-1.90
Benzaldehyde	-1.34
Anisaldehyde	-1.46
p-Hydroxybenzaldehyde	-1.75
o-Hydroxybenzaldehyde	-1.61
o-Hydroxyacetophenone	-1.64
Acetophenone	-1.52
p-Bromoacetophenone	-1.52

would make the measurement of half-wave potentials difficult. Table 4 gives their results. The depolarization potentials are referred to the normal hydrogen electrode.

These investigators rationalized their results by considering the inductive and tautomeric effects of the para substituent. They consider the order of these effects to change by the demand placed on them. Thus, when considering the alkyl groups, the order of their abilities to supply electrons to the polarizable carbonyl group changes with change in hydrogen ion concentration. Their predicted order of increasing depolarization potential in acid solution is



in neutral solution



and in slightly alkaline solution



As seen from Table 4 the order found agrees well with that predicted.

It would appear that the order of the ability of these groups to act as electron sources would not change appreciably by the demand placed on them. It seems then that this order should be the same regardless of the hydrogen-ion concentration.

Table 4
 Depolarization Potentials of $6.67 \times 10^{-3} M$ p-Substituted Benzaldehydes,
 RC_6H_4CHO , in a Solvent 33.3% Ethyl Alcohol
 (Baker, Davies, and Hemming²⁶)

Ground electrolyte	R								Anode potential	
	Cl	H	Me	Et	Pr ^{β}	Bu ^{γ}	OMe	NMe ₂	Obs. ¹	Corr.
Buffer, pH 1.4 ²	-0.59	-0.64	-0.66	-0.66	-0.70	-0.67	-0.72	-0.63	-0.008	0.328
Buffer, pH 4 a	-0.95	-1.02	-1.035	-1.02	-1.075	-1.05	-1.09	-1.07	0.031	0.367
b	-1.24	-1.27	-1.31	-1.315	-1.40	-1.48	-1.39			
Buffer, pH 7	-1.05	-1.14	-1.155	-1.14	-1.115	-1.11	-1.22	-1.175	0.044	0.380
Buffer, pH 8	-1.11	-1.19	-1.24	-1.22	-1.22	-1.22			0.034	0.370
0.1N NMe ₄ Br										
a	-1.12	-1.19	-1.25	-1.24	-1.24	-1.25	-1.31	-1.38	-0.139	0.197
b	-1.66	-1.74	-1.96	-1.99	-2.095	-2.11	-2.16	-2.18		
0.1N KCl	-1.14	-1.20	-1.25	-1.26	-1.25	-1.25	-1.30	-1.40	-0.008	0.328

- a. First wave, b. second wave.
 1. Measured against a 0.1 N calomel electrode.
 2. Clark and Lubs standard.

Also the differences in depolarization potentials of the para alkyl aldehydes should be small. The observed differences were small and within experimental error.

These investigators purposely avoid discussing the p-dimethylamino group and state that its anomalous behavior is probably due to its "ionogenic" character.

During the period 1941 to 1950 no series of substituted benzaldehydes or phenyl alkyl ketones have been studied. In this period most of the organic polarographic work was on natural products, analytical determinations and reinterpretation of older work.^{13b}

B. Experimental

1. Apparatus

A Sargent Model XXI visible recording polarograph was used for recording all polarograms of carbonyl compounds. All polarograms were recorded against a mercury pool in a Heyrovsky, Erlenmeyer style electrolysis vessel. The potential of the mercury pool was measured against a commercial saturated calomel electrode (Beckman, No. 4970). This electrode was introduced directly into the cell and the potential measured with a Leeds and Northrup student type potentiometer. The accuracy of the commercial calomel electrode was checked against a saturated calomel electrode with a known potential of 0.246 volts at 25° and found to agree within 0.002 volts. All measurements were made at 25 ± 0.1°. It was found that stray currents from the water bath affected the polarograph to a slight degree even when both were grounded well. To eliminate any error from these currents the constant temperature bath was turned off during the polarographic and other potentiometric determinations.

All solutions on which polarographic determinations were made were purged of oxygen by bubbling nitrogen through the cell for 8 to 10 minutes before making polarographic measurements. The commercial nitrogen was purified by means of an alkaline pyrogallolsulfuric acid train. Before entering

the cell the nitrogen passed through a solution of solvent and supporting electrolyte of the same concentration as that being used in the electrolysis vessel.

The same capillary was used in all studies. This capillary under a pressure of 65.5 centimeters of mercury had a drop time of 4.02 seconds and the mass of mercury flowing, m , was 1.453 mg./sec. measured in a solvent and supporting electrolyte (33.3% alcohol - 66.7% MacIlvaine buffer solution) the same as that used in making polarographic measurements. These measurements were made with an open circuit. The value of $m^{\frac{2}{3}} t^{\frac{1}{6}}$ is 1.618 $\text{mg.}^{\frac{2}{3}} \text{sec.}^{-\frac{1}{6}}$.

2. Benzaldehyde and Substituted Benzaldehydes

a. Purification and Preparation of Materials

Ethyl Alcohol. Commercial absolute ethyl alcohol was refluxed with 10 grams of silver nitrate and 3 grams of potassium hydroxide per liter for three hours to remove any aldehydes present. The flask was then fitted with a Vigreux column and distilled. A forerun of 100 milliliters per liter of alcohol being distilled was discarded and approximately the same amount left in the distilling flask. Eight hundred milliliters of the distillate was then refluxed with 1 gram of magnesium and 0.5 gram of iodine. It was then distilled and used in making solutions for polarographic analysis. All operations were carried out under an atmosphere

of nitrogen. After the first preparation of the alcohol it was found that the treatment with magnesium was not necessary.

MacIlvaine's Buffer Solution. This solution was prepared exactly as given in Lange²⁷ for a pH of 7. The pH was adjusted to exactly 7.00 with a Beckman Model G pH meter.

Benzaldehydes. Benzaldehyde, p-chlorobenzaldehyde, p-methylbenzaldehyde, m-methylbenzaldehyde, and anisaldehyde were commercial samples purified by the method of Fieser.²⁸ The liquids were dissolved in ether and washed with small portions of a 5% sodium carbonate solution until no precipitate formed upon acidification of the wash solution. The ether solutions were then washed twice with water and dried over anhydrous sodium sulfate. Dissolved oxygen was removed from the ether solution by means of nitrogen. Distillations were then carried out in an atmosphere of nitrogen with the first one-third and the last one-third of the aldehyde being discarded. The purified benzaldehyde had a boiling point of 176°, p-methylbenzaldehyde 198°, and m-methylbenzaldehyde 92° (19 mm.). The melting point of p-chlorobenzaldehyde was

27. N. A. Lange, "Handbook of Chemistry," Sixth Edition, Handbook Publishers, Inc., Sandusky, Ohio, 1946, p. 1099.

28. L. F. Fieser, "Experiments in Organic Chemistry," Second Edition, D. C. Heath and Company, New York, 1941, p. 224.

45-46°, and that of anisaldehyde was 0.8°. The solids, p-hydroxybenzaldehyde, p-nitrobenzaldehyde and m-nitrobenzaldehyde, were also commercial samples. The p- and m-nitrobenzaldehydes needed no further purification as their melting points, 105-106° and 56-58° respectively, agreed with the literature values. The melting point of p-hydroxybenzaldehyde was 114-115° after recrystallization from water. The m-chlorobenzaldehyde was prepared by the method of Organic Synthesis²⁹ and its melting point was 12-13°. All samples except m-chlorobenzaldehyde were used within two hours after purification.

b. Polarographic Studies

The liquid aldehydes were weighed as rapidly as possible in a small beaker and immediately transferred to a 100 milliliter volumetric flask with the purified absolute alcohol and made up to volume. The solid aldehydes were weighed directly on weighing paper and treated in a similar manner. Samples were pipetted from these solutions into 20 milliliters of the MacIlvaine buffer mixture. The final solutions in all cases contained 10 milliliters of alcohol to 20 milliliters of the buffer mixture. To this 30 milliliters of solution was added two drops of a 0.1% methyl orange solution as a maximum suppressor. The apparent pH of this

29. A. H. Blatt, "Organic Synthesis," Collective Volume II, Revised Edition, John Wiley and Sons, Inc., New York, 1943, p. 130.

mixture was measured with a Beckman Model G pH meter and found to be very close to 7.7 in all cases. Approximately 5 milliliters was used in making polarographic analysis.

The resistance of the cell was measured employing a 6-volt battery, 1000 cycle microhummer, Kohlrausch slide wire, standard resistance box and a sensitive vacuum-tube voltmeter. The resistance of the cell was found to be 560 ± 50 ohms. For a current of 12 microamperes the IR drop across the cell would be 0.007 volts. This is the maximum current obtained for all aldehydes with no other reducible group present. However, the correction at the half-wave potential would be $\frac{1}{2}$ of this value. The IR drop correction has been applied only in the case of the nitro compounds.

Table 5 is a typical sample of the data obtained. Results obtained from other compounds were treated in a similar manner and a summary of the data is given in Table 6.

Benzaldehyde, p-chlorobenzaldehyde, m-chlorobenzaldehyde, anisaldehyde and p-hydroxybenzaldehyde gave well-defined waves. With p-hydroxybenzaldehyde the diffusion current blended into the wave of that of the supporting electrolyte, thus making exact measurements somewhat difficult, the diffusion current line not being parallel to the residual current line. This would make the diffusion current lower than the true value.

The curves for the meta and para isomers of tolualdehyde gave an indication of a slight maximum as the rising portion

Table 5

Polarographic Investigations of m-Tolualdehyde
in MacIlvaine's Buffer Solution of pH 7, 33.3% Ethyl Alcohol

Run	Concentration	$E_{1/2}$ (Hg pool)	Anode potential		$E_{1/2}$ (S.C.E.)		Depolarization potential (Hg pool)
			Reading	Deviation from average	Found	Deviation from average	
1	$6.77 \times 10^{-3} M$	-1.552	0.112	0.001	-1.440	0.033	-1.452
2	$6.77 \times 10^{-3} M$	-1.533	0.119	0.008	-1.414	0.007	-1.440
3	$3.39 \times 10^{-3} M$	-1.528	0.130	0.019	-1.398	0.009	-1.453
4	$3.39 \times 10^{-3} M$	-1.515	0.112	0.001	-1.403	0.004	-1.450
5	$3.45 \times 10^{-3} M$	-1.460	0.068	0.043	-1.392	0.015	-1.388
6	$3.45 \times 10^{-3} M$	-1.520	0.127	0.016	-1.393	0.014	-1.433
Average			0.111	0.015	-1.407	0.014	-1.436 0.111 -1.325 ∇ (S.C.E.)

Table 5 - (continued)

Run	Concentration	Step height in mm.	Sensitivity	Diffusion current	
				Found	Deviation from average
1	$6.77 \times 10^{-3} \text{ M}$	217	0.150	4.80	0.13
2	$6.77 \times 10^{-3} \text{ M}$	218	0.150	4.83	0.10
3	$3.39 \times 10^{-3} \text{ M}$	171	0.100	5.05	0.12
4	$3.39 \times 10^{-3} \text{ M}$	163	0.100	4.81	0.12
5	$3.45 \times 10^{-3} \text{ M}$	172	0.100	4.98	0.05
6	$3.45 \times 10^{-3} \text{ M}$	175	0.100	5.08	0.15
Average				4.93	0.11

Table 6

Half-wave Potentials (S. C. E.) and Diffusion Currents of Substituted Benzaldehydes in MacIlvaine's Buffer Solution, 33.3% Ethyl Alcohol

Substituent	$E_{\frac{1}{2}}$ vs. S.C.E.		Anode potential		Diffusion current*		Depolarization potential (S.C.E.)
	Average reading	Average deviation	Average reading	Average deviation	Average reading	Average deviation	
m-Cl	-1.317	0.008	0.133	0.003	3.99	0.04	-1.234
p-CH ₃	-1.384	0.007	0.111	0.039	5.13	0.15	-1.311
p-Cl	-1.392	0.042	0.095	0.036	5.35	0.18	-1.309
m-CH ₃	-1.407	0.014	0.111	0.015	4.93	0.11	-1.325
H	-1.463	0.004	0.088	0.001	5.23	0.16	-1.387
p-CH ₃ O	-1.509	0.009	0.121	0.011	5.08	0.19	-1.405
p-OH	-1.567	0.001	0.139		3.98	0.12	
p-NO ₂	a	-0.523	0.001	0.128	8.65	0.11	-0.455
	b	-1.407	0.002	0.128			
	c	-1.575	0.002	0.128	7.78	0.37	
m-NO ₂	a	-0.616	0.008	0.128	8.50	0.21	-0.551
	b	-1.445	0.006	0.128	3.74	0.04	

* Microamps. x liters/mole.

of the curve was steeper than in the other compounds measured and the break from the rising portion of the curve into the diffusion current was not as sharp but more of a gradual change.

The Ilkovic equation³⁰

$$I_d = 605 n D^{\frac{1}{2}} C m^{\frac{2}{3}} t^{\frac{1}{6}}$$

which has been verified experimentally gives the relation of the diffusion current in microamperes (I_d) to the drop time of mercury in seconds (t), concentration in millimoles per liter (C), mass of the mercury flowing per second (m), the number of electrons (n) involved in the reduction of one molecule, and to the diffusion coefficient (D) of the electroactive material in $\text{cm.}^2 \text{ sec.}^{-1}$. For the compounds in which the aldehyde group only is reduced, n is constant and $m^{\frac{2}{3}} t^{\frac{1}{6}}$ is very nearly constant for any given solvent and supporting electrolyte. Then if the current for a given concentration is calculated, the only variable is the diffusion coefficient. One would expect this not to be greatly different for the series of aldehydes studied and as it is the square root of the diffusion coefficient that enters into the equation one would expect the diffusion current for a given concentration of the aldehydes to be relatively constant. This is qualitatively true for these compounds.

30. D. Ilkovic, Coll. Czech. Chem. Commun., 6, 498 (1914); see also 2a, p. 1.

As shown in Table 6, two waves were found for m-nitrobenzaldehyde and three for p-nitrobenzaldehyde. The second and third waves for the para compound were nearly blended together. A comparison of the wave heights with those of the other aldehydes which are reduced in a two-electron step gives a strong indication that the first wave in both cases is a four-electron reduction. By the same reasoning the second and third waves each require two additional electrons per molecule.

Baker, Davies and Hemming,²⁶ using the same solutions as used in these studies, found that the anode potential was a constant. They measured the potential with a 0.1 N calomel electrode. Their value when calculated to the saturated calomel electrode gives an anode potential of 0.139 volts. As seen in Tables 5 and 6 the anode potential was found to vary and in most cases to be lower than 0.139 volts. The variation found is probably due to the junction potential between the calomel electrode and the alcohol solution. This is indicated by the fact that the reduction potential would change with time, generally decreasing. The values for p-hydroxy-, m-chloro- and the nitrobenzaldehydes were made with a new Beckman electrode which did not change as rapidly with time. It is probably only fortuitous that the low half-wave potential found for m-methylbenzaldehyde, determination number 5, Table 5, against the mercury pool coincides with the low value found for the anode potential.

The junction potential cannot be evaluated so it is doubtful whether the measurements against a saturated calomel electrode have much more significance than those measured against the mercury pool. However, it is common practice to report half-wave potentials against the saturated calomel electrode.

3. Acetophenones and Substituted Acetophenones in Buffer Solution

a. Purification and Preparation of Materials

Ethyl Alcohol and MacIlvaine's Buffer Solution. Ethyl alcohol was purified and MacIlvaine's buffer solution was prepared in the same manner as that used for the study of benzaldehydes.

Acetophenones. Acetophenone, p-chloroacetophenone and p-methylacetophenone were commercial samples purified by distillation through a semimicro vacuum-jacketed column. The boiling points of the purified compounds were 220, 232 and 223° respectively. The p-bromoacetophenone, p-aminoacetophenone and m-nitroacetophenone were Eastman Kodak white label compounds which had melting points of 45-49°, 102-105°, and 76-78° respectively and were used without further purification. The m-aminoacetophenone was Eastman practical grade material. It was purified by dissolving in dilute sulfuric acid and filtering. The filtrate was neutralized with 10% sodium hydroxide and the resulting

precipitate filtered off, washed with water and dissolved in hot 50% ethyl alcohol. The ethyl alcohol solution was then decolorized with Norite A, and allowed to crystallize. The crystals were removed by filtration and washed with water and dried. The melting point of the purified material was 92-94°.

The Fries reaction³¹ was used to prepare p-hydroxyacetophenone. The product was purified by vacuum distillation and had a melting point of 106-107°. The p-methoxyacetophenone was prepared from the p-hydroxy compound by the Williamson synthesis. To a solution of 5.9 grams of sodium hydroxide in 100 milliliters of water was added an excess of methyl iodide (35 grams), 30 milliliters of dioxane and 20 grams of p-hydroxyacetophenone and the solution refluxed for two hours. At the end of this time the basic solution was extracted with ether and the ether extract dried over anhydrous calcium sulfate. The ether and dioxane were then removed by distillation at atmospheric pressure and the residue distilled under reduced pressure. The distillate was then recrystallized from Skelly A. The yield of pure product with a melting point of 34-36° was 4.5 grams.

b. Polarographic Studies

All samples were weighed to be exactly 0.01 molar when

31. A. H. Blatt in R. Adams, "Organic Reactions," Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1942, p. 342.

diluted with the purified alcohol to 100 milliliters in a standard volumetric flask. Exact weighing of the liquids was accomplished by adjusting the amount of sample in the weighing beaker with a medicine dropper drawn out to a fine capillary. In all cases, samples for polarographic analysis were made by pipetting 10 milliliters of the master solution into 20 milliliters of the buffer solution. Two drops of a 0.1% methyl orange solution were then added as in the case of the aldehydes. The apparent pH of the alcohol solution was read with the Beckman pH meter and found to be close to 7.7, in good agreement with the pH found for the aldehyde solutions.

All polarograms gave an indication of a double wave as seen in the typical polarograms obtained shown in Figures 1 and 2. The method of determining the step height is also indicated in these same figures. The break between the first and second wave was determined by visual inspection and a horizontal line drawn through this point. As seen in Table 8, the heights of the two waves are approximately equal except for p-bromoacetophenone. In this case the height of the first wave was probably increased by a maximum which blended into the second wave. This explanation is postulated because it is the only case in which the step heights for the two waves are not approximately equal.

For some compounds, those in which the half-wave potential was more negative than acetophenone, it was difficult to get

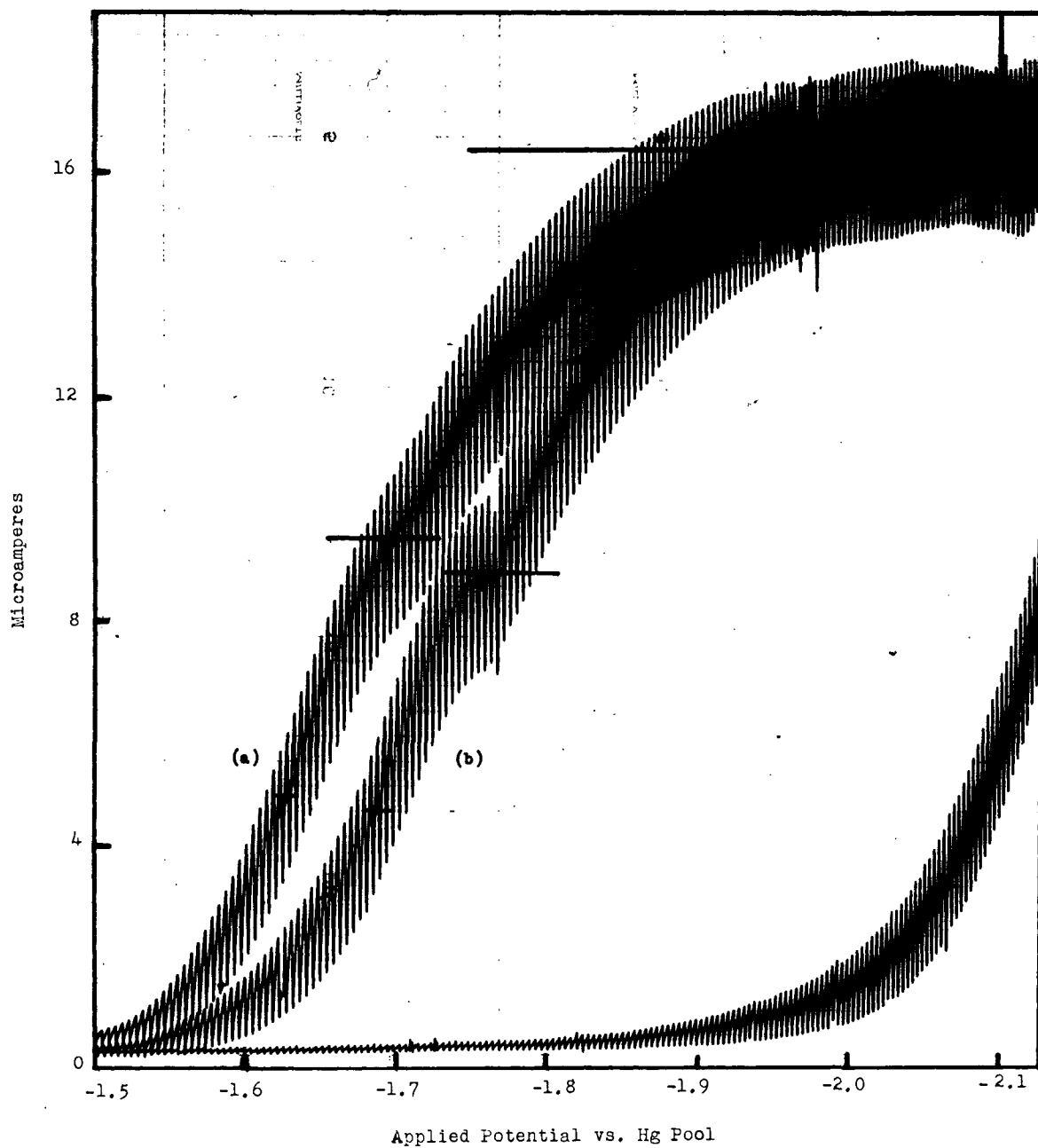


Figure 1. Polarograms of $3.33 \times 10^{-3} M$ p-chloroacetophenone (a) and acetophenone (b) in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol; anode potential, 0.113 v.

