

RECENT TRENDS IN ORGANIC POLAROGRAPHY

PHILIP J. ELVING

*Department of Chemistry, The University of Michigan,
Ann Arbor, Michigan, U.S.A.*

INTRODUCTION

The present paper does not attempt to be exhaustive in listing all of the current trends in the polarography of organic compounds. Rather, an attempt has been made to focus attention on those trends, which seem of major importance for future studies in organic polarography, with particular reference to some of the unsolved problems which still confront us.

Significant recent activity in organic polarography has been distinguished by attempts to define more precisely the paths followed by the electrode process, including the nature of the phenomena which occur in the electrical double layer preceding, accompanying and following the electron-transfer process. This has involved, among other features, the development of theoretical equations and practical approaches for (a) characterizing the interrelationship of the chemical and electrochemical steps involved, (b) defining the role of adsorption as a necessary or accompanying phenomenon, and (c) explaining the actual energy level and the actual concentrations in the interfacial region of the participants in the electrode reaction. The roles of protons and of the solvent in organic electrode reactions have received considerable attention, e.g., in reference to the identification of initial one-electron steps in multielectron processes. Techniques such as cyclic voltammetry and electron spin resonance have been useful in some cases in characterizing the free radicals produced in initial one-electron steps. Availability of satisfactory graphite indicating electrodes has extended the variety of organic electrochemical oxidations which can be studied.

Literature coverage

Reference to the literature in the present paper is not exhaustive; selected reviews and comprehensive studies are cited, which summarize and exemplify the trends discussed. The December 1965 issue of *Talanta*, honouring the 75th birthday of Professor Jaroslav Heyrovsky, contains a number of useful summaries of the polarographic behaviour of different types of organic compounds¹⁻⁶, of the application of polarography in certain areas⁷, and of the effect of the solvent on the behaviour of organic compounds⁸⁻¹⁰. Reference should also be made to the very useful reviews on organic polarography and allied areas which appear in the biennial review issues of *Analytical Chemistry* by Wawzonek, Stock, Bard, Hume and others.

INVESTIGATIVE TECHNIQUES

Since chemistry is, basically, an experimental science, it seems proper to consider first several developments in techniques, which seem particularly

relevant for the future investigation and utilization of organic electrode processes. For example, the development of three-electrode configurations, largely involving operational amplifier control systems, has minimized the problems associated with the large iR drop experienced with polarography in organic solvent solutions of high resistance¹¹.

Electrodes for electrooxidation

Until relatively recently, systematic study of the electrochemical behaviour of organic compounds was largely confined to the investigation of their reduction at the dropping mercury electrode, except for the rather limited number which were sufficiently reversible to be studied polarographically or potentiometrically at platinum electrodes¹².

Study of electrochemical oxidation was limited by the unavailability of an electrode, which would not itself be oxidized at the relatively positive potential necessary for investigating organic compounds, whose oxidation usually involves a high activation overpotential.

Consequently, although the polarographic reduction of many types of organic compounds has been investigated, only a relatively small amount of work has been done on their oxidation. The situation has been changed in recent years by the development of reliable indicating electrodes, based on various types of graphite^{13,14}. These have included wax-impregnated spectroscopic carbon rods, mixtures of graphite paste with various organic solvents, pyrolytic graphite and glassy graphite. The negative potential range available at graphite is less than that at mercury, although greater than that at platinum; however, the extended positive range available at graphite, e.g., up to 1.5 volt *vs.* S.C.E., is a decided advantage.

Mercury electrodes are at times far from ideal for studying organic reductions due to a variety of phenomena, e.g., mercury electrodes are apt to be unsuitable for studying electrode processes involving heterocyclic compounds containing divalent sulphur substituents because of the possible interfering effects of adsorption and surface activity, of catalytic hydrogen evolution, and of reaction between mercury and sulphur.

Cyclic voltammetry

The importance of cyclic voltammetry at constant area electrodes as a tool for mechanistic studies of electrode processes has been amply demonstrated. For example, it facilitates the identification of reversible redox couples and frequently of electroactive intermediates which may be formed either chemically or electrolytically. Recent papers by Shain, Nicholson, and others¹⁵⁻¹⁸, on the theory of stationary electrode polarography have provided the means of quantitatively resolving the electrochemical and associated chemical steps in such electrode processes.

Alternating current polarography

In view of the fact that Drs. B. Breyer and G. C. Barker have presented papers on alternating current polarography and tensammetry at the symposium (cf. pages 313 and 239), for which the current paper was prepared, the reader is referred to their papers for an indication of the utility of a.c. polarography in studying organic electrode processes.

Controlled potential electrolysis

Electrolysis at controlled electrode potential^{19,20} is a relatively old technique which the author and his collaborators still generally find to be essential in studying organic electrode processes. Such electrolysis permits the preparation of sufficiently large amounts of products to permit their isolation, characterization, identification and determination.

The products of transitory electrolysis at micro electrodes and of exhaustive electrolysis at massive electrodes are generally similar except in some cases where chemical rate phenomena can cause differences. Controlled potential electrolyses have permitted the elucidation of complex electrode processes with unexpected products, e.g., the reduction of acetylenedicarboxylic acid to *rac-a*, α' -dimethylsuccinic acid via reactions involving decarboxylation and dimerization, and the intermediate formation of fulgenic and dimethylmaleic acids, and some interesting stereochemistry²¹.