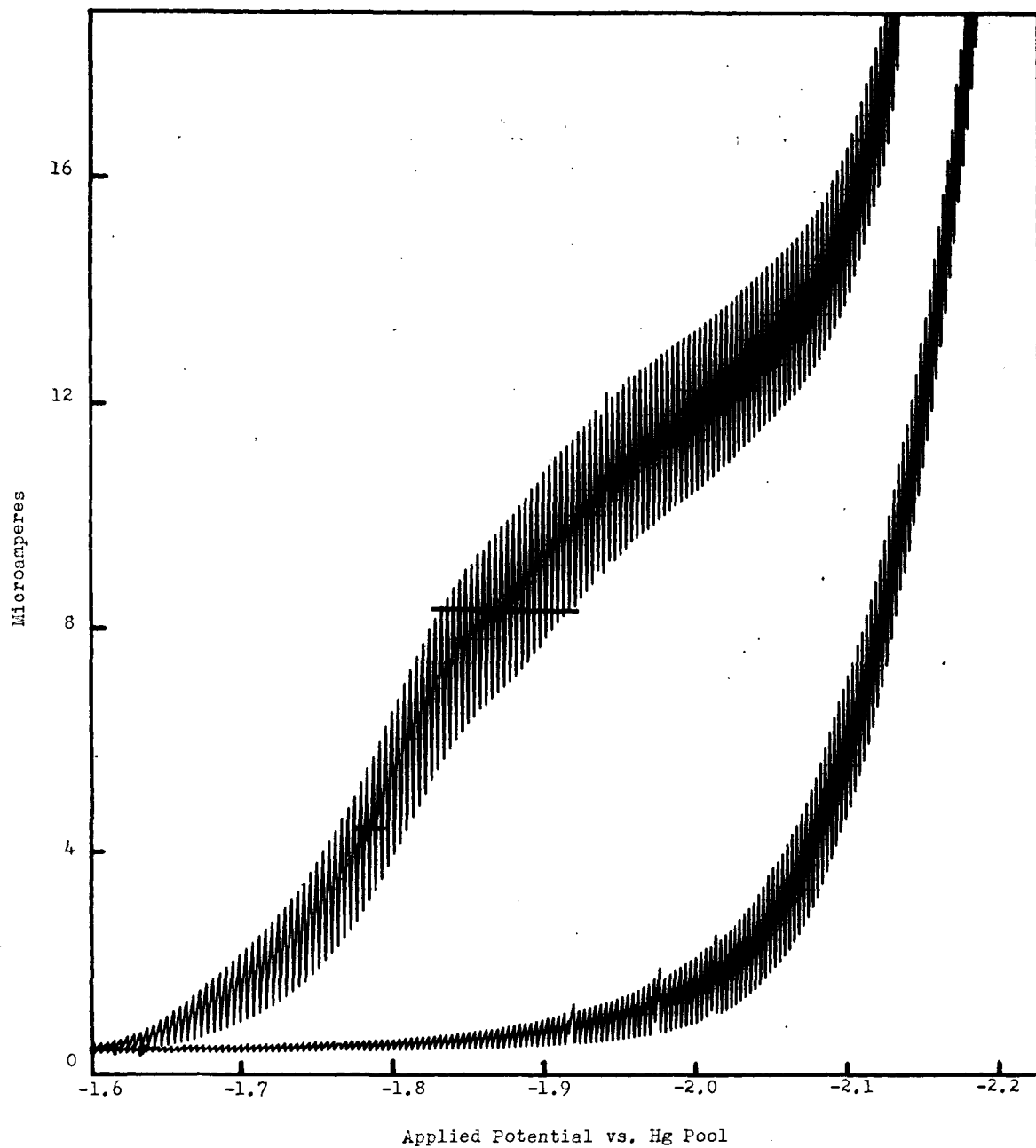


Figure 2. Polarogram of 3.33×10^{-3} M p-methoxyacetophenone in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol; anode potential, 0.138 v.

a wave height, and consequently a half-wave potential, because the second wave blended into that of the supporting electrolyte. In these cases only the first wave is given.

Table 7 is an average sample of the data obtained. The observed values are given as well as the deviation from the average value. Table 8 is a summary of the results obtained reported as averages.

With m-nitroacetophenone it was found that methyl orange would not suppress the maximum obtained on the first wave. This maximum was completely removed by the addition of a small amount of gelatin. The concentration of the gelatin was less than 0.01% in the final solution. The step heights in this case indicate that the first step is a four-electron reduction and that two more electrons are added at the second step.

4. Polarographic Runs Employing Tetramethylammonium Hydroxide

An attempt was made to reproduce the work of Adkins and Cox.²⁴ These authors report that the cation of 0.2 N tetramethylammonium hydroxide in 50% ethanol starts to reduce in the neighborhood of -2.1 volts measured against the mercury pool. It was found that with the sample employed that reduction occurred at approximately -1.6 volts. A sample of tetramethylammonium hydroxide prepared in these laboratories³²

32. This sample was furnished kindly by Dr. H. Diehl of the analytical department.

Table 7

Polarographic Investigation of p-Chloroacetophenone,
 3.33×10^{-3} M, in MacIlvaine's Buffer Solution of pH 7, 33.3% Ethyl Alcohol

Run	$E_{1/2}$ vs. Hg pool		Anode potential vs. S. C. E.		$E_{1/2}$ vs. S. C. E.				Depolar- ization potential vs. Hg pool
			Measured	Deviation from average	Wave 1		Wave 2		
	Wave 1	Wave 2			Found	Deviation from average	Found	Deviation from average	
1 a	-1.623	-1.770	0.119	0.010	-1.504	0.013	-1.651	0.009	-1.567
1 b	-1.626	-1.768	0.119	0.010	-1.507	0.010	-1.649	0.011	-1.570
2 a	-1.625	-1.764	0.114	0.005	-1.511	0.006	-1.650	0.010	-1.568
2 b	-1.629	-1.763	0.114	0.005	-1.515	0.002	-1.649	0.011	-1.593
3 a	-1.622	-1.770	0.098	0.011	-1.524	0.007	-1.672	0.012	-1.540
3 b	-1.624	-1.773	0.098	0.011	-1.526	0.009	-1.675	0.015	-1.550
3 c	-1.630	-1.770	0.098	0.011	-1.532	0.015	-1.672	0.012	-1.565
Average			0.109	.009	-1.517	0.009	-1.660	0.012	-1.563*

*To determine the depolarization potential vs. S. C. E. the average anode potential was added to the average depolarization potential vs. Hg pool.

Table 7 - (continued)

Run	Step height in mm.		Sensitivity	Found	Diffusion current Microamps. x liters/m mole			
	Wave 1	Wave 2			Wave 1	Wave 2		
					Deviation from average	Found	Deviation from average	
1 a	121	92	0.080	2.91	0.05	2.21	0.11	
b	125	89	0.080	3.00	0.14	2.14	0.04	
2 a	126	84	0.080	3.03	0.17	2.02	0.08	
b	128	82	0.080	3.08	0.22	1.97	0.13	
3 a	113	97	0.080	2.72	0.14	2.33	0.23	
b	110	82	0.080	2.64	0.22	1.97	0.13	
c	109	86	0.080	2.62	0.24	2.06	0.04	
Average				2.86	0.17	2.10	0.11	

Table 8

Summary of the Polarographic Reduction
of Meta- and Para-substituted Acetophenones
in MacIlvaine's Buffer Solution of pH 7, 33.3% Ethyl Alcohol

Compound		$E_{1/2}$ vs. S.C.E.	Average deviation	Anode potential	Average deviation	i_d microamps. \times liter/mole	Average deviation	Depolar- ization potential (S.C.E.)
p-Amino	c	-1.720	0.013	0.091	0.009	4.38	0.02	-1.614
p-Hydroxy	a	-1.704	0.010	0.124	0.002	2.12	0.11	-1.664
p-Methoxy	a	-1.667	0.022	0.119	0.021	2.28	0.17	-1.599
p-Methyl	a	-1.651	0.013	0.095	0.015	1.86	0.08	-1.595
	b	-1.804	0.014	0.095	0.015	1.92	0.11	
H	a	-1.582	0.008	0.105	0.007	2.72	0.12	-1.533
	b	-1.716	0.006			2.29	0.08	
m-Amino	c	-1.549	0.031	0.105	0.014	4.63	0.29	-1.564
p-Chloro	a	-1.517	0.009	0.117	0.003	2.86	0.17	-1.454
	b	-1.660	0.011	0.117	0.003	2.10	0.11	
p-Bromo	a	-1.463	0.008	0.133	0.007	3.40	0.03	-1.408
	b	-1.601	0.006	0.133	0.007	1.78	0.02	
m-Nitro*	a	-0.625	0.005	0.132	0.009	9.14	0.06	-0.563
	b	-1.625	0.009	0.132	0.009	4.77	0.32	

a - First wave

b - Second wave

c - Combined waves

* - Corrected for IR drop

was tried and the same reduction potential was observed. In Table 9 are found the results of the runs made employing 0.2 N tetramethylammonium hydroxide as a supporting electrolyte in 50% ethanol and those of Adkins and Cox employing the same conditions.

Table 9

Half-wave Potentials of Carbonyl Compounds
in 0.2 N Tetramethylammonium Hydroxide, 50% Ethanol

Compound	$E_{1/2}$ vs. mercury pool	
	Found	Adkins and Cox ²⁴
Benzaldehyde	-1.28 v	-1.34 v
Acetophenone	-1.45	-1.52
Benzophenone	-1.25	-1.35

III. ATTEMPTED POLAROGRAPHY OF ORGANOMERCURIC IODIDES

A. Historical

Little work has been done with synthetic organometallic compounds probably because of the instability of many of them in aqueous solvents. Working in non-aqueous solvents increases the resistance of the cell thus decreasing the accuracy with which the half-wave potentials can be determined.

Triethyllead chloride has been studied polarographically and found to undergo a valance change of 1.³³ Tetraethyllead is not reducible even at -2.0 volts.³⁴ Organolead compounds seem to be the only organometallics that have been studied at the dropping mercury electrode.

33. L. Riceboni, Gazz. chim. ital., 72, 47 (1942).

34. K. A. Hansen, T. D. Parks and L. Lykken, Anal. Chem., 22, 1232 (1950).

B. Experimental

1. Preparation and Purification of Materials

Dioxane. This material was refluxed with metallic sodium³⁵ under an atmosphere of nitrogen for 24 hours or longer then distilled.

Pyridine. Technical grade material was refluxed overnight with potassium hydroxide pellets and distilled.

Tetra-n-butylammonium Iodide. This material was prepared by the reaction of tri-n-butylamine with n-butyl iodide.³⁵ The melting point was 143-144°.

n-Butylmercuric Iodide. This compound was prepared by making the Grignard reagent from n-butyl iodide and treating this with mercuric iodide.³⁶ The melting point reported is 117° and that found was 114°.

Phenylmercuric Iodide. This compound was prepared by the reaction of phenylmagnesium iodide with mercuric iodide in dry ether, m. p. 271°, lit.,³⁷ 269°.

35. H. A. Laitinen and S. Wawzonek, J. Am. Chem. Soc., 64, 1765 (1942).

36. C. S. Marvel, C. G. Gauerke and E. L. Hill, J. Am. Chem. Soc., 47, 3009 (1925). See also R. L. Shriner and R. C. Fuson, "The Systematic Identification of Organic Compounds," Second Edition, John Wiley and Sons, Inc., New York, 1940, p. 158.

37. E. Krause and A. von Grosse, "Die Chemie der Metalle organischen Verbindungen," Verlag von Gebruder Borntraeger, Berlin, 1937, p. 149.

p-Chlorophenylmercuric Iodide. A good yield of this compound was obtained by adding a solution of 3.12 grams of p-chloroiodobenzene in 50 milliliters of dry ether dropwise to 1.0 gram of magnesium turnings in 100 milliliters of dry ether. This was allowed to stir for a couple of hours and then filtered through a cotton plug into an agitated suspension of 5.3 grams of mercuric iodide in 50 milliliters of dry ether. The ether was then evaporated over a steam bath. The residue was washed first with water than alcohol. It was then extracted with hot pyridine and filtered. Water was added to the filtrate until the turbidity which formed on addition redissolved with difficulty. The white shiny flakes which precipitated on cooling were filtered off and again precipitated from a pyridine-water mixture. After the second recrystallization the crystals were washed with 95% ethyl alcohol, then with ether and dried in a vacuum desiccator, m. p. 244°.

p-Chlorophenylmercuric iodide was also prepared by starting with p-bromochlorobenzene. The Grignard was prepared and treated with mercuric iodide as above. The p-chlorophenylmercuric halide was then treated with potassium iodide in a pyridine-water solution and allowed to cool. The resulting white needles gave no active halogen test with alcoholic silver nitrate. The melting point, 242°, agrees with the literature melting point for di-p-chlorophenyl

mercury.³⁸ A mixed melting point with the p-chlorophenyl-mercuric iodide from above showed a depression of 26°. When 1.00 gram of these needles was treated with 1.08 grams of mercuric iodide in boiling alcohol and allowed to cool, white shiny flakes precipitated which gave a melting point of 242-244°. No depression in melting point was observed when this compound was mixed with that prepared from p-chloro-iodobenzene.

Anal. Calcd. for C_6H_4HgClI : Hg, 45.9. Found: Hg, 45.6.

p-Tolylmercuric Iodide. To prepare this material the same procedure was used as that to prepare n-butylmercuric iodide. The literature values reported for this compound are 220°³⁹ and 213°.⁴⁰ That found was 211°.

Benzylmercuric Iodide. Dibenzylmercury was prepared by the method of Jones and Werner⁴¹ with an overall yield of 18%. To prepare benzylmercuric iodide 5 grams of dibenzylmercury and 6 grams of mercuric iodide were dissolved in boiling absolute ethanol and allowed to cool. The pale yellow flakes which precipitated were recrystallized from

38. E. Krause and A. von Grosse, ibid., p. 178.

39. E. Dreher and R. Otto, Ann., 154, 173 (1870).

40. W. Steinkoph, ibid., 413, 310 (1917).

41. L. W. Jones and L. Werner, J. Am. Chem. Soc., 40, 1257 (1918).

95% ethanol. A yield of 7.0 grams of pure product with a melting point of 115-117° was obtained.

5-Methyl-2-iodomercurifuran. The method of Gilman and Wright⁴² was used to prepare 5-methyl-2-chloromercurifuran. From this compound 5,5'-dimethyl-2,2'-difurylmercury, which has not been previously reported, was prepared by two methods. In one method 10 grams of 5-methyl-2-chloromercurifuran was treated with excess potassium iodide in 500 milliliters of boiling ethanol to which water was added until the solution just remained clear. On cooling some large flakes formed and some colloidal material remained in suspension. The suspension was removed by several decantations using 50% ethanol. The large crystals remaining in the flask were then recrystallized from alcohol. These crystals, which had a melting point of 89-91°, gave an active halogen test with alcoholic silver nitrate, so the potassium iodide treatment was repeated. No colloidal material was encountered in the second potassium iodide treatment. White leaflets with a melting point of 104-105° were obtained which gave no active halide test with alcoholic silver nitrate.

Gilman and Wright⁴² prepared 2,2'-difurylmercury by the reaction of sodium thiosulfate with 2-chloromercurifuran in a water solution. This same procedure was used to prepare

42. H. Gilman and G. F. Wright, J. Am. Chem. Soc., 55, 3302 (1933).

5,5'-dimethyl-2,2'-difurylmercury. To a solution of 25 grams of sodium thiosulfate in 100 milliliters of water was added 0.05 mole of 5-methyl-2-chloromercurifuran. The mixture was shaken vigorously for a few minutes and then allowed to stand overnight. The solid material was then removed by filtration under reduced pressure and washed thoroughly with water. This residue was extracted with boiling alcohol and filtered. Water was added to the filtrate to aid precipitation and the resulting solution allowed to cool. The resulting white flakes were recrystallized from an alcohol-water mixture. A yield of 16.0 grams (89%) with a melting point of 103° was obtained. A mixed melting point with that previously prepared by the first procedure gave no depression.

Anal. Calcd. for $C_{10}H_{10}O_2Hg$: Hg, 55.4. Found; Hg, 55.0.

To prepare the desired 5-methyl-2-iodomercurifuran, 3 grams of the previously prepared 5,5'-dimethyl-2,2'-difuryl mercury and 3.73 grams of mercuric iodide were treated with sufficient boiling 95% ethanol to effect solution. This was allowed to stand at room temperature overnight. Crystallization had not taken place but a small amount of colloidal material had settled and this was removed by filtration. The solution was warmed again and water added. On cooling a crude yield of 6.2 grams (92%) was obtained. It was again recrystallized from an alcohol-water mixture

and 3.9 grams (58%) of pale yellow flakes with a decomposition point of 96° was obtained.

Anal. Calcd. for C_5H_5OHgI : Hg, 49.2. Found: Hg, 49.1.

The 5,5'-dimethyl-2,2'-difuryl mercury and 5-methyl-2-iodomercurifuran are unstable compounds, both turning dark after standing for a few weeks.

2. Polarographic Studies

The polarograph used in these studies is discussed under carbonyl compounds. The characteristics of the dropping electrode and the resistance of the cell were not determined. All determinations were made at room temperature.

Due to the insoluble nature of organomercurials a high ratio of an organic solvent to water had to be used. The reduction of the organomercuric iodides listed above was attempted in a solvent consisting of 80% of the freshly prepared dioxane and 20% water with 0.1 M tetra-n-butylammonium iodide as the supporting electrolyte. A small wave was observed for 5-methyl-2-iodomercurifuran with a half-wave potential of -1.95 volts, p-tolylmercuric iodide gave no wave and phenylmercuric iodide gave a maximum starting at zero voltage. The only well-defined wave was that of the the n-butyl compound and was at a potential of -0.35 volts. The latter determination was made employing methyl red as a maximum suppressor. This suppressor appeared to be the most effective in the dioxane studies.

Pyridine, 75%, in water also was used as a solvent. The curve for p-tolylmercuric iodide in Figure 3 is typical of the maxima obtained with this compound, phenylmercuric iodide, p-chlorophenylmercuric iodide, and 5-methyl-2-iodomercurifuran. The curve for the n-butyl compound, Figure 3, was readily reproducible. Little difference in the curves was obtained when methyl red, methyl orange, gelatin or no maximum suppressor was used.

The current-voltage curves of mercurous and mercuric ions show very prominent maxima. In water solutions these maxima are easily suppressed by various dyes or gelatin. When a mercury pool anode is used the current-voltage curves start immediately at an applied potential of zero.⁴³ In these studies then the curves must have been due to the reduction of a species of mercury since the curves rose sharply from zero applied potential. The diffusion current for the compounds which showed maxima in the pyridine solution was very close to 2 microamperes per millimolar concentration in every case, indicating the equilibrium concentration of the reducible species was nearly the same for these four compounds.

43. Ref. 2a, p. 257.

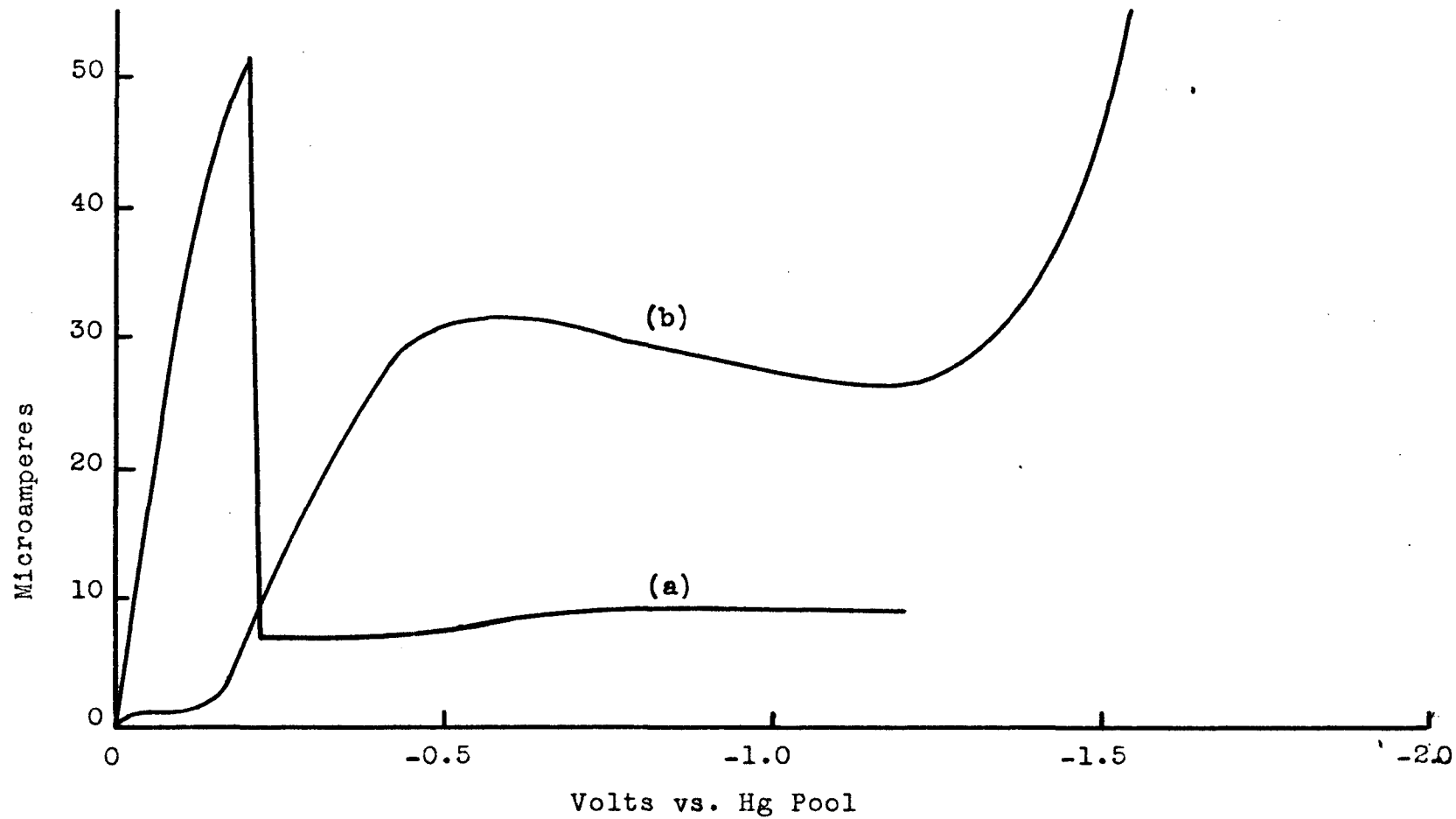


Figure 3. Polarograms of 5×10^{-3} M p-tolylmercuric iodide (a) and n-butylmercuric iodide (b) in a solvent 75% pyridine-water, 0.1 M tetra-n-butylammonium iodide.