It should be noted that the detailed examination of an electrolyzed solution provides excellent training in analytical chemistry for graduate students. The characterization of all of the solution components and the striking of a material balance between reactants and products usually involves considerable skill in the use of a variety of separation and measurement approaches.

The use of controlled potential electrolysis in organic synthesis will be briefly considered later.

Optical and magnetic resonance spectroscopy

An interesting development in recent years has been the use of optical and magnetic resonance spectroscopic techniques for identifying electrode reaction products and intermediates. In particular, electron spin resonance has been used to detect transitory intermediates. Probably the most extensive use of this approach has been by Adams and his collaborators^{22,23}. However, the technique must be used with caution since, as Adams²² recently pointed out, there are frequent failures to detect free radical formation and even to obtain patterns which are interpretable. In general, it would seem that electron spin resonance will detect free radical intermediates where the half-lives of these species are sufficiently long. However, where the free radical rapidly reacts either chemically or electrochemically, it may not be feasible to detect its presence.

Infrared analysis by attenuated total reflection and allied reflectance techniques are beginning to be used in an attempt to detect and identify intermediates in electrode processes by spectrum scanning of the solution-electrode interfacial region during electrolysis. The introduction of optically transparent electrodes may permit the concurrent examination of solutions during electrolysis by absorption spectrophotometry or internal reflectance spectroscopy^{24,25}.

Mention should be made of the considerable interest shown in recent years in the examination of the luminescence phenomena which accompany the electrolytic generation of certain free radicals.

ROLE OF THE CHEMICAL ENVIRONMENT

It is obviously not possible to explain completely or even satisfactorily the course of many electrochemical processes unless the relevant environment,

that is, the electrode-solution system, is sufficiently well characterized. Composition of the test solution, which is probably the critically decisive factor in determining the observed polarographic behaviour of organic compounds, is subsequently discussed. First, however, attention will be focussed on the locus of the electrode reaction, the solution-electrode interface or the electrical double layer.

Solution-electrode interface

The structure of the double layer is well known to be of importance in electrochemical kinetics and therefore in determination of the potentials of irreversible processes, which include most organic electrode reactions, for at least two reasons: (i) it influences the effective potential difference which favours the electrochemical reaction, and (ii) it causes the effective concentration of electroactive species to differ from the bulk concentration. The situation is well summarized in Delahay's recent book²⁶.

The question as to whether the organic species *must* be adsorbed on the electrode in a type of chemisorption prior to electron transfer would seem now to be answered in the negative, although there are many cases in which adsorption of organic reactant, products or both seems to be an essential feature of the overall electrode reaction. It is likely that an orientation of the organic species in the interphase is necessary before electron transfer occurs; the energy for such a process would be likely to vary similarly to that for an adsorption process. Thus, Streitweiser²⁷ recently pointed out that the variation in potential for carbon-halogen bond fission in certain alkyl halides is explicable on the basis of the carbon-halogen bond being parallel to the electrode surface during electron transfer rather than normal as customarily postulated for carbon-halogen fission^{28,29}.

Many investigators have considered the energy of adsorption, if involved, to be negligible compared to the other energies acting, although the possibility has been considered that adsorption energy may be the significant factor in the variation of half-wave potential for an aliphatic homologous series²⁸.

The all-important topic of adsorption will not be discussed further since the recognized authority on the subject, Dr. A. N. Frumkin, has discussed the adsorption of organic compounds at the mercury-solution interface in the present symposium (cf. page 263).

Reference should be made at this point to the assumption explicit in much discussion of organic polarography that the electrode is simply an inert imaginary plane through which electrons can pass in one direction or the other. Little attention is yet being given to the actual situation, as has been at least partially revealed by the extensive studies of Frumkin, Parsons, Mairanovskii and others³⁰⁻³², on the effects of adsorption on the electrode and of the potential variation in the double layer.

There is little doubt that, in the future, the definition of the potential variation in the double layer — as developed so largely from the work of Professor Frumkin and his collaborators — will be a dominant factor in obtaining a more detailed picture of electrode processes. At present, there is an unfortunate tendency by some polarographers to use *psi* and related potentials as a *deus ex machina* in explaining phenomena as being due to such potentials,

when their values either are not known or have been guessed at from other studies, whose relevancy may or may not be sufficient.

The treatment of the influence of the double layer structure on electrode processes on the basis of the Frumkin approach has been succinctly summarized by Koryta³³; Mairanovskii³² has considered the approach as applied to the polarographic reduction of organic compounds. Parsons³¹ has recently considered the form of the isotherm for the adsorption of organic compounds at electrodes, while general phenomena associated with adsorption at electrodes has been reviewed by Kastening and Holleck³⁴, and by Reilley and Stumm³⁵.

Two related items of increasing interest in the rationalization of organic electrode processes are the differentiation between surface and volume reactions as, for example, exemplified in the work of Mairanovskii, and the revival of interest in the correlation of electrocapillary and current-potential curves.