IV. DISCUSSION

A. Correlation of Polarographic Reduction Potentials with Hammett's $\rho\sigma$ Treatment

It has been mentioned that the equation

$$\log k - \log k^{\circ} = \rho\sigma \quad (1)$$

is valid for many series of reactions in which the members of a series differ only by a meta or para substituent in a benzene derivative. If it is assumed that the rate of dimerization of the free radicals, equation II, is essentially the same for all the compounds in any one series, reaction I may be treated by the above equation giving

$$\log K - \log K^{\circ} = \rho\sigma \quad (3)$$

where K and K° are the ratios, $\frac{[>C(OH)^{\cdot}]}{[>C=O^{\cdot}H^+]}$ for the substituted and unsubstituted carbonyl compounds respectively in equilibrium with some common reference electrode. For a reversible reduction this ratio is related to the half-wave potential if the hydrogen electrode is taken as a reference

$$nFE_{\frac{1}{2}} = 2.303RT\log K \quad (4)$$

When this equation is solved for $\log K$ and substituted into

equation 3 it becomes

$$E_{\frac{1}{2}} - E_{\frac{1}{2}}^{\circ} = \frac{2.303RT}{nF} \rho \sigma \quad (5)$$

and as n is constant for any series, $\frac{2.303RT}{nF}$ may be incorporated in the reaction constant ρ and equation 5 is simplified to

$$E_{\frac{1}{2}} - E_{\frac{1}{2}}^{\circ} = \rho' \sigma \quad (6)$$

where $E_{\frac{1}{2}}$ and $E_{\frac{1}{2}}^{\circ}$ are the half-wave potentials of the substituted and unsubstituted compounds respectively. It will be shown empirically that equation 6 is valid for the polarographic reduction of meta and para substituted phenyl carbonyl compounds.

Figure 4 is a plot of the half-wave potentials of substituted benzaldehydes against the σ values listed in Table 9. The agreement with a straight line is good except for the m- and p-methyl substituted compounds. These compounds developed slight maxima which would move the half-wave potentials to more positive values.

When the half-wave potentials of the first wave for substituted acetophenones were plotted in a similar manner (Figure 5) it was found that a straight line was obtained with the same slope as that obtained with the substituted benzaldehydes except that the m- and p-amino derivatives fall below the line, both by approximately the same amount. These

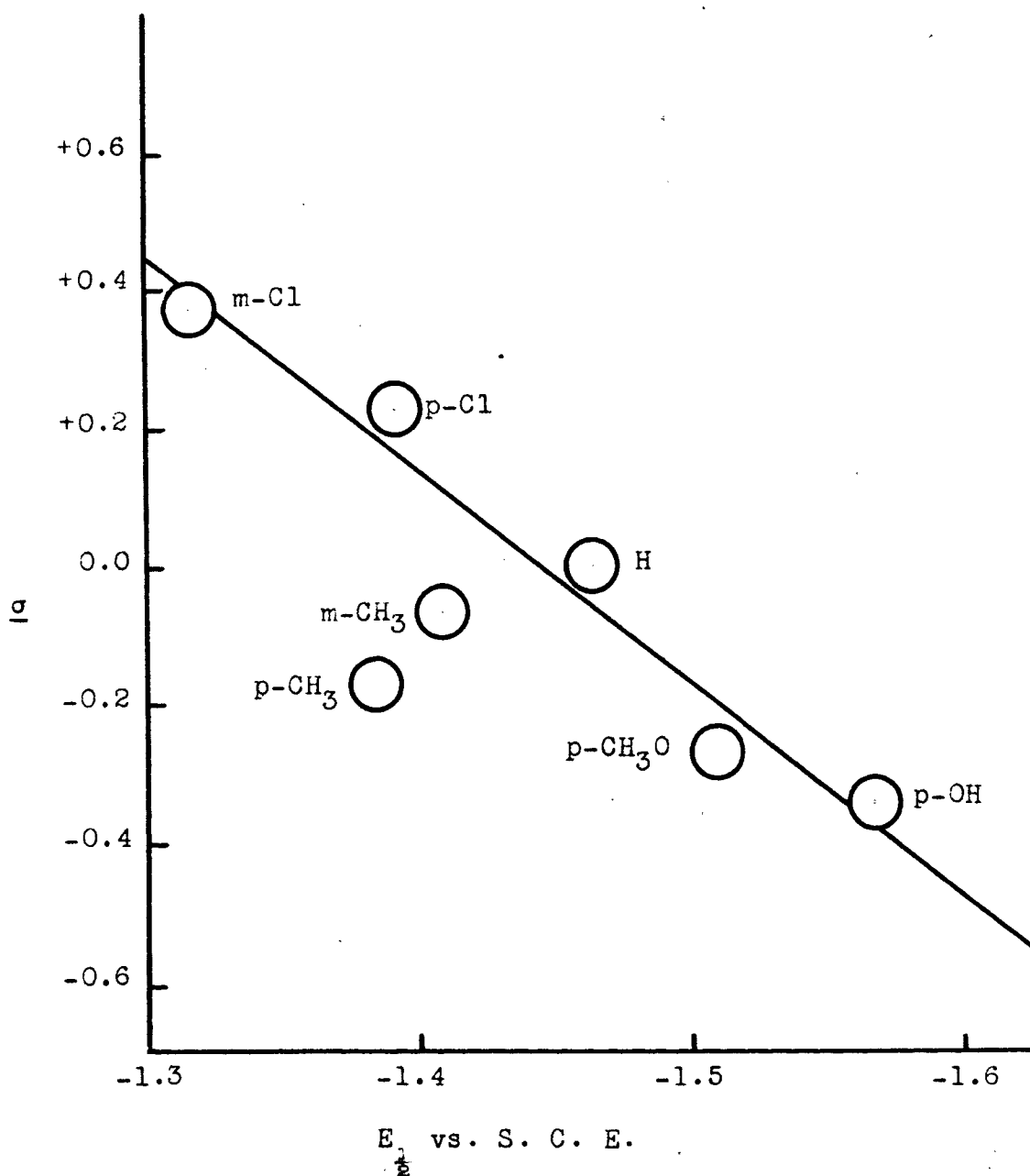


Figure 4. Half-wave potentials of m- and p-substituted benzaldehydes (see Table 6) in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol as a function of the substituents' σ values.

Table 9

Values of the Substituent Constants σ and ρ

Substituent	σ^*	ρ^{**}
p-NH ₂	-0.660	
p-OH	-0.341 ^a	2.93 ^c
p-CH ₃ O	-0.268	3.00
p-(CH ₃) ₂ N	-0.205	
	-0.570 ^b	
p-t-C ₄ H ₉	-0.197	
p-CH ₃	-0.170	3.40
m-NH ₂	-0.611	
p-C ₂ H ₅	-0.151	
p-i-C ₃ H ₇	-0.151	
m-CH ₃	-0.069	3.85
H	0.000	3.95
p-Cl	+0.227	4.65
p-Br	+0.232	4.90
m-Cl	+0.373	5.10
m-Br	+0.391	5.10
m-NO ₂	+0.710	5.74
p-NO ₂	+0.778	5.90
o-Cl		5.90
o-OH		6.42 ^d

*The σ values are from Hammett, Ref. 6, p. 188, except a, J. D. Roberts, E. A. McElhill and R. Armstrong, J. Am. Chem. Soc., 71, 2923 (1949), and b, Ref. 45.

**The ρ values are from Goodhue, Ref. 9f, h, except c, calculated by equation 11 using $-\log K = 4.48$ and c, by equation 2 using $-\log K = 2.97$.

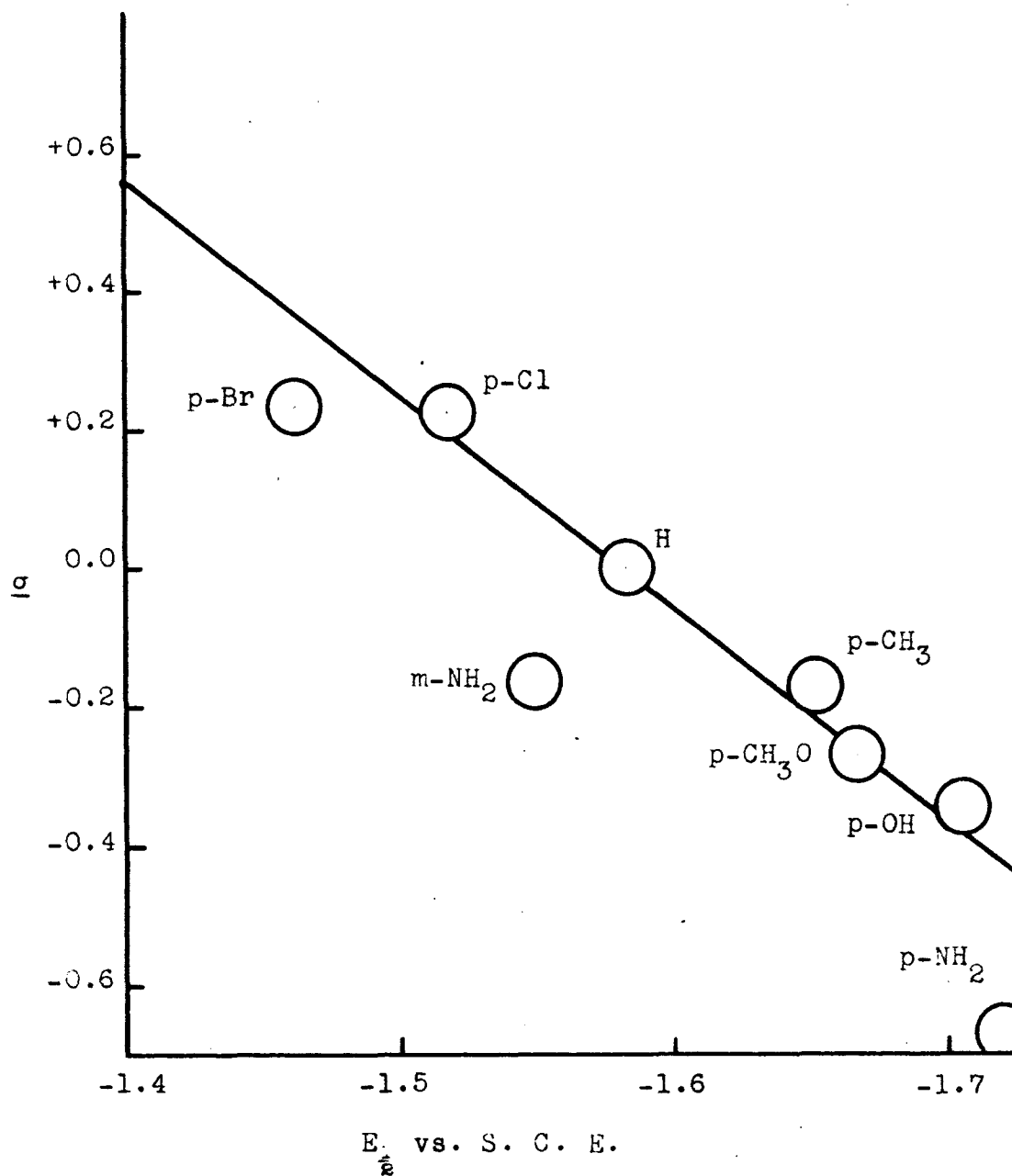


Figure 5. Half-wave potentials of the first wave of m- and p-substituted acetophenones (see Table 3) determined in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol as a function of the substituents' ρ values.

deviations will be discussed later. The slope of the line found is -0.325 when the voltage axis is taken as the ordinate and the \underline{g} axis as the abscissa. For acetophenones (Figure 5) the intercept on the \underline{g} axis is -1.58 volts. When these values are substituted into equation 6 it becomes

$$E_{\frac{1}{2}} = -1.58 + 0.325\underline{g} \quad (7)$$

By the use of this equation the values in Table 10 have been calculated and compared with the observed values.

To show that the equation

$$E_{\frac{1}{2}} + E_{\frac{1}{2}}^{\circ} = 0.325\underline{g} \quad (8)$$

is general for meta and para substituted phenyl carbonyl compounds the work of other investigators, who reduced a sufficient number of compounds of the type studied here to make a comparison possible, has been plotted. The lines in these plots have been drawn in order to fit the greatest number of points and still have a slope of 0.325.

Semerano and Chisini¹⁷ used as the reduction potential the point at which a tangent of $35^{\circ} 16'$ touched the current voltage curve. Since this point changes with concentration and galvanometer setting, the values taken from their data (Table 1) and plotted in Figure 6 have been so chosen that they have approximately the same concentration. Since this precaution has been taken the difference between the half-wave

potential and reduction potential should be essentially constant for the different compounds.

Table 10

Comparison of Observed and Calculated Half-wave Potentials vs. S. C. E. for Substituted Acetophenones

Substituent	$E_{1/2}$ vs. S. C. E.	
	Calculated	Observed
p-NH ₂	-1.79 v	-1.72 v
p-OH	-1.69	-1.70
p-CH ₃ O	-1.67	-1.67
p-CH ₃	-1.64	-1.65
m-NH ₂	-1.63	-1.55
H	-1.58	-1.58
p-Cl	-1.51	-1.52
p-Br	-1.51	-1.46

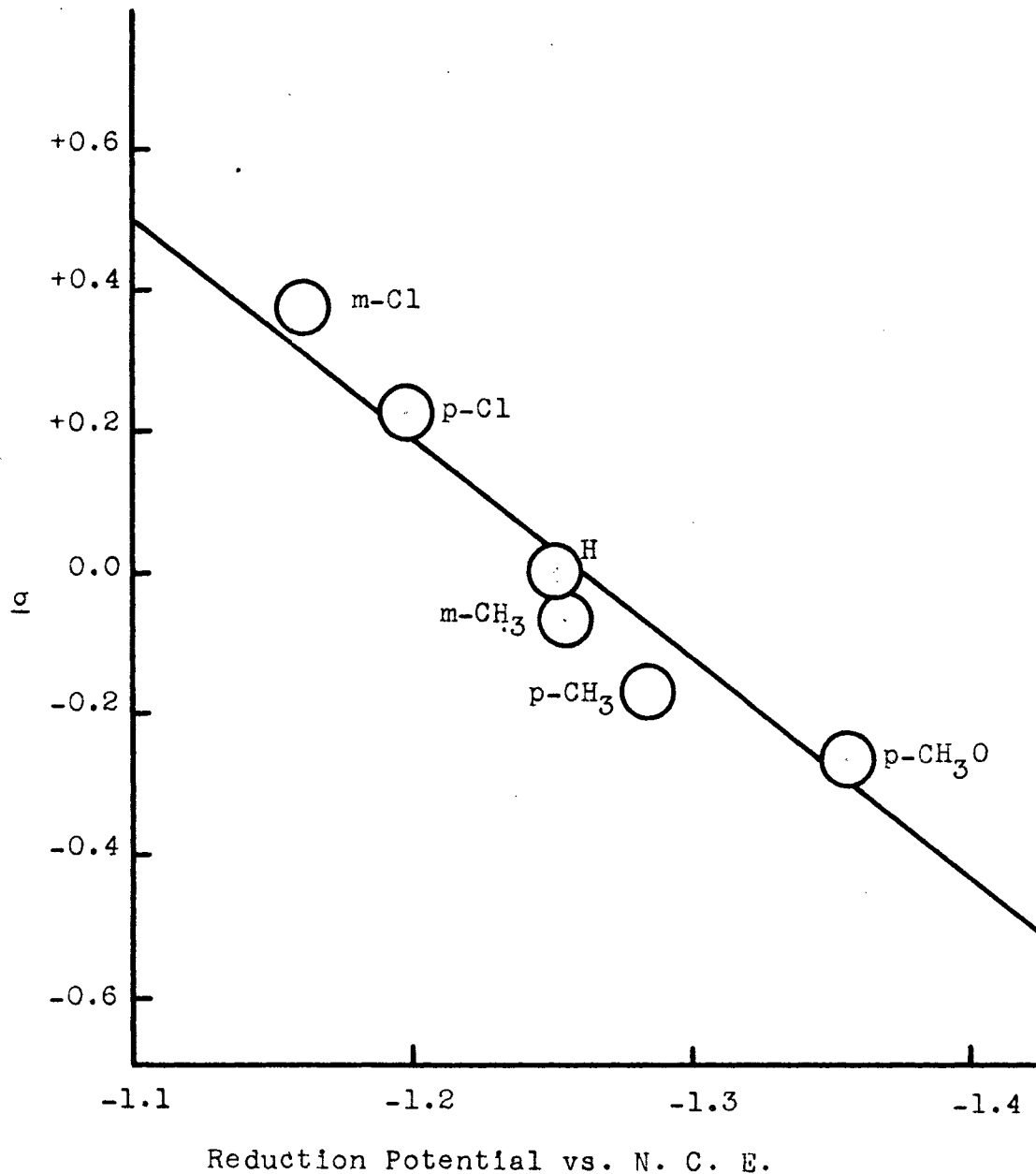


Figure 6. Reduction potentials of m- and p-substituted benzaldehydes (see Table 1) in 0.1 M NH₄Cl, 50% ethyl alcohol as a function of the σ values of the substituents.

Reduction potentials were reported by Winkel and Proske¹⁹ and Baker, Davies and Hemming.²⁶ This method of measurement has the same limitations as those mentioned above. The latter investigators used the same concentration of the reducible species in all their polarographic studies. In Figure 7 the data reported by Winkel and Proske for the reduction of substituted benzaldehydes have been plotted against \underline{g} and the agreement is good except for the m- and p-bromobenzaldehydes. The anomalous behavior of these compounds may be due to the higher alcohol content in the solvent.

The data of Baker, Davies and Hemming given in Table 4 for the polarographic reduction of para-substituted benzaldehydes are shown as a function of \underline{g} in Figures 8-12. In all cases it is the depolarization potential of the first wave or the one wave observed that has been related to \underline{g} . In buffered solutions of pH 1.4, 4, and 7 (Figures 8, 9, and 10) the para alkyl groups, $-\text{CH}_3$, $-\text{C}_2\text{H}_5$, $-\text{i-C}_3\text{H}_7$, and $-\text{t-C}_4\text{H}_9$, fall slightly below the line as was noticed with m- and p-methylbenzaldehydes (Figure 4) studied in these laboratories. When tetramethylammonium bromide and potassium chloride were used as the supporting electrolytes (Figures 11 and 12) these groups fall within the experimental error of the polarographic determination.

In Figures 8 to 12 two values of \underline{g} have been plotted for the dimethylamino group. Those marked (a) are for the \underline{g}

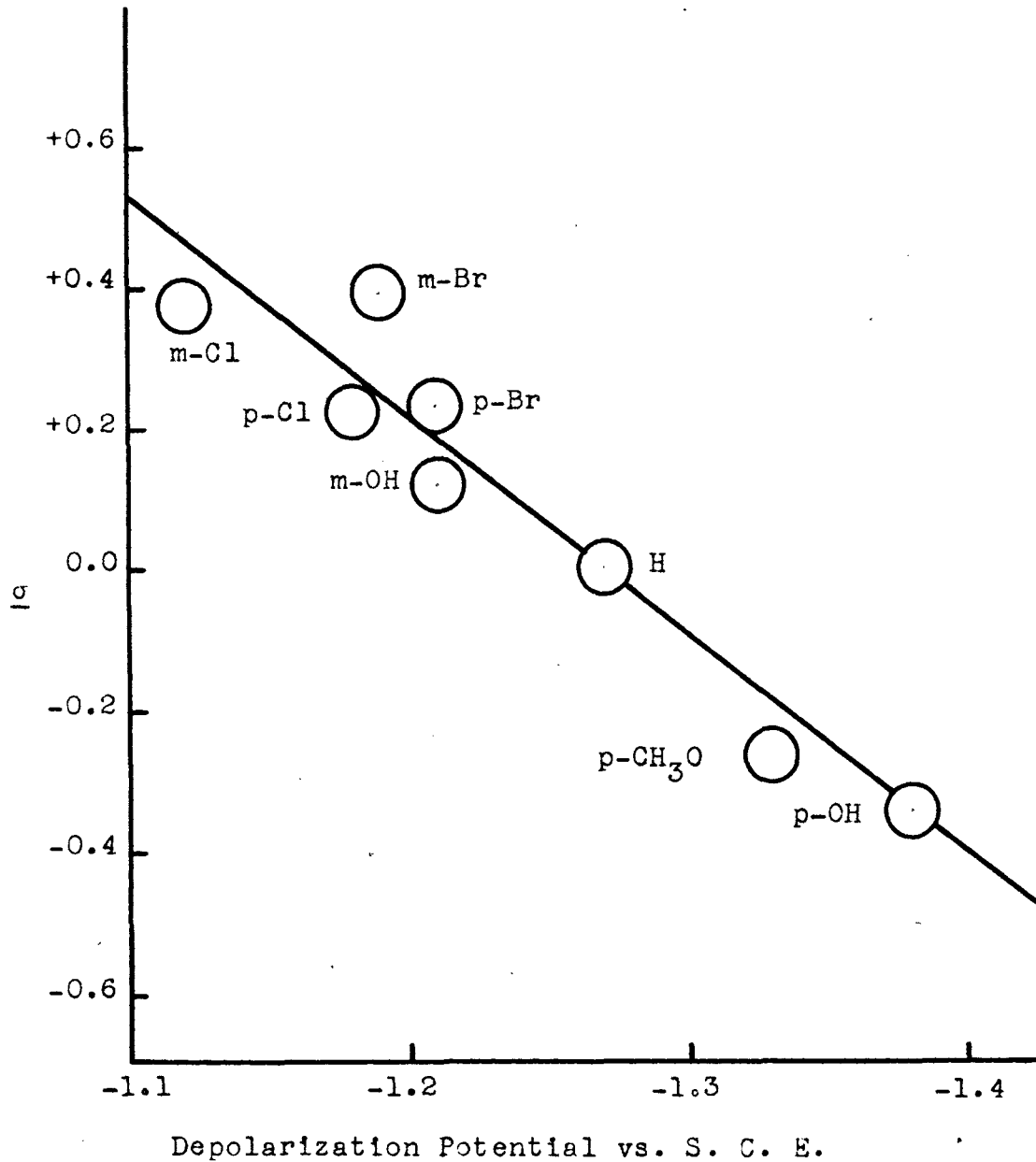
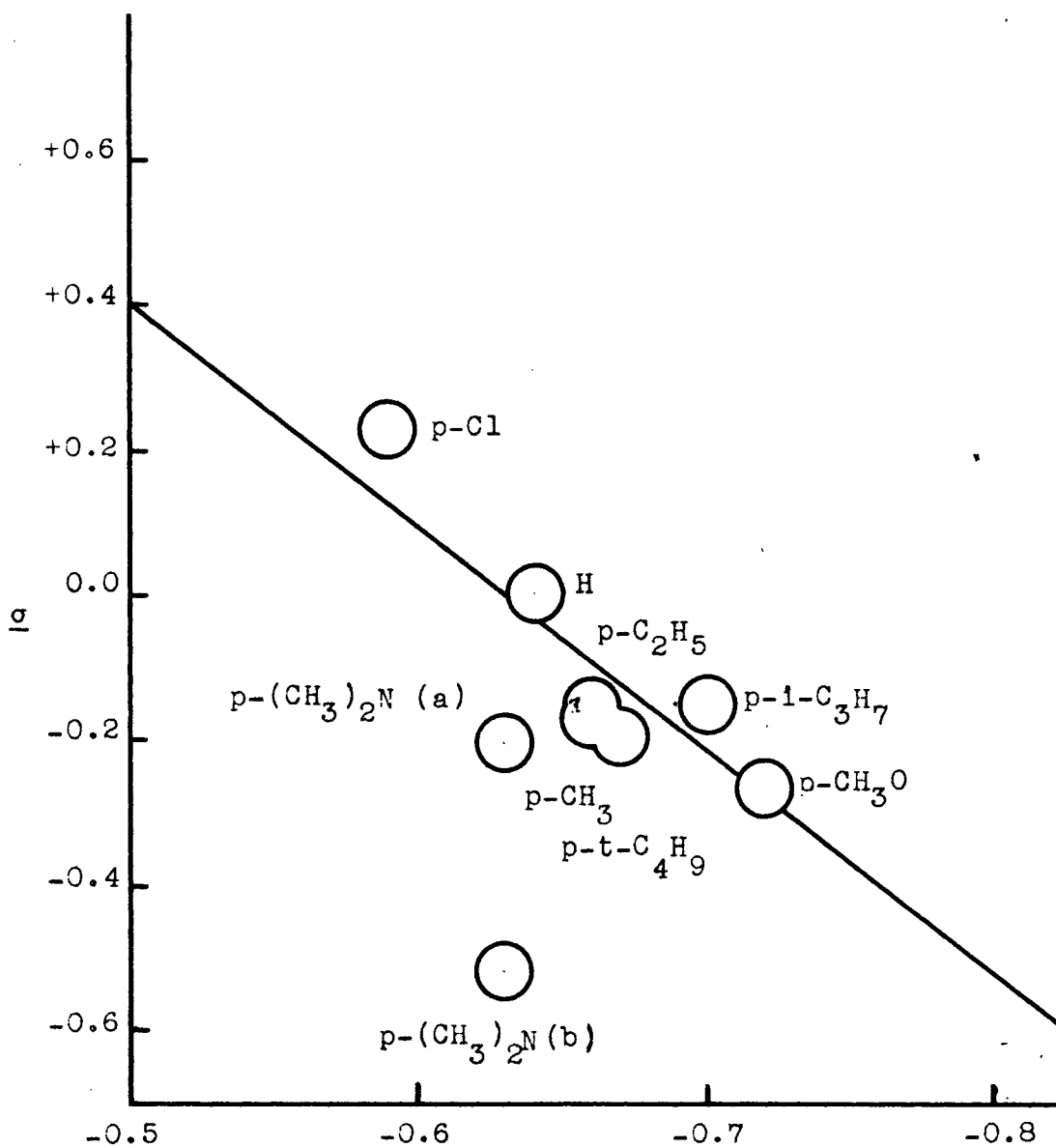


Figure 7. Depolarization potentials of m- and p-substituted benzaldehydes (see Table 2) in 0.1 M NH₄Cl, 2.5% alcohol (3.4% for m- and p-Br) as a function of the σ values of the substituents.



Depolarization Potential vs. 0.1 N Calomel Electrode

Figure 3. Depolarization potentials of p-substituted benzaldehydes (see Table 4) in a Clark and Lubs standard of pH 1.4, 33.3% ethyl alcohol as a function of the substituents' σ values; (a) Hammett, (b) Gilman and Dunn.

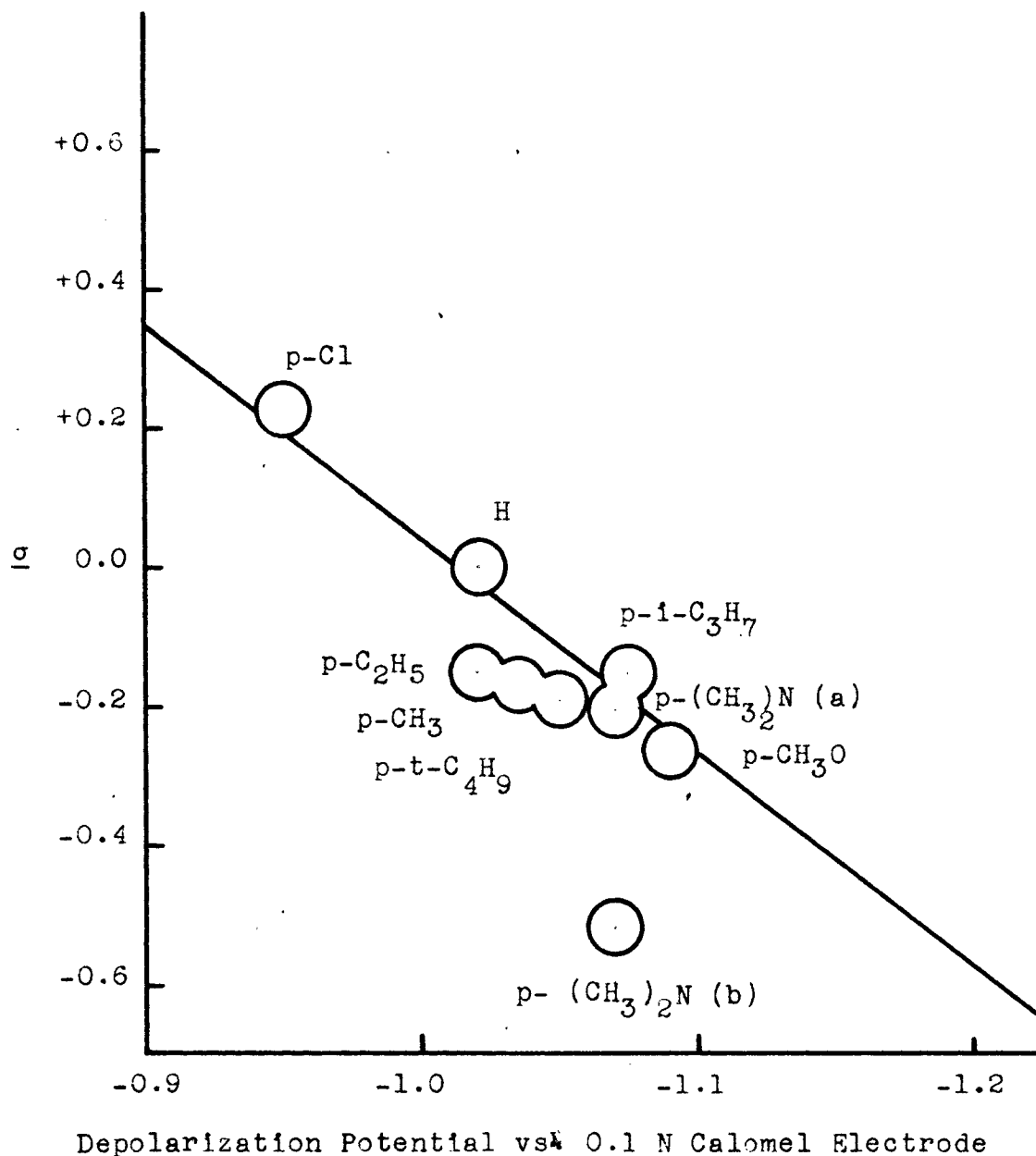
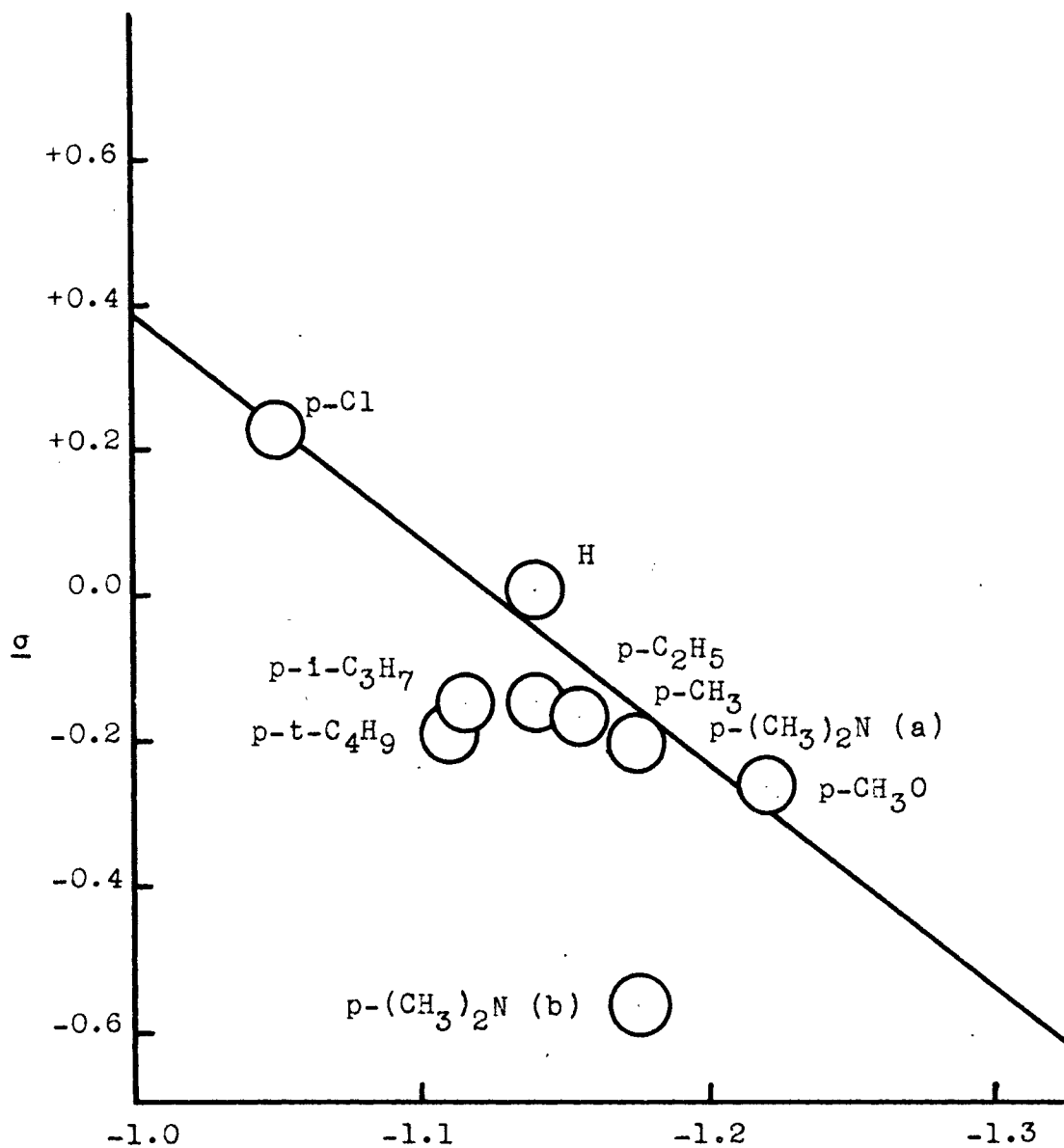
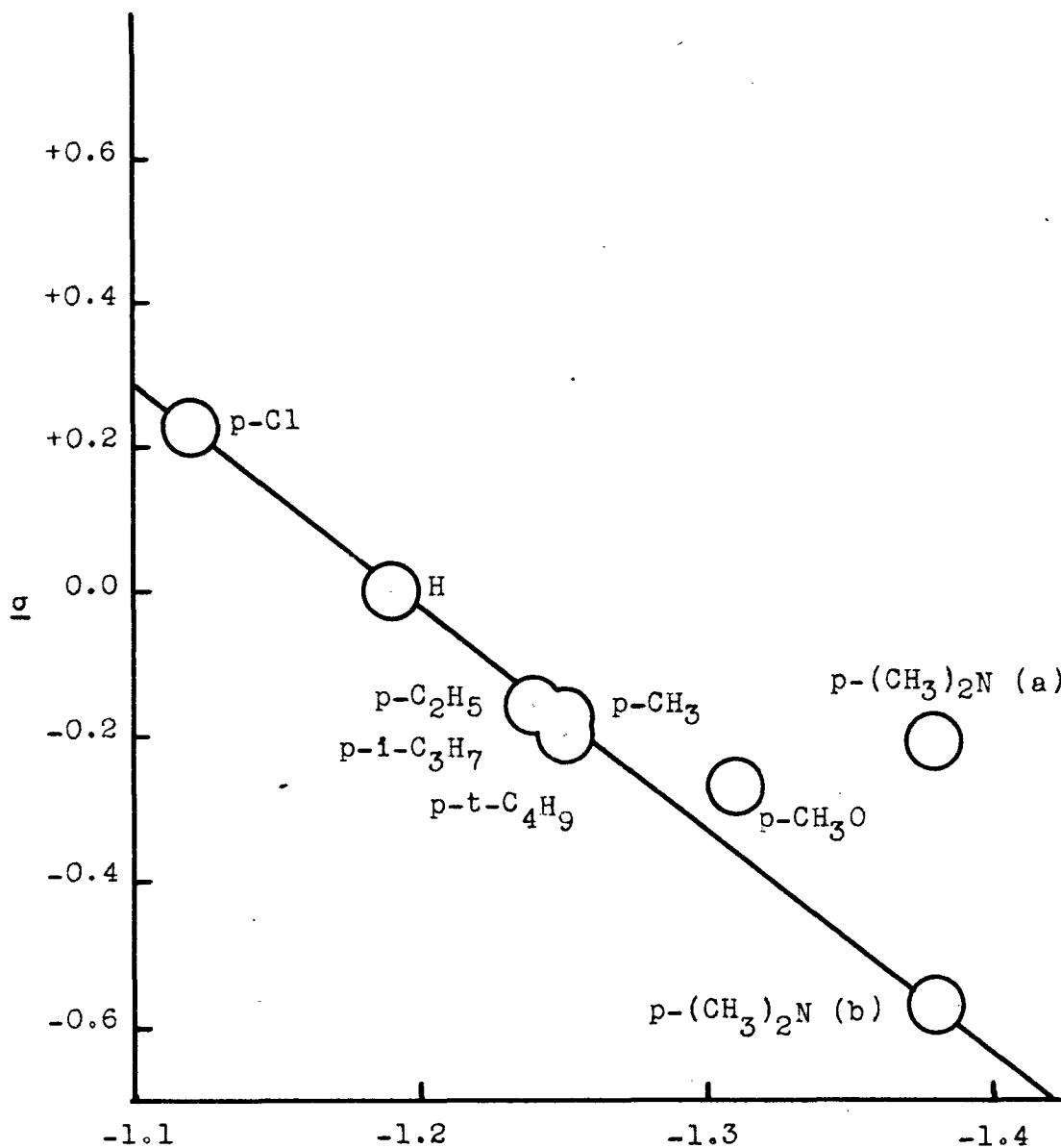


Figure 9. Depolarization potentials of the first wave of p-substituted benzaldehydes (see Table 4) in MacIlvaine's buffer solution of pH 4, 33.3% ethyl alcohol as a function of the substituents' σ values; (a) Hammett, (b) Gilman and Dunn.



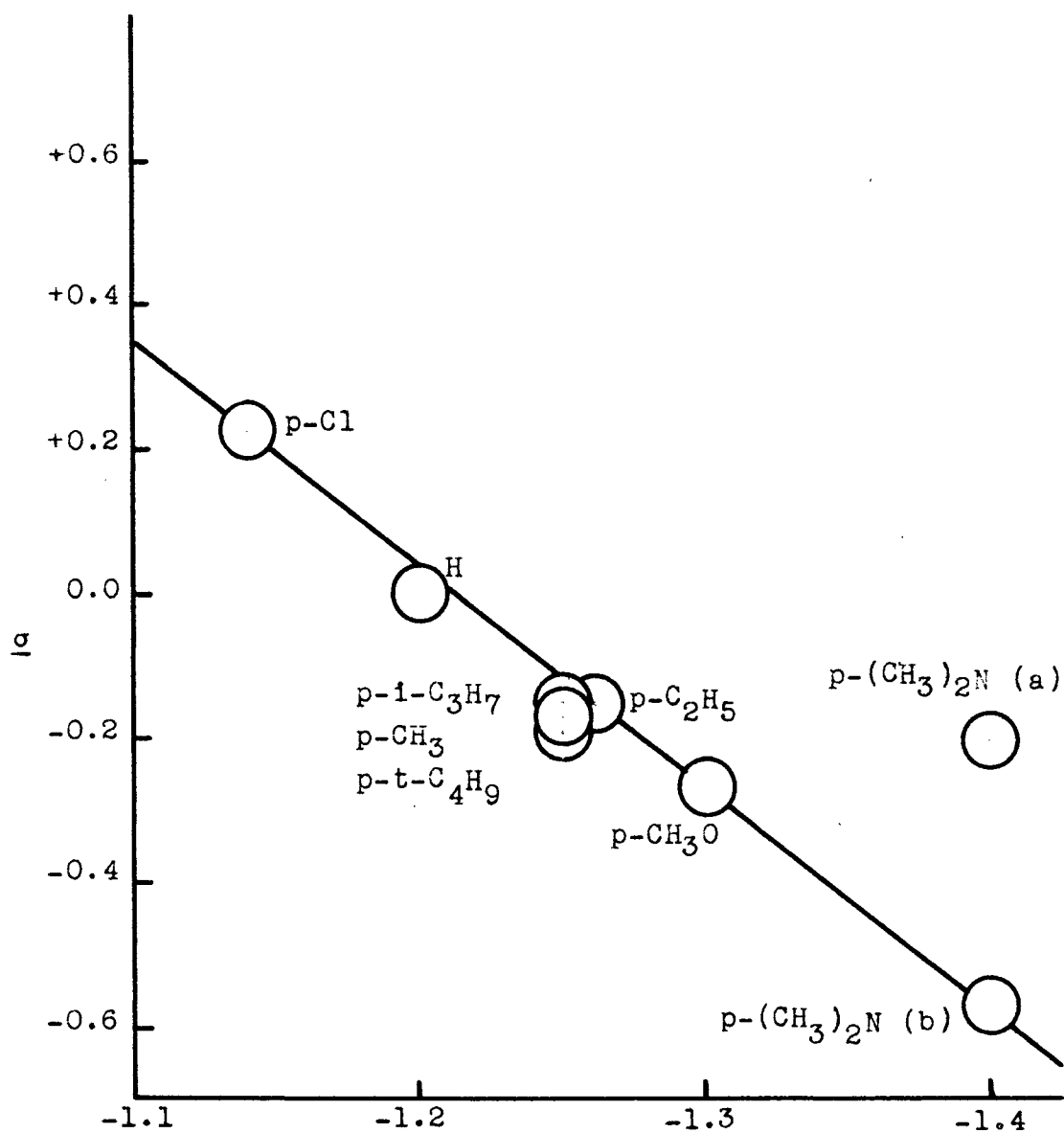
Depolarization Potential vs. 0.1 N Calomel Electrode

Figure 10. Depolarization potentials of p-substituted benzaldehydes (see Table 4) in MacIlvaine's buffer solution of pH 7, 33.3% alcohol as a function of the substituents' σ values; (a) Hammett, (b) Gilman and Dunn.



Depolarization Potential vs. 0.1 N Calomel Electrode

Figure 11. Depolarization potentials of the first wave of p-substituted benzaldehydes (see Table 4) in 0.1 N tetramethylammonium bromide, 33.3% alcohol as a function of the substituents' σ values.



Depolarization Potential vs. 0.1 N Calomel Electrode

Figure 12. Depolarization potentials of p-substituted benzaldehydes (see Table 4) in 0.1 N KCl, 33.3% alcohol as a function of the substituents' σ values; (a) Hammett, (b) Gilman and Dunn.

value of -0.205 reported by Hammett.⁴⁴ The points marked (b) have a g value of -0.570 determined by Gilman and Dunn.⁴⁵ The anomalous behavior of this group has been pointed out by several authors.⁴⁶ It is interesting to note that the value reported by Hammett was determined in acid solution while that of Gilman and Dunn was calculated from reaction rates in basic media. This agrees with the overall picture in the present correlation. From the depolarization potential in a buffer of pH 1.4 (Figure 8) one would expect the dimethylamino group to have a g value of -0.18 . In the unbuffered solutions in which the pH at the interface of the mercury drop may be quite high due to the electrode reaction (Figures 11 and 12) a g value of -0.57 satisfies equation 8.