Solvent nature

Current interest in the electrochemical behaviour of organic compounds in non-aqueous media is due not only to the practical factors of increased solvent power and decreased solvolysis, but also to theoretical considerations. For example, the solvent influences the mass transport process through viscosity and solvation effects and the potential-reaction relationship through its participating directly or via derived species in (i) the primary electrochemical reaction, (ii) polarization of the reactant molecules, (iii) accompanying and intermediate chemical reactions, and (iv) the structure of the double layer. The polarographic behaviour of organic compounds in organic solvents is summarized in references 9, 10 and 36 to 40.

In view of the fact that Drs. H. A. Laitinen and K. Schwabe discussed polarography in solvents other than water at the present symposium (cf. page 227), mention will only be made of two or three points of primary importance for organic polarography.

The first concerns the desirability of investigating solvents which are in themselves reactive. For example, pyridine is a non-proton releasing solvent of a type sufficiently different from those commonly used to warrant its investigation. Chemically, pyridine is a strong Lewis base, is apparently resistant to normal oxidation, and forms adducts with many carbonium ions, which are quite stable *N*-substituted pyridinium compounds. Consequently, since the oxidation of organic compounds frequently involves the removal of protons and/or the formation of carbonium ions, pyridine would greatly facilitate such reaction by acting as a proton acceptor and a carbonium ion stabilizer. This is illustrated by the behaviour of the quinone-hydroquinone system in pyridine⁴¹.

A second point involves the need for better evaluation of the purity of solvents, particularly in respect to the effect of small amounts of impurity. Thus, practically all commercially available pyridine contains material in the millimolar or lower concentration range, which show a variety of electrochemical behaviour, including appearance of a pre-wave to background discharge, formation of Lewis acid-base adducts more readily reducible than those of pyridine, and surface activity.

The possibly important effect of minute amounts of water in organic solvents needs to be more carefully considered than it usually is. The presence of 0.01 per cent water in a typical solvent corresponds to a 4 or 5 millimolar water solution, which is many times the concentration of the electroactive species. At the present time, the effect of such residual amounts of water is commonly overlooked except when the author requires the presence of a hydrogen ion source to complete a postulated reaction scheme.

Of major importance for future work in non-aqueous media is the establishment of potential scales which will permit correlation of the data obtained in aqueous and non-aqueous media. The problems involved and some possible solutions have been explored by Kolthoff³⁹ in a recent comprehensive paper on polarography in organic solvents.

Proton participation

The author has recently discussed⁴² at some length the variation of the half-wave potential of organic compounds with pH. In the present paper, attention is only being called to the fact that, while exploration of the experimental variation of half-wave potential with pH has been quite well done, the theories and equations which have been derived to rationalize such behaviour have not been entirely satisfactory. This would seem to be due primarily to three factors⁴²: first, the uncertainties in the assumptions, which have to be made, and in the terms, which are used in the equations; secondly, the lack of specificity in respect to the physical process which the equation aims to describe; and finally, the uncertainties in the experimental data themselves.

An important aspect of the study of organic electrode processes in non-aqueous solvents has been the elucidation of pH-dependent processes by investigation of such processes in proton-poor solvents coupled with the controlled addition of proton donor such as phenol and benzoic acid, e.g., discussion of Hoijtink's pioneering interpretation by Kolthoff³⁹.

One problem, which needs to be investigated, is that of the role of Lewis acids in facilitating organic reduction processes. The pH-dependence of the half-wave potentials for many organic processes, e.g., phenacyl fluoride and chloride in aqueous solution⁴³, indicates that hydrogen ion can participate in the electrode reaction by polarizing the carbon-halogen bond through formation of a C—X—H bond system; that is, the effect of hydrogen ion can be depicted in terms of a concerted push-pull attack on the carbon-halogen bond by both electrode and hydrogen ion. If this effect is a general acid-base phenomenon, half-wave potentials should similarly vary with the concentration of any Lewis acid, which can form a moderately stable bond with the halogen.

Background electrolyte

The effects of background electrolyte and other solution components on the observed polarographic behaviour of organic compounds are frequently quite marked and involve, among others, the following phenomena: (i) composition, structure and potential gradient in the electrical double layer, (ii) competitive adsorption on the electrode of electroactive species, its product and other solution components, (iii) activities as affected by ionic

RECENT TRENDS IN ORGANIC POLAROGRAPHY

strength, equilibrium constants, etc., (iv) solvation, (v) complexation, including protonation and other Lewis acid-base adduct equilibria, and charge-transfer complex formation, (vi) ion-pairing, (vii) proton activity and concentrational stability, e.g., buffering, and (viii) kinetics of the various equilibria listed as well as of others involving the electroactive species, e.g., its formation from a more stable solution component.

Thus, a change in background electrolyte cation may result in drastic alterations in the observed current-potential relations with the alterations being at times assigned on rather flimsy evidence to formation of stable ion pairs, insoluble compounds, double layer orientation, or other causes. Hopefully, future studies will provide more detailed models for the rationalization of electrolyte effects.

ELECTRODE REACTION MECHANISMS

The primary interest of the author in organic electrode processes has been in elucidating their reaction paths with particular attention to the chemical aspects of the mechanism, in which the electron is considered as one of the many reagents available to the chemist. In this sense, the electron is a rather versatile reagent which is capable of a variety of reactions from single bond cleavage, e.g., carbon-halogen bond fission, to double bond addition, e.g., reduction of carbonyl and olefin systems.