The poor fit of the amino acetophenones (Figure 5) is probably due to the same factors as those influencing the behavior of the dimethylamino aldehydes. The change of the amino group to the anilinium ion would make a profound difference in g as it would prevent electron-accession to the ring. Since the mobility of the hydrogen ion is very large compared to that of other ions, it is possible that at

44. Ref. 6, p. 188.

45. H. Gilman and G. E. Dunn, J. Am. Chem. Soc., 73, 000 (1951).

46. (a) G. E. K. Branch and M. Calvin, "The Theory of Organic Chemistry," Prentice-Hall, Inc., New York, N. Y., 1941, p. 418; (b) F. H. Westheimer, J. Am. Chem. Soc., 62, 1892 (1940); (c) F. H. Westheimer and R. P. Metcalf, ibid., 63, 1339 (1941).

the immediate surface of the electrode there is a high concentration of hydrogen ions which results in the conversion of the amines into anilinium ions in this surface layer prior to the reduction of the carbonyl group even though the solution as a whole is nearly neutral.

The good agreement in the cases studied, that is, the polarographic reduction of meta and para substituted benzaldehydes and acetophenones with the equation

$$E_{\frac{1}{2}} - E_{\frac{1}{2}}^0 = \rho' \sigma \quad (9)$$

may be considered as evidence that the original assumptions are essentially correct. These assumptions were that addition of an electron to the carbonyl group is a reversible reaction and the rates of dimerization of the free radical are approximately equal.

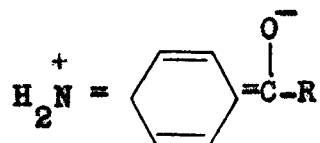
When the absolute value of ρ is calculated from ρ' ,

$$\rho = \frac{2.303RT}{nF} \rho' = 0.325$$

a value of +5.51 for ρ is found. This value is considerably greater than any value of ρ reported by Hammett. One would expect the value to be higher than the value 0.509 reported by Walling et al. since the resonance of a very polar group is being destroyed. However, one would not predict such a high value as that found. This result might lead one to believe that the value of ρ is sensitive to both the equilibrium constant and the rate of dimerization. The

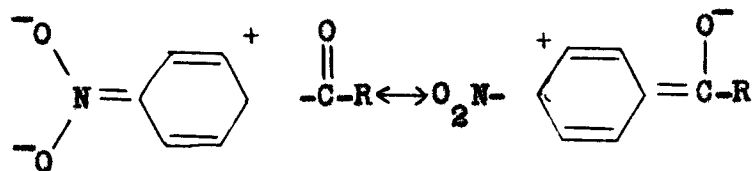
differences in $E_{1/2}$ would then be due to both of these factors which could conceivably give a cumulative effect of considerable magnitude. However, the evidence presented below concerning nitro compounds mitigates against this interpretation.

The sign of ρ indicates that electron-donating groups stabilize the carbonyl form relative to the radical formed. One might expect p-amino to be particularly good in stabilization of the carbonyl group due to resonance of the type



Similar structures can be written for other electron-donating groups such as hydroxyl and methoxyl. The poor fit of the amino group must be due to the reason previously given or possibly due to the increased adsorption of the amino compounds on the surface of the mercury drop.

With electron-withdrawing groups we have competition between the forms



both attempting to take electrons from the ring and no resonance interaction being possible. Also the two dipoles are opposed thus giving dipole-dipole repulsion. Thus the

addition of an electron and proton to form the free radical would involve a smaller loss in resonance energy than with the unsubstituted compounds. Consequently, electron-withdrawing groups would increase the ease with which the carbonyl group is reduced.

As the first wave in the reduction of nitro substituted benzaldehydes and acetophenones indicates a reduction requiring four electrons per molecule, the nitro group is being reduced before the carbonyl group. Consequently, one would not expect these compounds to fit the present treatment. The first wave is probably due to the reduction of the nitro group to hydroxylamine.⁴⁷ In the case of p-nitrobenzaldehyde contributions from structures such as those written above would account for the ease with which the nitro group would be reduced. Then the second wave is probably due to the complete reduction of the nitro group to the corresponding amine and the third wave to the simultaneous reduction of the nitro group and the carbonyl group. Since resonance of the above type is not possible when the nitro group is meta to the carbonyl group and a six-electron reduction is involved, the second wave of m-nitrobenzaldehyde and m-nitroacetophenone must be due to the simultaneous reduction of the carbonyl group and nitro group.

47. (a) J. Pearson, Trans. Faraday Soc., 44, 683, 692 (1948);
(b) S. F. Dennis, A. S. Powell and J. J. Astle, J. Am. Chem. Soc., 71, 1484 (1944).

Dennis, Powell, and Astle^{47b} have studied the polarographic behavior of substituted nitrobenzenes in buffered solutions of pH 7.4 in 50% ethanol. The half-wave potentials vs. saturated calomel electrode were: m-dinitro, -0.71; p-dinitro, -0.60; m-chloro, -0.86; p-chloro, -0.87; m-methyl, -0.93; and p-methyl, -0.95 volts. These values are shown in Figure 13 as a function of ρ . The agreement with a straight line gives strong indication that the present treatment will hold for the reduction of side chains other than the carbonyl group.

The slope of the line obtained is approximately the same as that obtained for carbonyl compounds. This indicates that a similar mechanism may be involved in the reduction of these compounds. As these compounds do not dimerize, the high absolute value of ρ indicates that only a reversible step is of importance in determining the influence of substituents in both cases.

When the present work was completed it was learned through Dr. D. J. Gram of the University of California at Los Angeles that D. M. Coulson⁴⁸ had obtained results similar to those reported here. From his studies he obtained the empirical equation

$$E_{\frac{1}{2}} = (0.804 \log \frac{\Sigma C_i}{1.0 \text{ Kcal}} - 2.02) \text{ volts} \quad (10)$$

48. D. M. Coulson, Unpublished studies, University of California at Los Angeles.

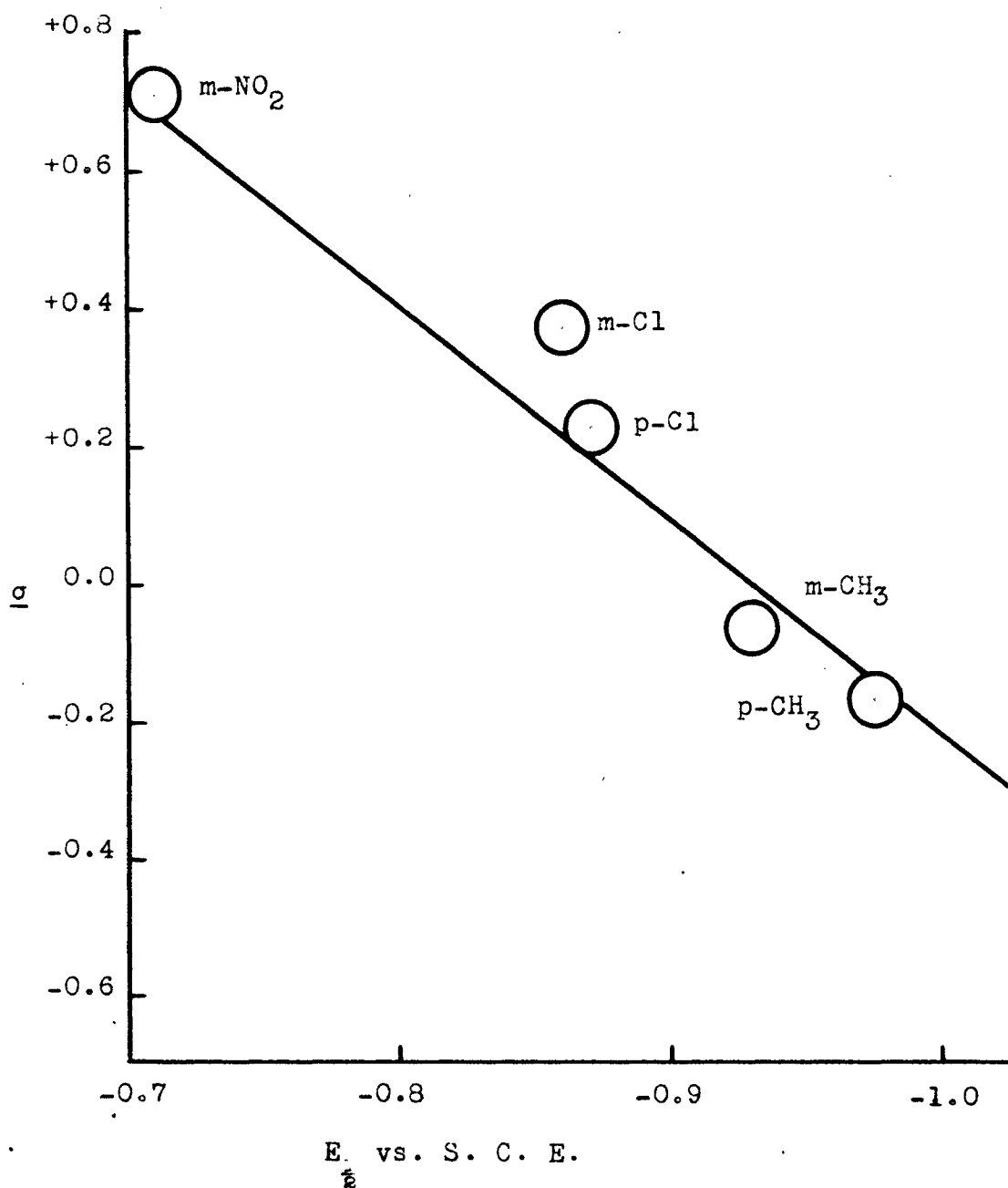


Figure 13. Half-wave potentials of m- and p-substituted nitrobenzenes (Dennis, Powell and Astle^{47b}) in MacIlvaine's buffer solution of pH 7.4, 50% ethyl alcohol as a function of the σ values of the substituents.

where ΣC_i is the stabilizing influence in Kcal of the free radical over the carbonyl compound. By neglecting the hydrogen in benzaldehyde and substituting the half-wave potential of -1.17 volts at pH 5 he found a value of C_i for the phenyl group to be 11.4 Kcal. By making similar substitutions he calculated C_i for a large number of groups. From these studies he found that the ratio, σ/C_i , was very nearly constant for meta and para substituents.

B. Correlation of Polarographic Reduction Potentials with Hixon-Johns' Treatment

Hixon and Johns⁸ state:

. . . If the electron theory of valence holds, then the polar properties of any series of compounds such as R(OH), R(COOH), R(CH₂-COOH), R(CH₂CH₂COOH), RNH₂, RSH, RASO(OH)₂, etc., must be a function of the 'electron-sharing ability' of R if we exclude from consideration under R all groupings which themselves have polar linkages.

The electron-sharing ability then must include such factors as resonance, dipole moments, steric effects, etc., but may be all expressed as a single parameter. The treatment was made broad so that it covered all types of groups from aliphatic and substituted aliphatic groups through the aryl groups. The values in Table 9, taken from the work of Goodhue,^{9f,h} have been calculated from equation 1 and from the equation

$$\log K_a = 20(e^{0.5x - 5.6} - 0.24) \quad (11)$$

for the dissociation of acids.

Hixon and Johns give the general equation for electron-sharing ability as

$$- \Delta F = kRT(e^{ax-b} - 0) \quad (12)$$

If this treatment is valid for oxidation-reduction reactions equation 12 may be written as

$$nFE = kRT(e^{ax-b} - 0) \quad (13)$$

or for a series of polarographic reversible reactions in which n is constant

$$E_{\frac{1}{2}} = K(e^{ax} - C) \quad (14)$$

Then if the same assumptions are made here as to the electrode reaction in polarographic reduction as were made in the Hammett treatment, a plot of the half-wave potential against the electron-sharing ability should be a smooth curve.

Figures 14 and 15 are plots of the half-wave potentials of the reduction of substituted benzaldehydes and acetophenones respectively as a function of x . The points for amines have not been plotted as these can be considered as being capable of having polar linkages and by definition should be excluded. A straight line has been drawn through these points because the probable error of the polarographic determination makes the drawing of any other curve difficult and its curvature doubtful. Figure 16 is a similar plot of the work of Winkel and Proske¹⁹ (Table 2). If the three curves are combined in such a manner that the reduction potential of the parent compounds all fall on the same vertical axis enough points are

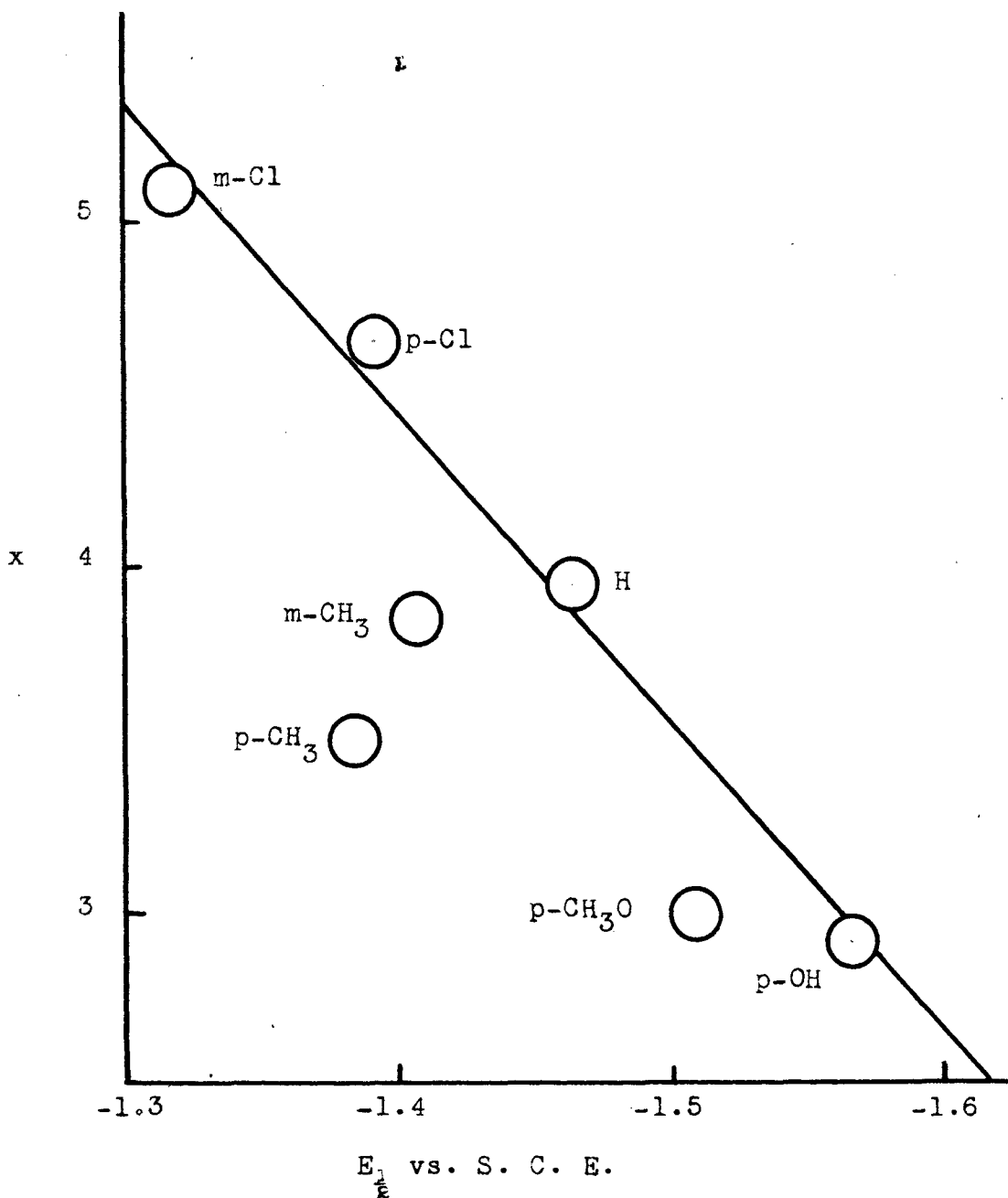


Figure 14. Half-wave potentials of m- and p-substituted benzaldehydes (see Table 6) in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol as a function of the electron-sharing ability, x, of the substituents.

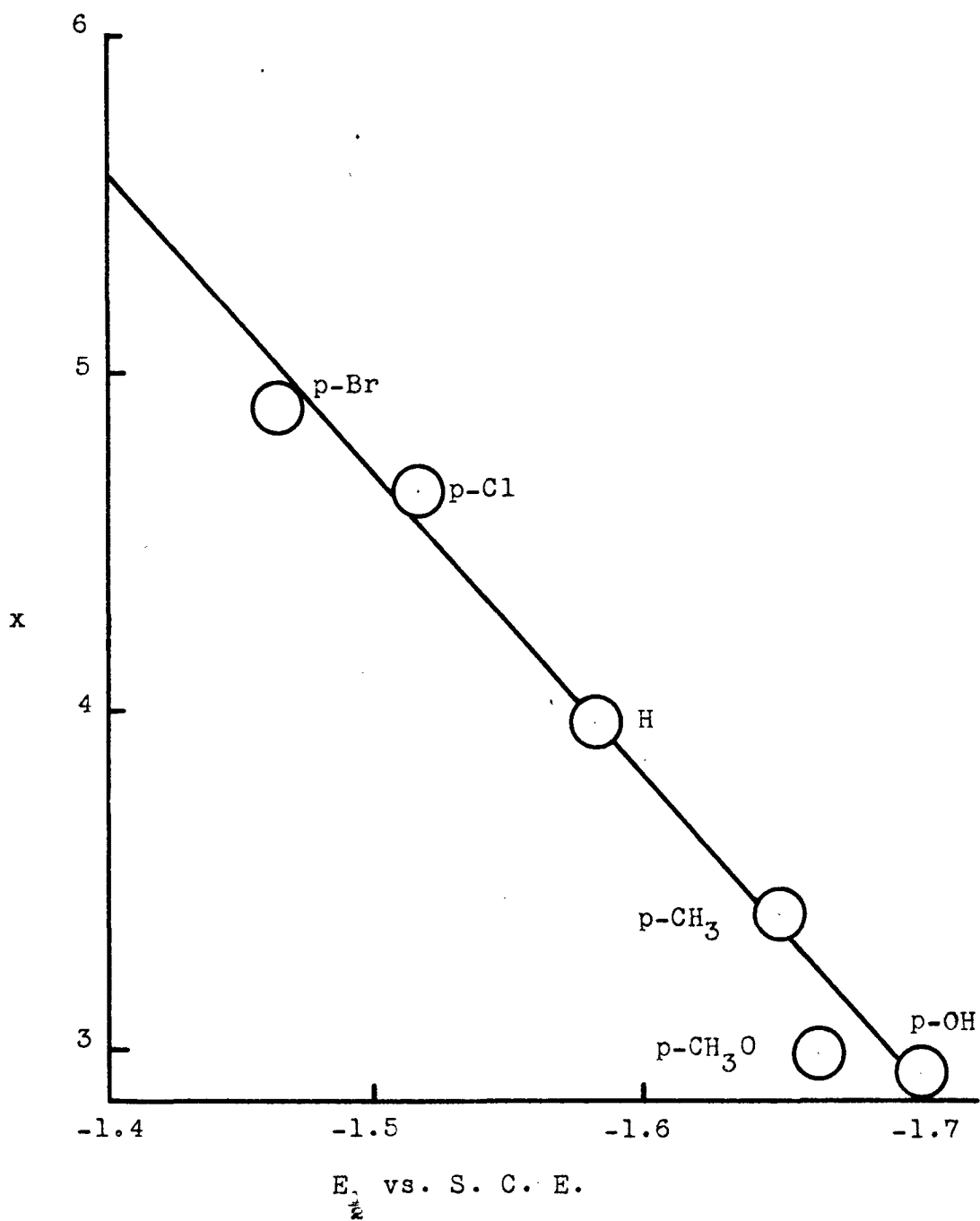


Figure 15. Half-wave potentials of the first wave of substituted acetophenones (see Table 8) in MacIlvaine's buffer solution of pH 7, 33.3% ethyl alcohol as a function of the electron-sharing ability, x , of the substituents.