Our current understanding of the mechanisms of organic electrode processes has recently been summarized by Perrin in a perceptive and critical chapter⁴⁴. Perrin emphasizes, as others have done, that, because an electrochemical reaction is a heterogeneous one, a thorough description of its mechanism must await a detailed understanding of the structure of the electrical double layer and of the surrounding layer of solvent. At the present time, descriptions of organic electrode processes frequently still merely involve the listing of the products of the electrode reaction with, in some cases, more or less speculative postulation of intermediates formed during the reaction. Only in a few cases has there been sufficiently detailed experimental evidence to allow the postulation of structures for the transition states involved.

General mechanistic path

Elving and Pullman²⁹ have outlined a general mechanistic pattern for organic electrode processes, which serves to rationalize not only the general course of such processes but also serves to explain the changes in mechanism with experimental conditions or between members of a homologous series, which occur in some cases. For example, the pattern explains why it is possible by selection of pH and applied potential to reduce a ketone either to a pinacol or to a carbinol.

The fundamental process in an organic electrochemical reduction is bond rupture, which requires only one electron to produce a free radical species; the addition of a second electron completes rupture of the bond to give a carbanion. As a consequence, only one- or two-electron processes need to be considered in mechanism discussion, even though multiple electron processes are frequently observed. The transfer of 4, 6 or even more electrons in a single polarographic wave is due to one or both of two possible causes: (i) the mechanical fusion of several merging waves due to a

succession of electrode processes occurring at only small potential separation from each other, and (ii) the more important situation, in which the species produced as a result of the first electron-transfer step is unstable at the potential of its formation and, consequently, is immediately reduced, that is, accepts more electrons, resulting in a multi-electron wave.

On the basis of such an approach, one can postulate the general mechanism outlined in *Figure 1*, in which a generalized carbon reaction site, $R:X$, is assumed, where R represents the reactive carbon centre and X represents another carbon, oxygen, nitrogen, halogen or other atom. There may be

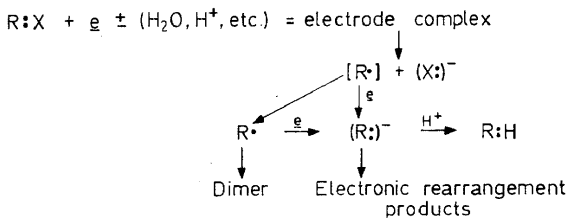


Figure 1. Generalized reaction mechanisms for an organic electrode reaction, in which $R:X$ represents a generalized reaction site. The steps in the path are discussed in the text. Allowance may have to be made for (i) the participation of protons, solvent, other solution constituents and the electrode surface in various steps, (ii) the presence of chemical reactions preceding, accompanying and following charge-transfer processes, and (iii) resulting modification of the species shown.

more than one bond between R and X , for example, in an olefinic or carbonyl group. (Electrochemical reduction is illustrated, since reduction has been studied much more extensively than oxidation; generally analogous patterns can be formulated for electrochemical oxidation.)

In the primary step of the electrode process, the reaction site accepts a single electron to form the electrode activated complex, which can then either revert to the original species or dissociate to give a free radical precursor and an anionic species; if there was originally a multiple bond connection between R and X , these two species will be present as a single free radical anion. The exact nature of these species will, naturally, be modified by the extent of participation of protons, solvent molecules and other solution or even electrode constituents. (The participation of the latter species in subsequent steps is not explicitly indicated, but may be involved.)

The free radical precursor can either immediately on formation accept a second electron and be reduced to a carbanion or can exist as a stable free radical species. The latter can either dimerize or, at more negative potential, be further reduced to the equivalent of a carbanion. The carbanion formed by either path, can also undergo one or two processes: neutralization of its charge either by acceptance of a proton from the solvent or by electronic rearrangement with the charge being transferred to another part of the molecule where it can be suitably handled.

Chemical reactions preceding, accompanying or following the charge-transfer process may, and often do, play significant roles in the overall process, e.g., the possibly profound effect of the kinetics of such reactions upon the observed polarographic pattern^{37,45,46}.

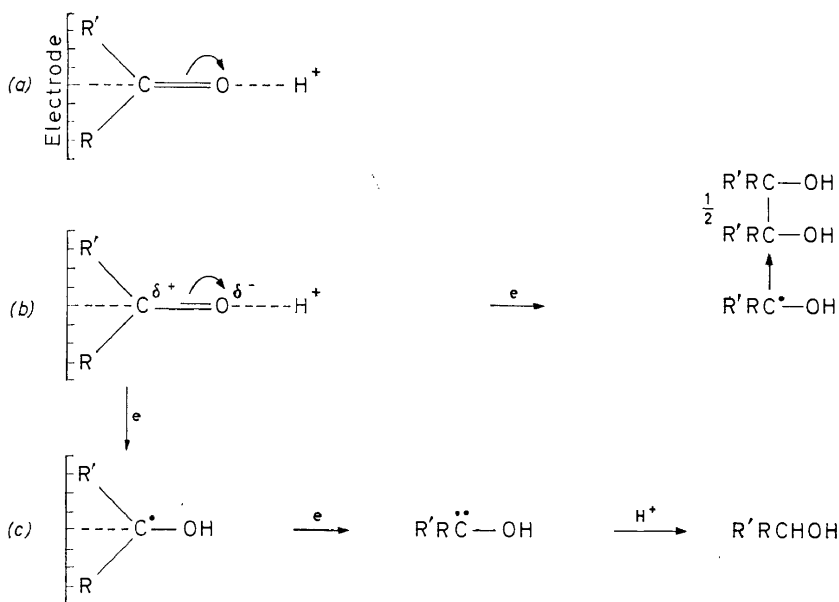


Figure 2. Reduction of a ketone at the d.m.e. in acidic and slightly alkaline media: (a) represents the initial diffusion-polarization process, (b) the formation of the carbinol-free radical (wave I), and (c) reduction of the carbinol-free radical (wave II) and subsequent acquisition of a proton. In neutral and slightly alkaline media the combined sequence of (b) and (c) represents the combined wave (From reference 50, courtesy of the *Journal of the American Chemical Society*.)

The behaviour of wave I is explicable as follows^{50,51}: As the ketone diffuses into the field of the electrode, the latter initiates polarization of the carbonyl group. Simultaneously, the carbonyl oxygen attracts neighbouring protons, thus favouring increased polarization. (The possibility that some of the ketone may be protonated before diffusing into the field of the electrode can be disregarded, since the effect of ionic strength is negligible, indicating that little, if any, of the diffusing material possesses a charge before it comes within the field of the electrode.) Finally, the ketone, under the influence of both protons and the field completes the diffusion, now supplemented by electromigration, into the interphase and acquires an electron.

The steps outlined are continuous and involve a transition state or species, in which, as an electron is transferred to the carbonyl carbon, a proton is simultaneously bonded to the carbonyl oxygen. The role of hydrogen ion in the "potential-determining" step and consequently in the transition state or species is made apparent by the strong pH-dependence of the reduction process.

The free radical produced dimerizes to the pinacol until a potential is reached at which it is reducible; it can then either dimerize to pinacol or be reduced to carbinol; the latter process, which may occur almost exclusively depending on structure, is pH-independent and produces wave II. As pH increases, the shift of the pH-dependent wave I results in its eventual merger with the pH-independent wave II, with only the combined wave being usually observed above pH 6.

Stereochemical effects

The author has discussed elsewhere the importance of stereochemical phenomena in the case of many organic electrode processes, for example, in reference to the importance of structure in causing steric hindrance, in the steric control of products, and in stereospecific electrode reactions^{52,53}.

Electrode kinetics

Measurements of the heterogeneous rate constants and transfer coefficients for organic electrode reactions have been relatively scanty; the difficulties in applying the Koutecky approach to organic compounds have been discussed^{37,51,54,55}. Recent developments in electrochemical relaxation and other cyclic techniques⁵⁶ offer hope for the revival of interest in the accumulation of adequate data on the subject. The effect of adsorption of organic compounds on their electrochemical kinetics has been considered⁵⁷.

HALF-WAVE POTENTIAL CORRELATION

The general basis for the correlation of polarographic half-wave potentials with numerical structural and reactivity characteristics has been the postulation that the characteristic half-wave potential of a compound is a function of electron density and other factors, which, in turn, are also relatively simply related to some biological, physical or chemical property. This approach frequently results in a linear relationship between the half-wave potentials for a series of more or less closely related compounds and a suitably selected mathematical function of the values of the given property for that series of compounds. Such a linear relationship permits both the prediction of the magnitude of the physical or other property of a compound from its readily measured half-wave potential and the rapid comparative evaluation of properties based on comparison of half-wave potentials.

The large variety of experimental and theoretical properties and phenomena, which have been compared to polarographically determined potential data, include photoionization potentials, degree of carcinogenesis, wavelengths of spectrophotometric absorption maxima, antioxidant ability, quantum-mechanically calculated parameters, and structural summation characteristics of various types.

One of the as yet relatively unexploited applications of half-wave potential property correlations is the use of deviations from the expected linear relationship to shed light on the natures of the property and of the electrochemical process. Thus, deviations from the expected Hammett-Taft relation for electrochemical carbon-halogen bond fission can be related to adsorption on the mercury electrode and resulting polarization of the molecules and to other stabilizing effects^{28,58}.

Hammett-Taft relation

The best known and most extensively used of the correlations have been those involving various forms of the Hammett *sigma-rho* equation based on polar substituent quantities, and the Taft modification of this relation. The application of the Hammett-Taft relations to polarographic potentials has

been periodically reviewed by Zuman, to whose papers the reader is referred⁵⁹⁻⁶³.

Quantum-mechanical calculations

The quantum-mechanically calculated energies are generally those for adding an electron to the lowest unoccupied molecular orbital or removing one from the highest occupied molecular orbital. Since the latter energies have been correlated with various types of chemical and biochemical activity, e.g., cf. Pullman⁶⁴, a successful correlation of molecular orbital calculations with polarographic data will further facilitate correlation of chemical and polarographic data.