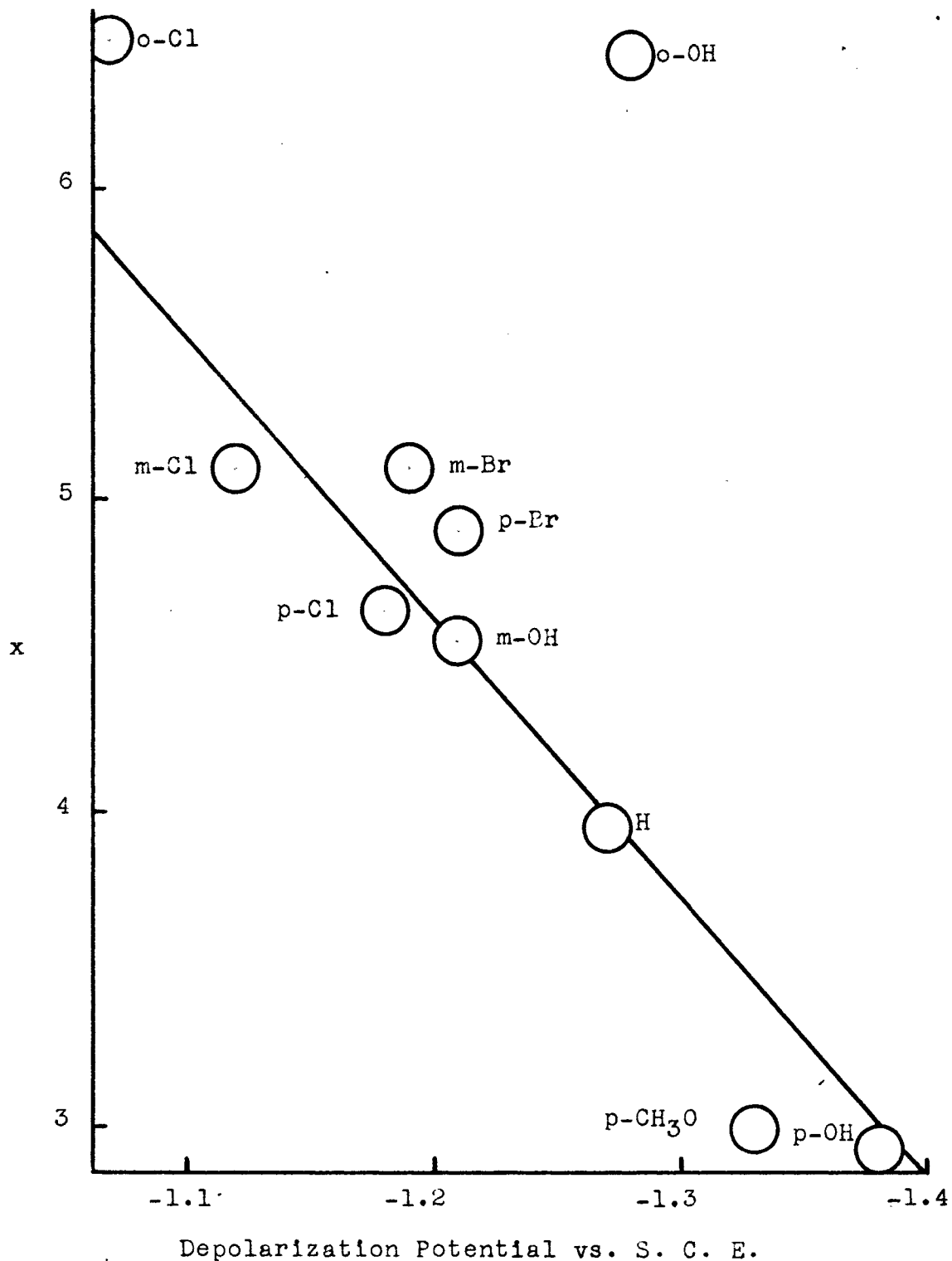


Figure 16. Depolarization potentials of m- and p-substituted benzaldehydes (see Table 2) in 0.1 M NH₄Cl, 2.5% alcohol (3.4% for m- and p-Br) as a function of the⁴electron-sharing ability, x, of the substituents.

obtained so that it is possible to draw a non-linear curve. The convex curvature is very slight, undoubtedly due to the large expansion of the electron-sharing ability axis.

In Figure 16 are also plotted the depolarization potentials of o-chloro and o-hydroxybenzaldehydes. It is seen that these compounds do not fit the treatment. When the data of Adkins and Cox²⁴ are plotted similar results are obtained. This indicates that in some cases this treatment, as with the Hammett equation, will not hold for reactions on side chains of ortho-substituted benzene derivatives.

The plots of the reduction potentials of meta and para substituted benzaldehydes and of meta and para substituted acetophenones against ρ indicates that the treatment of Hixon and Johns holds for the polarographic reduction of these compounds.

C. Correlation of Hammett's $\rho\sigma$ Treatment with Hixon-Johns' Electron-Sharing Ability Treatment

Hammett's $\rho\sigma$ treatment holds for the dissociation of meta and para substituted benzoic acids. The Hixon-Johns' treatment has been extended to cover alkyl as well as all aryl carboxylic acids. If equation 1 is solved for $\log K_a$ and set equal to equation 11 the relation between the two sets of parameters is

$$\log K_a = \log K^0 + \rho\sigma = 20 e^{0.5x-5.6} - 4.8 \quad (15)$$

This equation is readily simplified to

$$e^{0.5x} = \frac{e^{5.6} (\log k^0 - 4.8)}{20} + \frac{e^{5.6}}{20} (\rho\sigma) \quad (16)$$

Substituting -4.203 for $\log k^0$, the dissociation constant of benzoic acid, and $\rho = 1$, the reaction constant for the dissociation of substituted benzoic acids, the equation reduces to

$$e^{0.5x} = 8.06 + 13.51\rho\sigma \quad (17)$$

or

$$0.5x = 2.303 \log (8.06 + 13.51\rho\sigma) \quad (18)$$

which correlates the treatments for meta and para substituted compounds only. This equation has been plotted in Figure 17

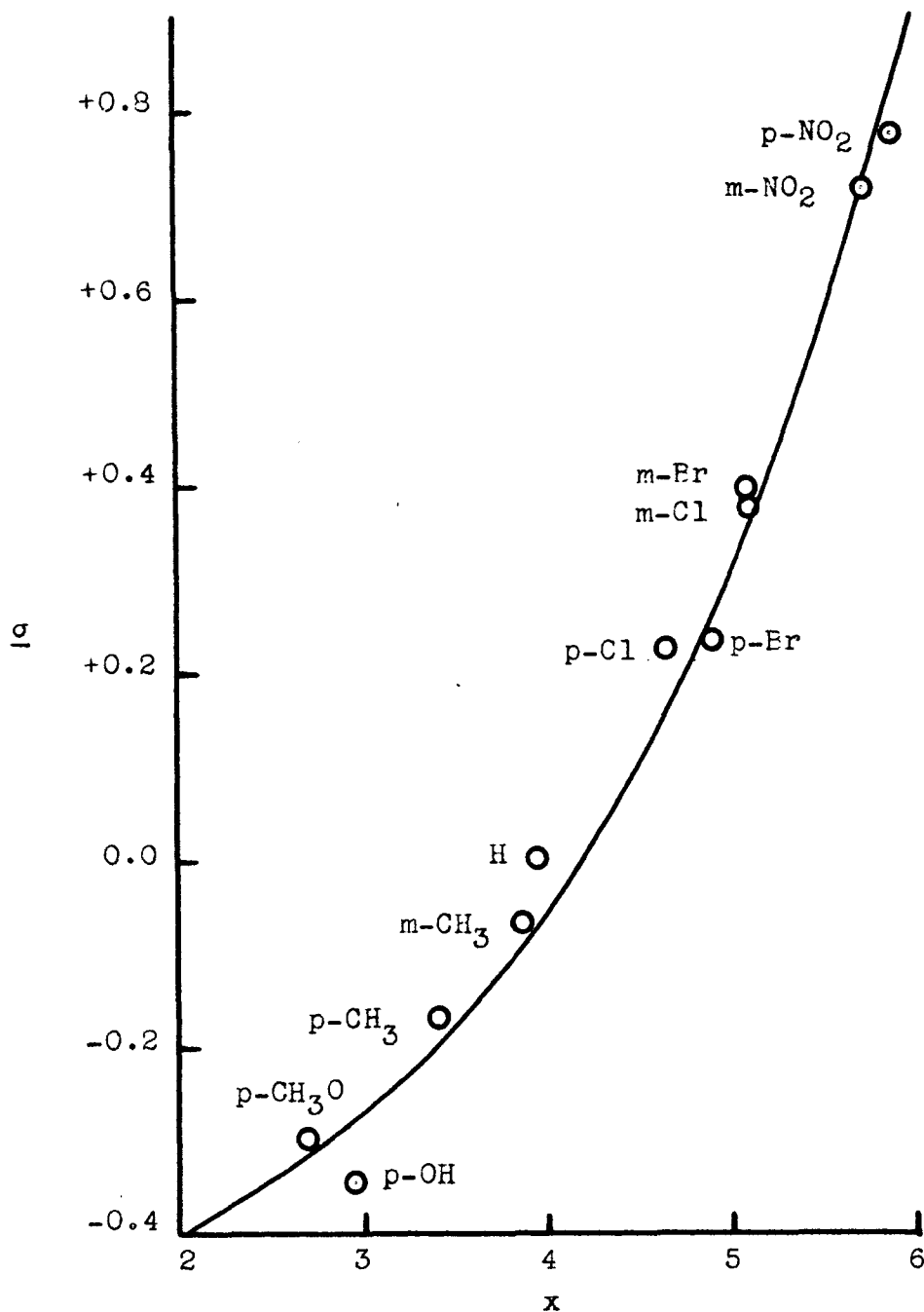


Figure 17. Relation between Hammett's σ constant and electron-sharing ability, x . The curve is plotted from equation 18, and the small circles are the reported values for the same substituents.

and the points are the values of \underline{g} and x given in Table 9.

A similar equation giving the same curve for \underline{g} and x can be derived for the dissociation constants of amines. In this case, however, a value of ρ of 3.79 determined by plotting the dissociation constants of meta and para substituted anilines against \underline{g} must be used rather than the value of 2.73 reported by Hammett.

It is apparent that over the range in which a comparison has been made the two treatments are similar. While the number of groups involved in Hammett's treatment is limited, its application, within this framework, is quite broad as attested by the 52 different reactions to which he applied it. The Hixon-Johns treatment covers a wide range of organic groups, but its applicability has not been tested in a sufficient number of reactions to enable one to give a fair estimate as to its scope.

V. SUMMARY

1. The half-wave reduction potentials of a series of meta and para substituted benzaldehydes and acetophenones have been determined in a 33.3% ethyl alcohol, 66.7% 0.2 M MacIlvain buffer mixture and reported.
2. The half-wave potential moves to more positive potentials when electron-attracting groups are substituted in the benzene nucleus. When electron-donating groups are the substituents the half-wave potential is moved to more negative values.
3. Except for amino groups, the half-wave potentials for the reduction of side chains of meta and para substituted benzene derivatives may be represented by the equation

$$E_{\frac{1}{2}} - E_{\frac{1}{2}}^{\circ} = \rho' \underline{g}$$

where $E_{\frac{1}{2}}$ and $E_{\frac{1}{2}}^{\circ}$ are the half-wave potentials of the substituted and unsubstituted compounds respectively. For polarographic reductions of phenyl-carbonyl compounds ρ' has a value of 0.325 and \underline{g} is the Hammett constant for the substituent.

4. A plot of the half-wave potentials for the reduction of side chains of meta and para substituted benzene derivatives against the electron-sharing ability of the

radicals indicates a smooth curve. The reduction potential can be represented by the equation

$$E_{\frac{1}{2}} = K(e^{ax} - c).$$

5. For reactions on side chains of meta and para substituted benzene derivatives the Hixon-Johns "electron-sharing ability" theory is quite comparable to the treatment of Hammett. The relation between the electron-sharing ability and the substituent constant g is

$$e^{0.5x} = 8.06 + 13.51g.$$

6. The polarographic reduction of organomercuric iodides was attempted but maxima rendered the curves uninterpretable. The compounds p-chlorophenylmercuric iodide, 5-methyl-2-iodomercurifuran and 5,5'-dimethyl-2,2'-difurylmercury, which have not previously been reported, have been prepared and characterized.

PART II

REACTIVITY OF FURANS
BEARING ELECTRON-ATTRACTING SUBSTITUENTS

I. INTRODUCTION

An understanding of a reaction mechanism may broaden the applicability of a given reaction. Mechanisms are usually established by kinetic studies and examination of the products formed. Such studies have not been extensive in the chemistry of furans. The probable reason for this lack of study is that in many reactions of furans the yield of the desired product is quite low and an important side reaction in many cases is resin formation.

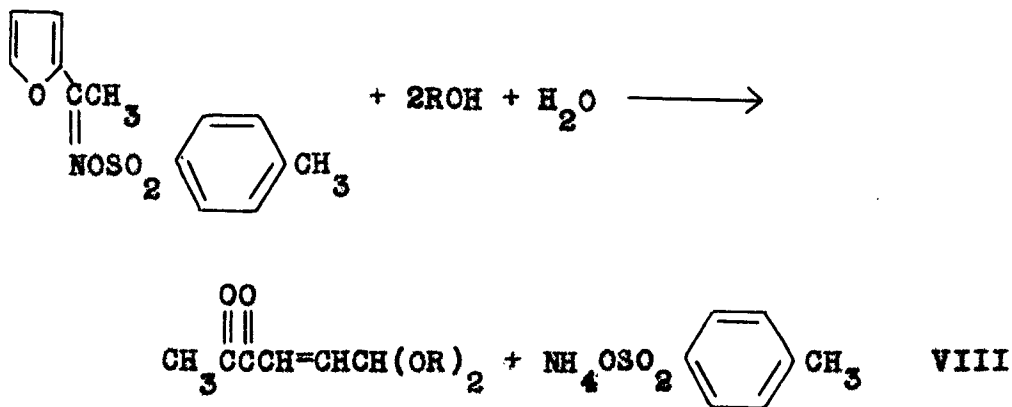
Approximately 5,000 articles have been published, each dealing with some phase of furan chemistry.⁴⁹ Several review articles⁵⁰ are available on the subject none of which are, in any sense, complete. A forthcoming book by Dunlop⁵¹ will be the most complete works yet compiled on the chemistry of furans.

49. F. N. Peters, Ind. Eng. Chem., 40, 200 (1948).

50. (a) H. Gilman and G. F. Wright, Chem. Revs., 11, 323 (1932);
(b) A. A. Morton, "The Chemistry of Heterocyclic Compounds,"
Chap. I, McGraw-Hill Book Company, Inc., New York, N. Y., 1946;
(c) R. C. Elderfield and T. N. Dodd, Jr., in R. C. Elderfield,
"Heterocyclic Compounds," Vol. I, Chap. IV, John Wiley and
Sons, Inc., New York, N. Y., 1950.

51. A. P. Dunlop, Quaker Oats Company, Personal Communication.

Vargha et al.⁵² discovered that when p-toluenesulfonyl-2-acetofuranoxime was treated with alcohol the furan ring opened giving the products ammonium p-toluenesulfonate and the acetal of 4,5-diketo-2-hexanal.



This reaction is particularly well suited for kinetic studies as it is practically quantitative. It was found that the absorption maxima of these compounds in the ultraviolet region of the spectra were sufficiently different so that analysis for the starting material could be made spectrophotometrically.

Many ring opening reactions of furans are recorded in the literature. If an alcoholic solution of furan is treated with a small amount of hydrogen chloride an acetal is formed.⁵³

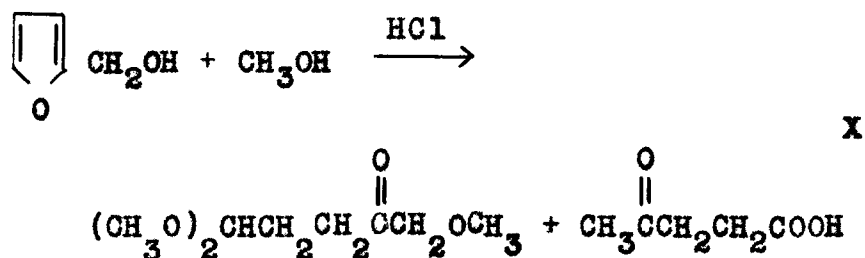


52. L. Vargha, J. Ramonczai and P. Bite, J. Am. Chem. Soc., 70, 371 (1948).

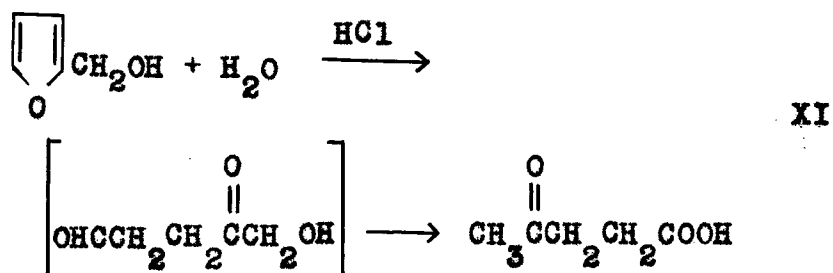
53. C. Harries, Ber., 31 (1898); 34, 1488 (1901).

and with α -methylfuran the product is the methylal of levulinic aldehyde.

When furfuryl alcohol is treated in a similar manner an acetal can be isolated.⁵⁴



When this reaction is carried out in aqueous solutions a good yield of levulinic acid is obtained.⁵⁵ This reaction is postulated as involving an aldehyde intermediate which undergoes an intramolecular disproportionation.



This reaction may be somewhat analogous to that observed by Vargha since in that reaction too, intramolecular oxidation and reduction must occur.

54. R. Pummerer, O. Guyot and L. Birkofer, Ber., 68, 480 (1935).

55. R. Pummerer and W. Gump, Ber., 56, 999 (1923).

It was hoped that a study of reactions such as those listed above might lead to a better understanding of the mode of resin formation by furan compounds. A study of this type could also lead to a better understanding of the scope and limitations of a given reaction thereby enabling the chemist to know to what extent it could be used in synthetic work.

During the preliminary work to study the decomposition of p-toluenesulfonyl-2-acetofuranoxime in alcohol it was necessary to prepare α -acetylfuran. This was attempted by reacting furoyl chloride with dimethyl cadmium. We observed a side reaction which must have involved the enolate anion of the ketone. That α -acetylfuran will readily undergo enolization is indicated in that it readily condenses with furfural in basic media to give high yields of furfuralacetofuran.⁵⁶ The products of this side reaction have been subjected to careful scrutiny since their appearance in considerable yield may well be related to the special properties of functional groups attached directly to the furan nucleus. The results are also of importance since they may yield information as to the course of a reaction which has general synthetic utility.

56. (a) C. Weygand and F. Strobelt, Ber., 68, 1839 (1935);
(b) K. Alexander and G. H. Smith, Jr., J. Am. Chem. Soc.,
71, 735 (1949).

II. REACTION OF DIMETHYL CADMIUM WITH FUROYL CHLORIDE

In an attempt to prepare relatively large amounts of 2-acetylfuran by the reaction of 2-furoyl chloride with dimethyl cadmium a side reaction, acylation, leading to di- α -furoylmethane and tri- α -furoylmethane took place. These compounds have not been reported previously. The products of the side reaction were easily isolable as they were readily extracted from the reaction mixture with base. The fact that each had a good sharp melting point, re-crystallized in well-defined needles and gave but one break in a titration curve when titrated with base indicated that they were well defined compounds.

The structure proof of the new compounds depends on their synthesis. Di- α -furoylmethane and tri- α -furoylmethane were synthesized by methods which have been used to prepare dibenzoylmethane⁵⁷ and tribenzoylmethane respectively.⁵⁸ The determination of neutral equivalents, study of absorption spectra, preparation and characterization of derivatives, quantitative oxidation by the iodoform reaction, and degradation studies all give confirmation of their structure.

57. (a) L. Claisen, Ber., 20, 655 (1887); (b) L. Claisen, Ann., 291, 25 (1896).

58. A. Baeyer and W. H. Perkin, Ber., 16, 2128 (1883).

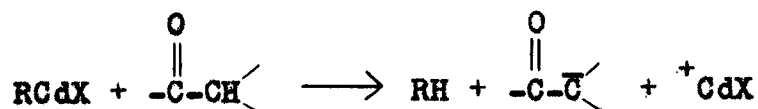
A. Review of Pertinent Literature

The reaction of choice for the preparation of many ketones is that of an organocadmium compound with an acid chloride.⁵⁹ This method of preparing ketones has been very useful in the sterol series and with aliphatic acid chlorides of high molecular weight. Organocadmium reagents usually react very slowly with carbonyl groups⁵⁹ and will not add to an amide or nitrile group.⁶⁰ It has, therefore, the distinct advantage that it can be used for the preparation of polyfunctional compounds containing a keto group. An excellent review covering nearly all the work through 1946 on the use of organocadmium reagents for the preparation of ketones has been written by Cason.⁶⁰ In this work he compares it with other methods, gives the scope and limitations, known side reactions and the experimental conditions.

In the early studies it was shown that organocadmium reagents could bring about condensations. Gilman and Nelson condensed benzaldehyde with acetophenone in the presence of diethylcadmium to give benzalacetophenone.⁵⁹ A condensation of this type probably proceeds through the formation of an enolate ion.

59. H. Gilman and J. F. Nelson, Rec. trav. chem., 55, 518 (1936).

60. J. Cason, Chem. Rev., 40, 15 (1947).



Cason⁶⁰ points out that reaction of the enol form with the cadmium reagent is probably a very minor side reaction in the preparation of ketones since no significant racemization took place when d-methylphenylacetyl chloride was heated with dimethyl cadmium.⁶¹ The fact that racemization did not take place may not be significant as the enolization step as written above would be irreversible and the fraction which enolized would be lost by condensation.

When preparing α -chloro ketones by the reaction of an α -chloro acid chloride and an organocadmium reagent it was found that the yields were significantly lower⁶² than when preparing the corresponding unsubstituted ketones. Cason's study of this reaction showed that when dibutylcadmium was treated with chloroacetyl chloride considerable quantities of butane could be collected before hydrolysis of the organometallic complex. Enolization must have been assisted by the α -halogen atom. By treating a benzene solution of dibutylcadmium with 1-chlorohexanone-2, 70% of the butyl bromide used to prepare the original Grignard reagent was recovered as butane. Only a small portion of

61. A Campbell and J. Kenyon, J. Chem. Soc., 1946, 25.

62. J. Cason, J. Am. Chem. Soc., 68, 2078 (1946).

the original ketone was recovered and the other products of the reaction were not characterized except that it was found that they were non-volatile at 4 millimeters pressure. He suggests that the chloroketone was lost by some type of self-condensation or alkylation of the enolate ion.

In preparing α -acetyfuran by reacting α -furoyl chloride with dimethylcadmium no attempt was made to get optimum yields.