A priori, it would seem that the optimum approach would involve the use of polarographic data based on initial one-electron processes, since the molecular orbital data apply to such processes. While such one-electron processes can be observed for some organic compounds in aqueous media, in the case of other compounds, it will be necessary to obtain the measurements in non-aqueous media. The validity of this approach is shown by the work of Streitwieser^{65,66}, Pysh and Yang⁶⁷, and Neikana and Desmond⁶⁸ who have recently described the correlation of the potentials for the oxidation of organic compounds in nonaqueous media at platinum electrodes with a variety of calculated values based on molecular orbital theory.

However, there are certain anomalous situations in respect to correlations, which need to be resolved. One example is that of two compounds of fundamental interest because of their importance in DNA, RNA and other biological species: adenine and cytosine. Molecular orbital calculations suggest that the first stage in the reduction of cytosine should occur at less negative potential than that of adenine. Experimentally, however, the reduction of cytosine at the dropping mercury electrode is energetically more difficult than that of adenine. At the present time, polarographic reduction and oxidation of these two compounds is being investigated by a variety of electrochemical techniques based on polarography in the attempt to identify the potentials of the initial electron-transfer steps as well as reversible couples and intermediates in the overall system. One factor that has to be evaluated is the influence of adsorption of the compounds on the electrode.

Zahradnik and Parkanyi⁶⁹ recently reviewed the empirical correlations of half-wave potential data with Hückel molecular orbital characteristics and compared these relationships with analogous dependences for electronic spectra and ionization potentials. Perrin⁴⁴ provides a succinct general summary of half-wave potential correlations.

APPLICABILITY OF ORGANIC POLAROGRAPHY

Finally, the author would like to comment on some applications based on information about organic electrochemical processes, which is generally obtained by polarographic approaches. Zuman⁷⁰ has reviewed the application of polarography to problems in organic chemistry involving equilibria, rates and mechanisms, synthesis and structural problems.

Use of non-aqueous media

The use of non-aqueous media in connection with the elucidation of the theoretical significance of half-wave potentials and of correlations involving half-wave potentials has already been considered.

An example of the study in non-aqueous media of systems, where water interferes, is the investigation of the ease of reduction of maleic anhydride in order to compare it with those of maleic and fumaric acids and esters⁷¹.

An interesting example of the study of interactions in non-aqueous media, such as those involving donor-acceptor charge transfer complexes, are the studies of Peover⁷², who was able to detect the formation of intermediate species by polarography which could not be picked up by spectrophotometry⁷³. The equilibrium constants for the adducts determined polarographically are in agreement with those determined by other techniques.

Preparative procedures and analytical methods have used non-aqueous media primarily for reasons of solubility. However, greater attention will probably be given in the future to the use of non-aqueous media for analytical methods, where possible increases in specificity and perhaps even in sensitivity may result from a change in solvent and background.

Correlation of electrolytic and biological processes

The correlation of the mechanisms of electrochemical and biological processes is a provocative possibility, which is related to the fact that electrolytic oxidations and reductions occur under conditions resembling those of enzymatic and other biological transformations:

1. Both involve heterogeneous electron transfer reactions, in which the nature of the electrical double layer and adsorptive phenomena are important factors.

2. Both occur in dilute aqueous solution of generally similar pH range with electrolyte compositions which probably do not differ too greatly in ionic strength.

3. The temperature range involved is roughly comparable between electrochemical studies at 25° and biological reactions at animal body temperature.

4. The mass transport processes of convection and diffusion are operative and are not too dissimilar for both types of processes.

Although postulation of the degree of correlation that may exist between electrolytic and enzymatic processes must at present be speculative, nevertheless, there is this similarity of conditions under which the two kinds of processes occur. Hopefully, knowledge gained in the investigation of the electrochemical behaviour of compounds of biological interest may allow evaluation of the extent to which correlations can be made. For example, a recent study⁷⁴ has shown that the electrolytic oxidation of uric acid proceeds by a mechanism analogous to that postulated for the enzymatic oxidation.

Synthesis

Synthesis at controlled electrode potential has already been mentioned as an aid in the elucidation of the mechanisms of electrode reactions. However, the potentialities of preparative organic electrochemistry at

controlled potential have, by and large, not yet been realized. The main advantages are (i) precise control of the intensity of reactivity of the reagent, which is the electron, (ii) possibly high selectivity of reaction resulting in a high yield of pure product, and (iii) facilitation of product recovery due to the presence of minimum amounts of side products and absence of excess reagent. Furthermore, electrolytic processes often require a minimum of operator attention, are usable on a micro to macro scale, and can use polarography as a screen to select optimum conditions.

The principal reason for the limited use of preparative organic electrochemistry has been the difficulty of controlling the applied potential which generally has to be very large because of the iR drop encountered when an appreciable current flow occurs as would be desirable in a preparative process. This difficulty is basically an engineering problem.

At present, controlled potential electrolysis is used commercially only for the small scale production of relatively costly products. With the greater drive towards obtaining specialized products, the use should increase.

Frequently, it is possible to control the potential by control of experimental conditions and the current drawn. An outstanding example of this approach is seen in the work of Baizer and his collaborators⁷⁵, who have extensively investigated both intermolecular and intramolecular electrolytic reductive coupling of unsaturated species and have produced a variety of useful industrial compounds, many of which are not readily accessible by more conventional synthesis employing chemical reagents. Adiponitrile, used in the manufacture of nylon, is now being made on a commercial scale from the electrolytic reductive coupling of acrylonitrile.

An interesting area of application of electrosynthesis is the generation of free radical species for study by electron spin resonance.

Analysis

The value of polarographic methods for organic analysis is so well known^{63,76}, that there is no need to discuss it further except to refer to the determination of organic compounds at trace levels by polarography and allied techniques. For example, it is possible to analyze mixtures of maleic and fumaric acids at the 10^{-7} M level by the use of pulse polarography.

The author thanks the U.S. Atomic Energy Commission, which has long supported his work on the polarographic behaviour of organic compounds.

References

- 1 H. Berg and K. Kramarczyk. *Talanta* **12**, 1127 (1965).
- 2 R. Brdicka, M. Brezina and V. Kalous. *Talanta* **12**, 1149 (1965).
- 3 H. Lund. *Talanta* **12**, 1065 (1965).
- 4 J. Tirouflet and E. Laviron. *Talanta* **12**, 1105 (1965).
- 5 J. Volke. *Talanta* **12**, 1081 (1965).
- 6 P. Zuman. *Talanta* **12**, 1337 (1965).
- 7 J. Ukida, S. Usami and T. Kominami. *Talanta* **12**, 1163 (1965).
- 8 P. J. Elving and M. S. Spritzer. *Talanta* **12**, 1243 (1965).
- 9 S. G. Mairanovskii. *Talanta* **12**, 1299 (1965).
- 10 S. Wawzonek. *Talanta* **12**, 1229 (1965).
- 11 Symposium on Operational Amplifiers. *Anal. Chem.* **35**, 1770-1833 (1963).
- 12 W. M. Clark. *Oxidation-Reduction Potentials of Organic Compounds*, Williams & Wilkins, Baltimore, 1960.