B. Experimental

1. Method of Reaction

a. Run I

Methyl bromide gas was passed into a flask containing a mechanically stirred mixture of 2 moles of magnesium and 1500 milliliters of dry ether until all the magnesium had reacted. To this ether solution was then slowly added one mole of cadmium chloride which had been dried at 120° to constant weight. Agitation was continued until a Gilman color test was negative.⁶³ The flask was fitted with a Claisen head and condenser and placed on a steam plate. Distillation was continued until a total of 1200 milliliters of distillate was collected. The flask was removed from the steam plate, the Claisen head removed and 1200 milliliters of dry benzene added to the pasty material remaining. The flask was then fitted with a reflux condenser and 150 grams of furoyl chloride was added from a dropping funnel at such a rate that a rapid reflux of the solution was maintained. The material in the flask soon had a paste-like consistency and became difficult to stir. The cake around the sides of the flask was broken and the stirring continued for a

63. (a) H. Gilman and F. Schultz, J. Am. Chem. Soc., 47, 2002 (1925); (b) H. Gilman and L. L. Heck, Ibid., 52, 4949 (1930).

short period of time. The mixture was allowed to stand overnight. Water was added, dropwise, to the stiff paste. This addition was accompanied by a vigorous exothermic reaction. Water was added until solution was nearly complete and then 10% sulfuric acid was added until the solution was completely clear. The resulting two-phase system was transferred to a separatory funnel and the water layer removed. The water layer was washed twice with small amounts of benzene and the benzene extracts added to the original benzene solution. When a small amount of 5% potassium hydroxide was added to the latter solution a white curdy precipitate immediately formed. This precipitate redissolved on the addition of an excess of water. The water layer was removed and the benzene solution washed with water; ether was added to break the emulsion formed. The benzene-ether solution was dried over anhydrous sodium sulfate and distilled through a well-insulated column packed with glass helices until the distillation temperature reached 80.5° . On cooling, the flask contained a considerable quantity of crystals which were removed by filtration and washed with a small quantity of ether. These crystals weighed approximately 8 grams and proved to be tri- α -furoylmethane. Distillation of the ether filtrate gave 36 grams (38.5% based on the acid chloride) of impure α -acetylfuran.

b. Run II

To an agitated mixture of 17.5 grams of magnesium in 500 milliliters of dry ether was added dropwise 100 grams of methyl iodide dissolved in 100 milliliters of ether. To this Grignard solution 130 grams of dry cadmium chloride was added slowly. The agitation was continued until a negative Gilman test was obtained.⁶³ The ether solution was then filtered through a cotton plug and the ether removed by distillation until a vapor temperature of 40° was obtained. The flask was removed from the heat and 300 milliliters of benzene added. To this benzene solution 60 grams of furoyl chloride diluted to 100 milliliters with benzene was added rapidly. The resulting paste-like mixture was refluxed for 30 minutes and left overnight. It was refluxed for another hour the following morning, removed from the heat and allowed to cool. Water was cautiously added dropwise to the benzene solution. This addition was accompanied with a strong exothermic reaction. A total of 100 milliliters of water was added and the contents of the flask transferred to a separatory funnel. The water layer was removed, washed once with benzene and the benzene was added to the original benzene solution. When this solution was washed with 10% potassium hydroxide a yellow-white precipitate formed immediately. Ether was added to the mixture to aid in separation of the layers. The potassium hydroxide layer

containing the precipitate was removed and the ether-benzene solution given a second potassium hydroxide wash, followed by a water wash. Drying of the ether-benzene solution over anhydrous sodium sulfate and subsequent distillation gave 16.2 grams (32%) of α -acetylfuran.

The combined potassium hydroxide wash solutions containing the precipitate were filtered and the residue dissolved in ethyl alcohol acidified with dilute sulfuric acid and placed in an ice bath. There was obtained two grams of fine yellow needles, m. p. 74-77°. These proved to be di- α -furoylmethane.

The filtrate from above was acidified with 10% sulfuric acid and the resulting precipitate filtered off and recrystallized from ethyl alcohol. There was obtained 3 grams of large colorless needles, m. p. 191-195°. This material was found to be tri- α -furoylmethane. Dilution of the alcohol filtrate with water gave a second crop weighing one gram which melted over a wide range. Separation by a Soxhlet extraction with Skelly A gave 0.8 gram of di- α -furoylmethane. The yields of di- and tri- α -furoylmethane based on the acid chloride used in the reaction are 6% and 7% respectively.

2. Synthesis of Di- α -furoylmethane

To a round bottom flask fitted with a reflux condenser,

mechanical stirrer and dropping funnel, were added 100 milliliters of dry ether, 13 grams of ethyl furoate and 6 grams of sodium methoxide. Ten grams of α -acetylfuran was dissolved in 50 milliliters of dry ether and added dropwise to the stirred, refluxing solution of the ester. After the addition was complete the refluxing was continued for five hours. The resulting dark solution was transferred to a separatory funnel and extracted with 100 milliliters of 10% potassium hydroxide solution. It was necessary to add 400 milliliters more ether to effect good phase separation. A second extraction employing 50 milliliters of the potassium hydroxide was made. On acidification of the combined extracts with sulfuric acid a dark oil separated. The acidified solutions containing the oil were placed under an aspirator vacuum to remove the dissolved ether and the dark oil solidified. This solid material was removed by filtration, washed with water and dissolved in methanol. Treatment of the dark methanol solution with Norite A failed to effect decolorization. The methanol solution was brought to a boil and water added. On cooling 10.5 grams (57%) of very fine needles was obtained. If too much water is added or the solution cooled too rapidly, the compound precipitates as mucous-like material. These needles were found to be soluble in carbontetrachloride, chloroform, glacial acetic, benzene, ether, alcohol and slightly soluble in Skelly A. With ferric chloride they give a wine-red color.

The crystals were further purified in a Soxhlet apparatus using Skelly A. A brown residue remained in the extraction thimble. The crystals in the flask were removed by filtration and the filtrate evaporated to dryness. There was recovered 9 grams of pure material with a melting point of 70.5-72.0°. A mixed melting point with the low melting material recovered from the reaction of dimethyl cadmium on α -furoyl chloride showed no depression.

This compound is a sufficiently strong acid to be titrated. The sample was dissolved in 50% ethanol and titrated employing standard sodium hydroxide and a Beckman Model G pH meter. The sodium salt is insoluble and precipitates. The end point is not sharp but more of a gradual rise in the pH. A differential plot was not enlightening so the midpoint of the rising portion of the curve was taken as the end point.

Anal. Calcd. for $C_{11}H_8O_4$: C, 64.71; H, 3.95; neut. equiv., 204.2. Found: C, 64.57; H, 3.90; neut. equiv., 195.

3. Di- α -furoylmethane Dioxime

A solution of 5 milliliters of pyridine, 3 milliliters of absolute ethyl alcohol, 0.5 gram of di- α -furoylmethane and 0.75 gram of hydroxylamine hydrochloride was refluxed overnight over a steam plate.⁶⁴ The solution was then placed

64. R. L. Shriner and R. C. Fuson, "The Systematic Identification of Organic Compounds," Second Edition, John Wiley and Sons, Inc., New York, N. Y., 1940, p. 167.

in a beaker and evaporated to dryness under a slow stream of air. A few drops of water were added and again evaporated. The solid material was titrated with 5 milliliters of water and recrystallized from an ethanol water mixture. The yield was 0.5 gram (87%) with a melting point of 174-178°.

Anal. Calcd. for $C_{11}H_{10}O_4N_2$: N, 11.96. Found: N, 11.90.

4. 3,5-Di-2-furylisoxazole

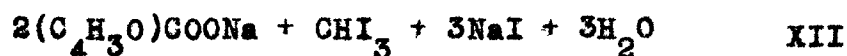
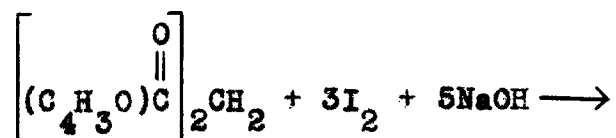
The method of preparation is similar to that used to prepare 3,5-diphenylisoxazole.⁶⁵ Di- α -furoylmethane was refluxed for four hours with excess hydroxylamine hydrochloride in 95% ethyl alcohol. The alcohol solution was then poured into ice water and the resulting gray-white precipitate removed by filtration. The solid was dissolved in 95% ethyl alcohol, treated with Norite A and filtered. A small amount of water was added to the filtrate and allowed to cool. The resulting white needles had a melting point of 108-109°. These needles were washed with 0.1 N sodium hydroxide by placing them in a beaker with the base and stirring rapidly for a few minutes. The undissolved crystals were then filtered off, washed with water and recrystallized from an alcohol-water mixture, m. p. 112°.

Anal. Calcd. for $C_{11}H_7O_3N$: N, 6.97. Found: N, 6.83.

65. J. Wislicenus, Ann., 308, 219 (1898).

5. Iodine Titration of Di- α -furoylmethane

Di- α -furoylmethane gives a good iodoform reaction by the ordinary qualitative method.⁶⁶ The reaction was found to be quantitative.⁶⁷



A weighed sample of the compound was placed in a 250 milliliter glass stoppered flask. To this was added 5 milliliters of dioxane, 50 milliliters of 1 N sodium hydroxide and 75 milliliters of 0.0914 N iodine solution. The solution became cloudy when approximately 10 milliliters of the iodine solution had been added. This solution was allowed to stand for 9 hours at 40°. At the end of this time 2 N sulfuric acid was carefully added until an iodine color developed (the solution was still basic). It was then left for 2 hours more at 40°. To the cooled solution was added 5 milliliters of 2 N sulfuric acid and the excess iodine titrated with standard thiosulfate. Blanks were run

66. N. D. Cheronis and J. B. Entrikin, "Semimicro Qualitative Organic Analysis," Thomas Y. Crowell Company, New York, N. Y., 1947, p. 145.

67. L. F. Doodwin, *J. Am. Chem. Soc.*, 42, 39 (1920); see also N. H. Furman, "Scott's Standard Methods of Chemical Analysis," Fifth Edition, D. Van Nostrand Company, Inc., New York, N. Y., 1939, p. 2136.

simultaneously and treated in the same manner. Results: Calculated milliequivalents of the compound titrated, 2.85 and 2.91. Milliequivalents of iodine consumed, 2.90 and 2.93 respectively.

6. Synthesis of Tri- α -furoylmethane

To 50 milliliters of sodium dried toluene was added 3.68 grams of di- α -furoylmethane and 0.326 grams of metallic sodium. The solution was stirred and refluxed until all the sodium had reacted, the solution becoming quite pasty due to the precipitation of the sodium salt. To the suspension of the sodium salt was added 3 grams of furoyl chloride. Refluxing was continued for one-half hour and the solution was cooled and transferred to a separatory funnel. Ether was added and the resulting solution was extracted with 10% sodium hydroxide solution. The basic extract was acidified with dilute sulfuric acid and the dissolved ether removed under an aspirator vacuum. The solid material which precipitated was filtered off, washed with water and dried in an evacuated desiccator. This solid, which was quite dark, was placed in a Soxhlet extraction apparatus and extracted with Skelly A. In this manner 0.39 grams of the di- α -furoylmethane was recovered.

The material remaining in the thimble was extracted with 95% ethyl alcohol. The resulting brown solution was

diluted slightly with water and allowed to cool. In this manner 2.67 grams of crude tri- α -furoylmethane (55% based on di- α -furoylmethane consumed) was obtained. Recrystallization from 95% ethyl alcohol gave colorless needles, m. p. 193°. A mixed melting point with the high melting material recovered from the reaction of dimethyl cadmium on furoyl chloride gave no depression.

This compound is soluble in carbon tetrachloride, chloroform, dioxane, ether, slightly soluble in ethanol and insoluble in Skelly A. An alcohol solution gives a deep red color with ferric chloride.

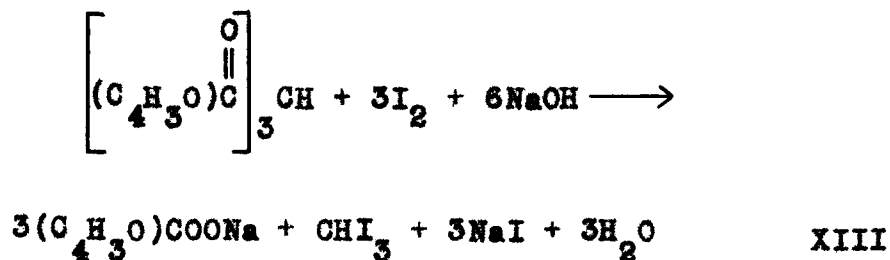
Tri- α -furoylmethane is comparable to potassium acid phthalate in acid strength as indicated by comparable titration curves in 50% ethanol. The compound is quite insoluble in 50% ethanol so the titration had to be carried out slowly with rapid stirring of the solution. At the endpoint the curve rises sharply with the equivalence point at an apparent pH of 9.5. When potassium acid phthalate is titrated in a similar manner the equivalence point is found at an apparent pH of 9.6.

Anal. Calcd. for $C_{16}H_{10}O_6$: C, 64.43; H, 3.38; neutral equivalent, 289.2. Found: C, 64.22; H, 3.23; neutral equivalent, 294.5.

7. Iodine Titration of Tri- α -furoylmethane

As is the case with di- α -furoylmethane this compound

gives an iodoform test.⁶⁶ However, by the qualitative test the solution became dark colored indicating some side reaction had occurred. A quantitative determination was run employing exactly the same procedure as that used with the di- α -furoylmethane.



No coloring of the solution occurred in the quantitative determination. It was found that 2.31 and 1.97 milli-equivalents of the compound consumed 1.97 and 1.55 milli-equivalents of iodine respectively.

8. Decomposition of Tri- α -furoylmethane with Base

When a small amount of this compound was refluxed for 3 hours with 2 N potassium hydroxide no product was isolated by extraction of the basic solution with ether or by acidification and extraction.

Furoic acid and di- α -furoylmethane were recovered when tri- α -furoylmethane was treated with pyridine. Approximately one-half gram was refluxed 10 hours with 10 milliliters of pyridine and 4 milliliters of water. The resulting dark solution was evaporated to dryness under a

slow stream of air and the residue extracted with 10 milliliters of hot water, filtered and evaporated to dryness. A dark oil remained which soon solidified. Incomplete sublimation of this material over a steam plate yielded a small amount of crystalline material with a melting point of 130°. A mixed melting point with furoic acid was 131°.

From the dark residue remaining after the water extraction some difuroylmethane was isolated. The residue was dried and extracted in a Soxhlet apparatus with Skelly A. The solution was evaporated and the resulting crystals had a melting point of 68-69.5°. A mixed melting point with the previously prepared di- α -furoylmethane was 67-69°.

9. Preparation of the Oxime and Isoxazole of
Tri- α -furoylmethane

When attempting to prepare an oxime of tri- α -furoylmethane it was found that one furoyl group was replaced by hydrogen. A solution of 7 milliliters of pyridine, 3 milliliters of water, 0.50 gram of tri- α -furoylmethane and 1 gram of hydroxylamine hydrochloride was treated as given under the procedure for preparation of the di- α -furoylmethane dioxime. A yield of 0.3 grams with a melting point of 176-178° was obtained. A mixed melting point with the oxime of di- α -furoylmethane gave no depression.

Furoic acid was isolated from the filtrate as p-nitrobenzylfuroate. This was accomplished by acidification of the filtrate from above with a few drops of dilute sulfuric acid, extraction with ether and evaporation of the ether extract. The brown solid which remained was treated by the method of Shriner and Fuson,⁶⁴ giving a product with a melting point of 125-128°. A mixed melting point with an authentic sample of the ester was 127-129°.

In an attempt to prepare 3,5-difuryl-3-furoylisoxazole from tri- α -furoylmethane the product isolated was the 3,5-di- α -furylisoxazole as indicated by the melting point, 108-109°, and mixed melting point, 108-109°. The method of preparation was the same as that given for di- α -furoylmethane. Furoic acid was found to be a by-product on this reaction. This was recovered by acidification of the original filtrate with dilute sulfuric acid, extraction with ether, evaporation of the ether extract and subsequent sublimation. The melting point of the sublimed material was 128-130°. A mixed melting point with furoic acid was 129-130°.

10. Absorption Spectra

Further proof of the structure of the compounds prepared above is given by the absorption spectra data. Table 11 gives the features of interest in the ultraviolet absorption spectra of these compounds. Samples were run in 95% ethanol on a Cary

Table 11

Ultraviolet Absorption Spectra Data
on Furyl Ketones and Their Derivatives

Compound	Wave Length of Maxima in Millimicrons	Extinction Coefficient	
		Cary	Beckman
α -Acetylfuran	226	2,520	2,365
	270	14,450	13,500
Di- α -furoylmethane	284	8,280	8,690
	365	30,450	28,600
	380	24,850*	
Tri- α -furoylmethane	225	8,530	8,470
	281	33,000	32,800
	370	10,820	10,520
	382	10,090*	
Ethyl- α -furoylacetate	225		2,635
	275		13,090
α -Acetofuranoxime	265		15,000
Di- α -furoylmethane dioxime	264	27,600	27,400
3,5-Di- α -furylisoxazole	253	15,300	
	292	23,600	
Di- α -furoylmethane ^a	276		10,300
	375		29,300
Tri- α -furoylmethane ^b	225	7,520	
	282	23,610	23,150
	370	18,215	17,650

*Shoulder

a. Two milliliters of the master alcohol solution plus 10 milliliters of alcohol diluted to 100 milliliters in a standard flask with 0.06 N sodium hydroxide.

b. Two milliliters of the master alcohol solution diluted to 100 milliliters in a standard flask with 0.06 N sodium hydroxide.

recording spectrophotometer and checked on a Beckman Model DU spectrophotometer.

The maxima for α -acetyfuran are in good agreement with literature values.⁶⁸ The similarity in the position of the maxima for mono-, di- and tri- α -furoylmethane gives additional evidence for the structure of these compounds.

In determining the absorption spectra of di- and tri- α -furoylmethane in basic solution it was observed that the maximum at 375 millimicrons for the diketone decreased with time while that for the triketone remained practically constant. For example, in one determination a solution, 2.112×10^{-5} M di- α -furoylmethane in 1.0 N potassium hydroxide, gave an initial optical density reading in a one centimeter cell of 0.548 and in 15 hours the reading was 0.030. A similar determination with the triketone at 370 millimicrons showed no appreciable change.

68. R. F. Raffauf, J. Am. Chem. Soc., 72, 753 (1950).

III. KINETICS OF SOLVOLYTIC DECOMPOSITION
OF p-TOLUENESULFONYL-2-ACETOFURANOXIME

A. Review of Pertinent Literature

Vargha et al.⁵² have shown that the furan ring opens when p-toluenesulfonyl-2-acetofuranoxime is treated with alcohol. These men were attempting to prepare the toluene-sulfonic acid salt of 2-aminofuran but instead isolated ammonium p-toluenesulfonate and cis-hexen-2-dion-4,5-diethylacetal. The structure of the latter compound was proven by hydrogenation, functional group tests, preparation of the oxime and oxidative studies. Further proof of structure is given by the fact that when attempting to prepare the free aldehydes from the saturated acetals pyrocatechol was the product isolated.

In latter studies it was found that p-toluenesulfonyl-2-acetofuranoxime is relatively stable in a water solution and that the ring opening took place in absolute ethanol even though water is necessary in a stoichiometrical proportion.⁶⁹ They also found that when the tosylate group was replaced by a benzoyl or trichloroacetyl group the reaction did not take place even in boiling alcohol. When the tosylate of 2-propionylfuranoxime, 2-hydroxyacetylfuranoxime and

69. L. Vargha and F. Goneyz, J. Am. Chem. Soc., 72, 2738 (1950).

and 5-methyl-2-acetylfuranoxime were treated with alcohol it was found, except in the case of the 2-hydroxyacetyl-derivative, that higher reaction temperatures were required to effect the reaction. The products could not be isolated due to their instability.

B. Experimental

1. Preparation of Materials

p-Toluenesulfonyl-2-acetofuranoxime. Furan was treated with an excess of acetic anhydride in the presence of phosphoric acid to prepare 2-acetofuran.⁷⁰ To prepare 2-acetofuranoxime, the ketone was treated with hydroxylamine hydrochloride and anhydrous sodium acetate in ethyl alcohol.⁵² The tosylate was prepared by treating the oxime with p-toluenesulfonyl chloride in pyridine at -10° .⁵² The melting point with decomposition was $76-77^{\circ}$ while that reported is 80° . Repeated recrystallizations failed to raise the melting point. This compound soon turns pink on standing in the light and after a few weeks becomes a black tar. It can be kept for considerable periods of time in an evacuated container. By keeping it in this manner the compound had turned only slightly pink after several months.

Ethyl Alcohol. Commercial 95% ethanol was used where this is indicated. Absolute ethanol was prepared by treating commercial absolute material with magnesium and subsequent distillation under anhydrous conditions.⁷¹

70. H. D. Hartough and A. I. Kosak, U. S. Pat. 2,460, 823.

71. L. F. Fieser, "Experiments in Organic Chemistry" Second Edition, D. C. Heath and Company, New York, N. Y., 1941, p. 359.

2. Kinetic Studies

Hexen-2-dion-4,5-diethylacetal-1 was prepared from p-toluenesulfonyl-2-acetofuranoxime by the method of Vargha.⁵² A study of the ultraviolet absorption spectra of the reactants and products of this reaction were made and the results are given in Table 12. At 274 millimicrons, the wave length of maximum absorption for p-toluenesulfonyl-2-acetofuranoxime, ammonium p-toluenesulfonate and hexen-2-dion-4,5-diethylacetal-1 show a minimum. The extinction coefficient at this wave length for these compounds is 50 and 70 cm.^{-1} liters moles⁻¹ respectively. In following the disappearance of p-toluenesulfonyl-2-acetofuranoxime spectrophotometrically the small extinction of these compounds can be neglected until the reaction is approximately 80% complete. This was indicated when the logarithm of the concentration was plotted against time (Figure 18).

The kinetic runs were made at $26.4^{\circ} \pm 0.05^{\circ}$ in a constant temperature bath. The weighed samples were placed in a 100 milliliter volumetric flask and made to volume with solvent which had previously been brought to temperature. As soon as solution was complete the volumetric flask was placed in the constant temperature bath and a sample removed. Two milliliter samples were removed at intervals and diluted to 100 milliliters with ethanol. The optical density at 274 millimicrons of the diluted solution was determined immediately.