RECENT TRENDS IN ORGANIC POLAROGRAPHY

- 13 A. L. Beilby. *Bibliography on the Use and Nature of Carbon as an Electrode Material in Electro-analytical Methods*, Pomona College, Claremont, 1965.
- 14 P. J. Elving, I. Fried and W. R. Turner in G. J. Hills (ed.), *Polarography 1964*, Interscience Publishers, New York, 1966, pp. 277-97.
- 15 R. S. Nicholson. *Anal. Chem.* **37**, 1351 (1965); **38**, 1406 (1966).
- 16 R. S. Nicholson and I. Shain. *Anal. Chem.* **36**, 706, 1212 (1964); **37**, 178, 190 (1965).
- 17 R. S. Nicholson, J. M. Wilson and M. L. Olmstead. *Anal. Chem.* **38**, 542 (1966).
- 18 M. L. Olmstead and R. S. Nicholson. *Anal. Chem.* **38**, 150 (1966).
- 19 L. Meites. *Record Chem. Progress (Kresge-Hooker Lib.)* **22**, 81 (1961).
- 20 L. Meites in A. Weissberger (ed). *Physical Methods of Organic Chemistry*, Part IV, 3rd ed., Interscience Publishers, New York, 1960, pp. 3281-333.
- 21 I. Rosenthal, J. R. Hayes, A. J. Martin and P. J. Elving. *J. Am. Chem. Soc.* **80**, 3050 (1958).
- 22 R. N. Adams. Fourth International Congress on Polarography, Prague, July, 1966.
- 23 R. N. Adams. *J. Electroanal. Chem.* **8**, 151 (1964).
- 24 T. Kuwana, Seventeenth Meeting of CITCE, Tokyo, September 1966.
- 25 R. A. Osteryoung, W. N. Hansen and T. Kuwana. Seventeenth Meeting of CITCE, Tokyo, September 1966.
- 26 P. Delahay. *Double Layer and Electrode Kinetics* Interscience Publishers, New York, 1965.
- 27 A. Streitwieser, Gordon Research Conference on Electrochemistry, January 1965.
- 28 P. J. Elving. *Record Chem. Progress (Kresge-Hooker Lib.)* **14**, 99 (1953).
- 29 P. J. Elving and B. Pullman in I. Prigogine (ed.). *Advances in Chemical Physics*, Vol. III, Interscience Publishers, New York, 1961, pp. 1-31.
- 30 A. N. Frumkin and B. D. Damaskin in J. O'M. Bockris and B. E. Conway (ed.). *Modern Aspects of Electrochemistry*, Vol. 3, Butterworths, London, 1964, pp. 149-223.
- 31 R. Parsons. *J. Electroanal. Chem.* **8**, 93 (1964).
- 32 S. G. Mairanovskii. *J. Electroanal. Chem.* **4**, 166 (1962).
- 33 J. Koryta. *Rev. Polarography (Japan)* **13**, 13 (1965).
- 34 K. Kastening and L. Holleck. *Talanta* **12**, 1259 (1965).
- 35 C. N. Reilley and W. Stumm in P. Zuman (ed.). *Progress in Polarography*, Interscience Publishers, New York, 1962, pp. 81-121.
- 36 P. H. Given and M. E. Peover in I. S. Longmuir (ed.), *Advances in Polarography*, Pergamon Press, London, 1960, pp. 948-64.
- 37 P. G. Grodzka and P. J. Elving. *J. Electrochem. Soc.* **110**, 225 (1963).
- 38 G. Le Guillant. *Bull. Soc. Chim. France*, 2359 (1963).
- 39 I. M. Kolthoff in G. J. Hills (ed.). *Polarography 1964*, Interscience Publishers, New York, 1966, pp. 1-24.
- 40 S. G. Mairanovskii in G. J. Hills (Ed.). *Polarography 1964*, Interscience Publishers, New York, 1966, pp. 719-30.
- 41 W. R. Turner and P. J. Elving. *J. Electrochem. Soc.* **112**, 1215 (1965).
- 42 P. J. Elving. *Pure Appl. Chem.* **7**, 423 (1963).
- 43 P. J. Elving and J. T. Leone. *J. Am. Chem. Soc.* **79**, 1546 (1957); **82**, 5076 (1960).
- 44 C. L. Perrin in S. G. Cohen, et al. (ed.). *Progress in Physical Organic Chemistry*, Volume III, Interscience Publishers, New York, 1966.
- 45 J. W. Ashley, Jr., and C. N. Reilley, *J. Electroanal. Chem.* **7**, 253 (1964).
- 46 R. Brdicka, V. Hanus and J. Koutecky in P. Zuman (ed.). *Progress in Polarography*, Interscience Publishers, New York, 1962, pp. 145-99.
- 47 D. L. Smith and P. J. Elving. *J. Am. Chem. Soc.* **84**, 2741 (1962).
- 48 D. L. Smith and P. J. Elving. *J. Am. Chem. Soc.* **84**, 1412 (1962).
- 49 P. J. Elving, W. A. Struck and D. L. Smith. *Mises au Point de Chimie Analytique Organique, Pharmaceutique et Bromatologique*, **14**, 141 (1965).
- 50 P. J. Elving and J. T. Leone. *J. Am. Chem. Soc.* **80**, 1021 (1958).
- 51 M. Suzuki and P. J. Elving. *J. Phys. Chem.* **65**, 391 (1961).
- 52 P. J. Elving. *Contributi Teorici e Sperimentali di Polarografia*, **5**, 205 (1960).
- 53 P. J. Elving, I. Rosenthal, J. R. Hayes and A. J. Martin. *Anal. Chem.* **33**, 330 (1961).
- 54 P. G. Grodzka and P. J. Elving. *J. Electrochem. Soc.* **110**, 231 (1963).
- 55 M. Suzuki and P. J. Elving. *Coll. Czech. Chem. Commun.*, **25**, 3202 (1960).
- 56 W. H. Reinmuth. *Anal. Chem.* **36**, 211R (1964); **38**, 270R (1966).
- 57 S. G. Mairanovskii. *Electrochim. Acta* **9**, 803 (1964).
- 58 P. J. Elving and J. M. Markowitz. *J. Org. Chem.* **25**, 18 (1960).
- 59 P. Zuman. *Chem. Listy* **48**, 94 (1954).
- 60 P. Zuman. *Contributi Teorici e Sperimentali di Polarografia*, **5**, 3 (1960).
- 61 P. Zuman. *Rev. Polarography (Japan)* **11**, 102 (1963).
- 62 P. Zuman in P. Zuman (ed.). *Progress in Polarography*, Interscience Publishers, New York, (1962), pp. 319-22.
- 63 P. Zuman. *Organic Polarographic Analysis*, Pergamon Press, London, 1964.
- 64 B. Pullman and A. Pullman. *Quantum Biochemistry*, Interscience Publishers, New York, 1963.

PHILIP J. ELVING

- ⁶⁵ A. Streitwieser. *Molecular Orbital Theory for Organic Chemists*, John Wiley & Sons, New York, 1961.
- ⁶⁶ A. Streitwieser and C. Perrin. *J. Am. Chem. Soc.* **86**, 4938 (1964).
- ⁶⁷ E. S. Pysh and N. C. Yang. *J. Am. Chem. Soc.* **85**, 2124 (1963).
- ⁶⁸ W. C. Neikana and M. M. Desmond. *J. Am. Chem. Soc.* **86**, 4811 (1964).
- ⁶⁹ R. Zahradnik and C. Parkanyi. *Talanta* **12**, 1289 (1965).
- ⁷⁰ P. Zuman in G. J. Hills (ed.). *Polarography 1964*, Interscience Publishers, New York, 1966, pp. 687-710.
- ⁷¹ R. Takahashi and P. J. Elving, Seventeenth Meeting of GITCE, Tokyo, September 1966.
- ⁷² M. E. Peover and J. D. Davies in G. J. Hills (ed.). *Polarography 1964*, Interscience Publishers, New York, pp. 1003-16.
- ⁷³ M. E. Peover. *Trans. Faraday Soc.* **60**, 417 (1964).
- ⁷⁴ W. A. Struck and P. J. Elving. *Biochem.* **4**, 1343 (1965).
- ⁷⁵ M. M. Baizer. *J. Electrochem. Soc.* **111**, 215 (1964) and subsequent papers in *J. Electrochem. Soc.*, *J. Org. Chem.* and *Tetrahedron Letters*.
- ⁷⁶ P. J. Elving in P. Zuman (ed.). *Progress in Polarography*, Interscience Publishers, New York, 1962, pp. 625-48.