Table 12
Molar Extinction Coefficients
at the Wave Length of Maximum Absorption

Compound	Wave lengths millimicrons	Extinction coefficient
p-Toluenesulfonyl-2-acetofuranoxime	226	14,570
	271	16,050
	274	16,200*
Ammonium p-toluenesulfonate	222	10,680
	256	210
	262	249
	268	182
Hexen-2-dion-4,5-diethylacetal-1	293	86
Hexen-2-dion-4,5-aldoxime	233	11,700**
	333	11,290

* This value is undoubtedly low because this compound dissolves with difficulty in alcohol and its rate of decomposition in 95% ethyl alcohol is quite rapid. A value of 16,800 was found when absolute ethyl alcohol was used.

** Curve rises sharply to this extinction and remains practically horizontal to 220 millimicrons.

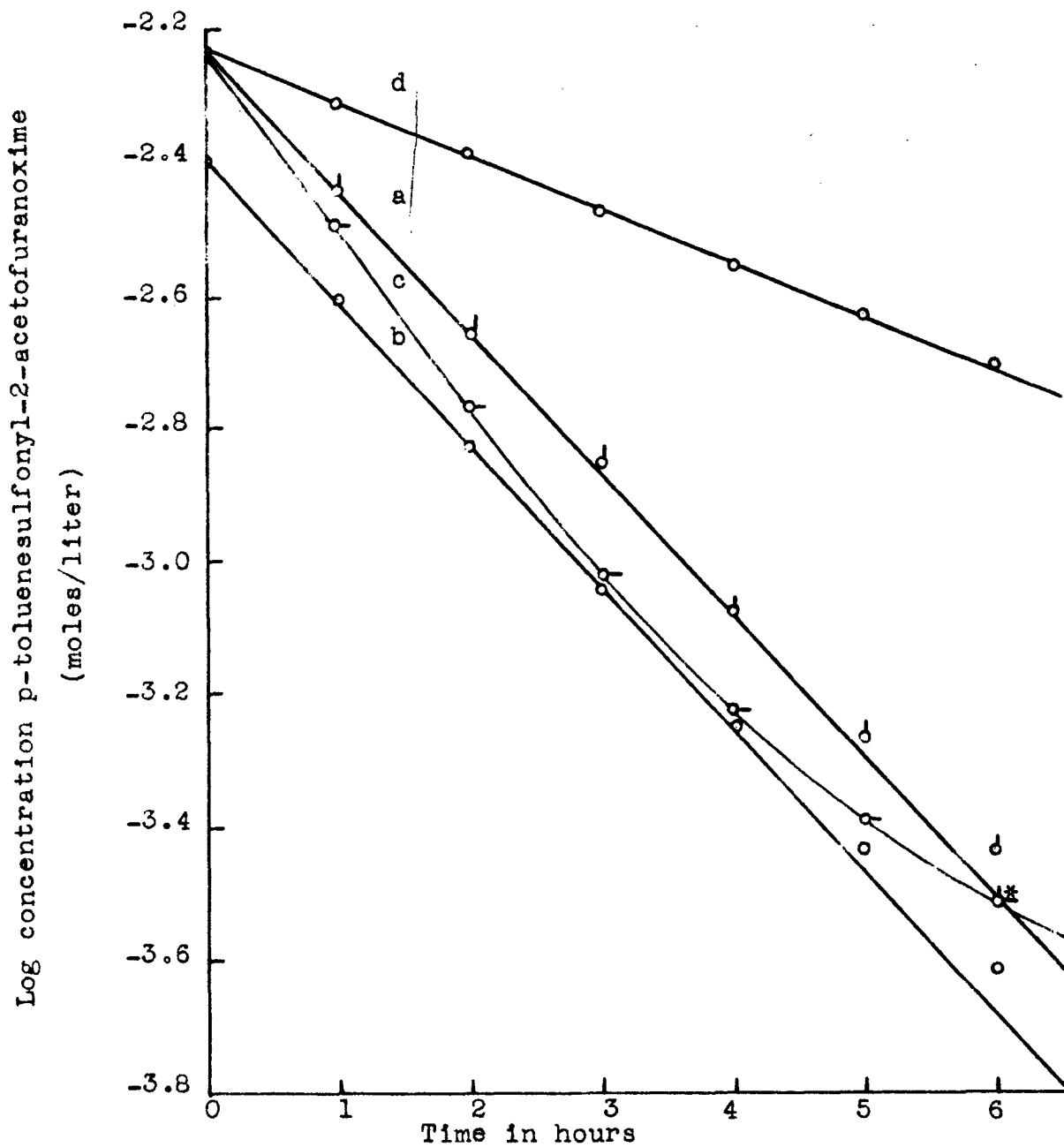


Figure 12. First-order rate plots of the solvolytic decomposition of p-toluenesulfonyl-2-acetofuranoxime: (a) 6×10^{-3} M in 95% EtOH; (b) 4×10^{-3} M in 95% EtOH; (c) 6×10^{-3} M in 95% EtOH, 0.1 M sodium perchlorate; (d) 6×10^{-3} M in absolute ethanol.

Four runs were made, two in commercial 95% ethyl alcohol, one in 0.1 M sodium perchlorate in 95% ethyl alcohol and one in absolute ethanol. The results are shown in Figure 18.

The rate in 95% ethyl alcohol was found to be $1.36 \times 10^{-4} \text{ sec.}^{-1}$ and that in absolute alcohol $5.52 \times 10^{-5} \text{ sec.}^{-1}$. Assuming that the rate follows the first order law for the first three hours when sodium perchlorate is present a rate of $1.75 \times 10^{-4} \text{ sec.}^{-1}$ is obtained. The points lying above the lines (a) and (b) in Figure 18 are not due to a decrease in rate but rather to interference of the products in determining the optical density. Since optical densities are additive one can write

$$D = E_A C_A + E_B C_B + E_C C_C \quad (19)$$

where C_A , C_B and C_C are the concentrations of the tosylate, acetal and ammonium tosylate respectively. The E's are the respective extinction coefficients at 274 millimicrons.

At any time

$$C_B = C_C \quad (20)$$

and

$$C_A = C_A^0 - C_C \quad (21)$$

where C_A^0 is the original concentration of the tosylate.

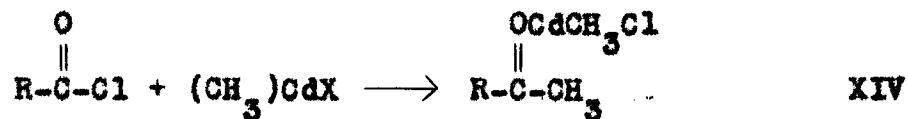
Substituting equations 20 and 21 into equation 19:

$$D = E_A(C_A^0 - C_C) - E_B C_C - E_C C_C \quad (22)$$

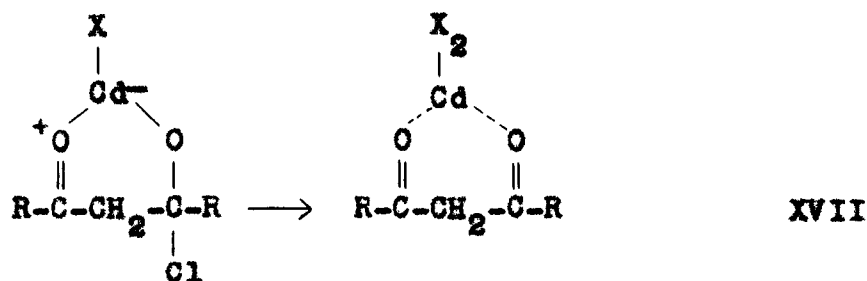
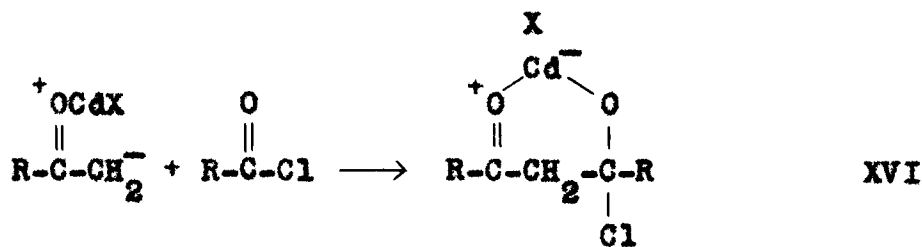
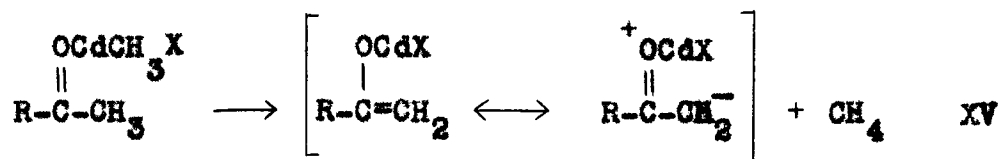
in which D is the optical density at any time and C_C then is the only unknown quantity. By the use of this equation the point marked with an asterisk on curve (a) has been calculated. This indicates that the rate is still the same after six hours when the reaction is 95% complete.

IV. DISCUSSION

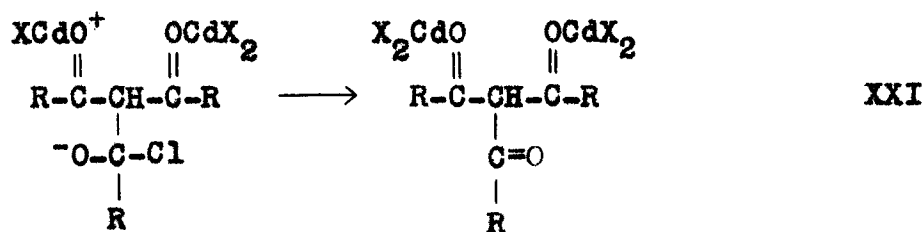
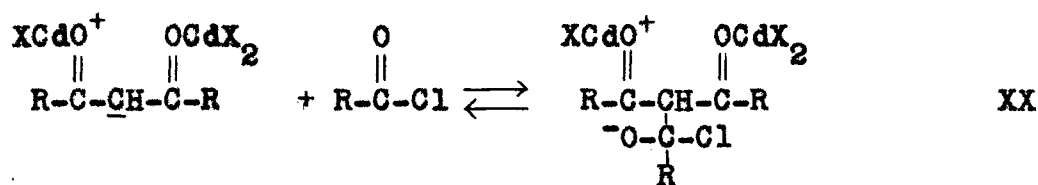
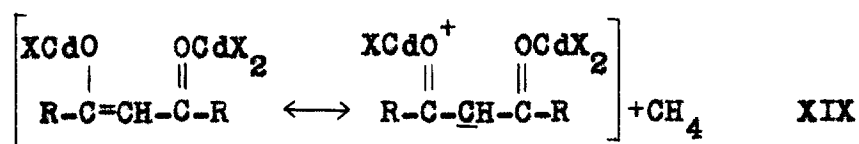
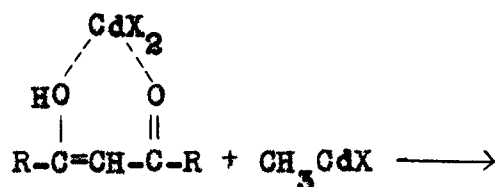
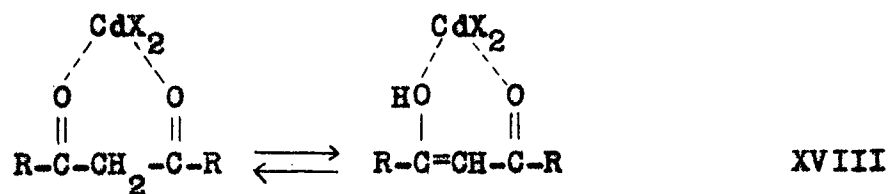
The side reaction of acylation in the preparation of α -acetylfuran from α -furoyl chloride and dimethyl cadmium can be explained on the basis of the following mechanism:



(A)



(B)



(C)

In the above equations X may be either a halogen or a methyl group. With our present knowledge of the reaction it is not possible to state which group would be present in any stage of the reaction. R is the furan ring. The

compounds marked A, B and C are converted to the observed reaction products on hydrolysis.

The formulation of the first product, A, is justifiable in view of the fact that in reactions of organocadmium compounds with an acid chloride an insoluble complex is formed. Analogy for reactions XV and XIX is found in the work of Cason in which he reacted dibutyl cadmium with 1-chlorohexanone-2 and collected 70% of the theoretical yield of butane based on dibutyl cadmium.

The relative ease with which reactions XV and XIX take place to give the amounts of di- and tri- α -furoylmethane found may be due to electron withdrawal from the carbonyl carbon by the furan ring as well as by the carbonyl oxygen. The resulting partial positive charge on the carbonyl carbon withdraws electrons from the methyl group resulting in a weakening of the carbon-hydrogen bonds. This work suggests an interesting study. A careful search should be made for analogous products from the reactions with other acid chlorides and cadmium compounds. The low recovery of the furoyl grouping indicates that considerably higher yields might be obtained by careful fractionation of the mixture.

As stated previously, the similarity in the position of the ultraviolet absorption maxima of di- and tri- α -furoylmethane to those of α -acetyl furan is evidence that the same groups are present. However, the former compounds have

an additional maximum in the 370 millimicron range. These maxima are probably due to the enol forms of the di- and tri-compounds. If this is true the larger apparent extinction coefficient of the diketone may indicate that these compounds are quite similar to the corresponding benzene derivatives, in that the di-compound is more highly enolized than the corresponding tri-compound.⁷²

Enolization would decrease the concentration of the carbonyl form present thus decreasing the apparent intensity of absorption in the 225 and 280 millimicron ranges. Another factor which may contribute to the low absorption of di- α -furoylmethane in these ranges is a conjugation effect. It has been shown that if the conjugation can be extended the absorption would change from that expected for a given group. However, if steric effects effectively shorten this conjugation the absorption spectra becomes more nearly like the parent compound.⁷³ There is, undoubtedly, considerable steric hindrance in tri- α -furoylmethane which explains its high absorption at 225 and 281 millimicrons.

Raffauf⁷³ has studied the syn- and anti- forms of furoidoxime and found that they have maxima at 270 and 265 millimicrons respectively. This compound is quite analogous

72. W. Dieckmann, Ber., 55, 2470 (1922); see also G. W. Wheland, "Advanced Organic Chemistry," Second Edition, John Wiley and Sons, Inc., New York, N. Y., p. 606.

73. R. F. Raffauf, J. Am. Chem. Soc., 68, 1765 (1946).

to α -acetofuranoxime for which the maximum was found at 265 millimicrons. The high extinction coefficient and position of the maximum gives strong evidence for the structure of di- α -furoylmethanedioxime.

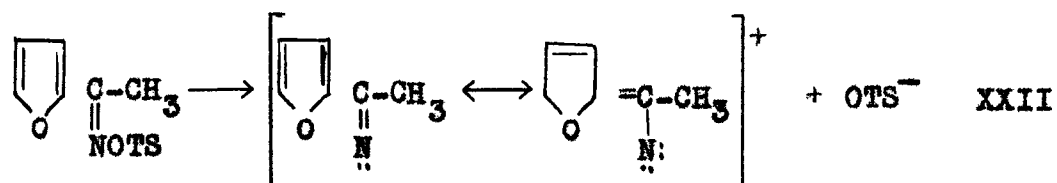
The spectra of the sodium salts of di- and tri- α -furoylmethane are not greatly different than those for the unionized compounds (Table 11). One would expect the absorption maxima to move to longer wave lengths for the ionized compounds. Although the band in the 370 millimicron region is broader in the case of the sodium salts the position of the maximum remains practically the same. No explanation can be offered for this phenomenon.

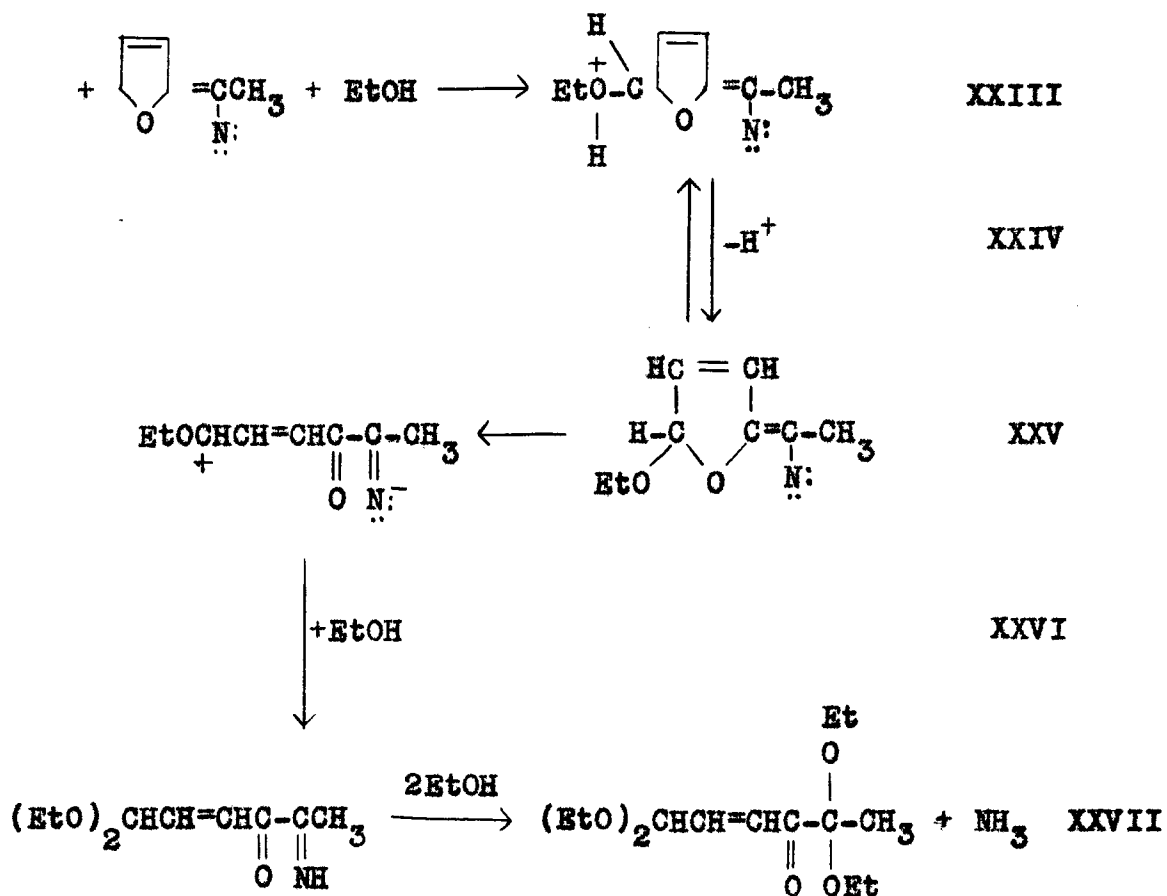
Another phenomenon that is not readily explained is the recovery of di- α -furoylmethane when tri- α -furoylmethane was treated with pyridine. Spectrophotometric studies show that di- α -furoylmethane cleaves readily in 1 N potassium hydroxide while over the same period of time no change was observed in the concentration of tri- α -furoylmethane. It appears that the rate determining step would be the cleavage of the tri-compound and the concentration of the di-compound would not become appreciable.

The study of the decomposition of p-toluenesulfonyl-2-acetofuran in alcohol is not complete. Further kinetic runs should be made with varying amounts of water, acid and base present.

On the basis of the absorption spectra of the kinetic solutions it appears that a different product is formed in the presence of sodium perchlorate. The deviation from the first-order kinetics is attributed to the production of one or more secondary products which have larger extinction coefficients at 274 millimicrons than the acetal and ammonium tosylate. Further, a complete ultraviolet absorption curve made after a lapse of two days shows slight maxima at 310 and 332 millimicrons. These maxima do not agree with those obtained for the starting material and the expected products.

The difference in rate of decomposition in absolute ethanol and 95% ethanol is probably due to the difference in dielectric constant rather than to the participation of water in the rate-determining step since going from no water to a large excess (5%) only doubled the rate. The rate-controlling step must therefore be ionization of the tosylate followed by attack by alcohol. The following equations offer a logical mechanism for the reaction:





The ketal shown as a product of step XXVII would probably be unstable in the presence of water or decompose to the ketone on distillation.

Vargha found that when the tosylate group (TS) was replaced with a trichloroacetyl or benzoyl group the reaction did not take place. Hammett states that p-toluenesulfonic is a stronger acid than trichloroacetic or benzoic acid.⁷⁴ Then with these groups reaction XXII was probably extremely slow. When the methyl group is replaced with a phenyl group

74. Ref. 6, p. 260.

a Beckman rearrangement to form furanilide takes place rather than the ring opening observed with alkyl groups. This may be due to a different stereo-isomer being present. The reaction observed shows that in this case the phenyl group is trans to the tosylate. Also the fact that the phenyl group is known to have a higher migratory aptitude than alkyl groups,⁷⁵ might, in itself, be sufficient to account for the difference in the reactions of the methyl and phenyl ketones even if it should develop that the two compounds have the same configuration.

75. G. W. Wheland, "Advanced Organic Chemistry," Second Edition, John Wiley and Sons, Inc., New York, N. Y., p. 513.

V. SUMMARY

1. In the reaction of dimethyl cadmium with α -furoyl chloride to prepare α -acetylfuran, a side reaction yielding two new compounds, di- and tri- α -furoylmethane, took place. A mechanism for this acylation has been postulated.
2. Di- and tri- α -furoylmethane have been synthesized by a sequence of unambiguous reactions and characterized. The ultraviolet absorption spectra indicate that these compounds are quite similar to di- and tri-benzoylmethane in that the diketone is more highly enolized than the triketone.
3. The decomposition of p-toluenesulfonyl-2-furanoxime in alcohol has been found to obey the first-order law for the tosylate.
4. The rate of the reaction is only slightly dependent on the water concentration. Therefore we infer that water is not directly involved in the rate-determining step but rather affects the reaction velocity by causing a change in the dielectric constant of the medium. Addition of an inert electrolyte also brings about an increase in rate.

5. A mechanism for the solvolytic decomposition of p-toluenesulfonyl-2-acetofuranoxime has been postulated.

VI. ACKNOWLEDGMENT

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