

ELECTROCHEMICAL REDUCTION OF SUBSTITUTED PYRIMIDINES IN ACETONITRILE *

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ABSTRACT

Polarographic studies of several substituted pyrimidines were reinforced by the results from cyclic voltammetry, controlled-potential electrolysis, and spectrophotometric examination of electrolyzed solutions, as well as by the examination of model compounds. Pyrimidines substituted with non-reducible groups (amino, methyl) are reduced in a single, one-electron ($1e$), diffusion-controlled process, very similar to that for pyrimidine itself. Pyrimidine-4-carboxylic acid exhibits three reduction waves: a very drawn-out acid-reduction wave with unusual properties and, at more negative potential, an adsorption pre-wave and a wave corresponding to the $1e$ reduction of the pyrimidine moiety. 2-Chloro- and 2-bromopyrimidine each exhibit two polarographic waves; the first, corresponding to irreversible scission of the carbon-halogen bond, has electrochemical properties quite different from those normally expected; the second is due to reduction of the electro-generated pyrimidine. Results are compared with those for the reduction of bromobutane, bromobenzene, and 2-bromopyridine.

INTRODUCTION

In the course of our investigations of the electrochemical reduction of azabenzene and related compounds in nonaqueous media [1-4], the effects of various substituents on the basic reduction patterns of the azabenzene rings were investigated. The present paper summarizes the results obtained for the monoazine (pyridine) and, more particularly, for 1,3-diazine (pyrimidine). Pyridine is the parent compound for the biologically important pyridine (nicotinamide) coenzymes, e.g., NAD^+ and $NADP^+$, and pyrimidine is the parent compound for the pyrimidines and purines found in the nucleic acids, ATP, barbituric acids and other biologically essential species. In these studies, some highly unusual results were obtained on the carbon-halogen bond fission reaction for halopyrimidines.

* In honour of Dr. G.C. Barker's 60th birthday.

The polarographic and related behavior of pyrimidines and nicotinamides has been reviewed by the authors [5]. The phenomena and mechanisms for carbon-halogen bond fission have also been recently reviewed [6,7,36]. Czochralska and Wrona [8,9] have investigated the polarographic behavior of halopyrimidines in aqueous buffered media.

Briefly summarized, in nonaqueous media, pyrimidine undergoes an initial reversible one-electron ($1e$) reduction to a radical anion which rapidly dimerizes; pyridine is apparently reduced in an overall $2e$ ECE process involving $1e$ reversible reduction to a radical anion, which abstracts a proton from the solvent and/or residual water to produce a free radical species that is unstable at the potential of its formation and is, consequently, immediately reduced in a second $1e$ process. The situation in respect to the carbon-halogen (C-X) scission is less clear; while the overall process observed is considered by most investigators to be a $2e$ one, there is some question as to the component steps involved.

(An ECE mechanism for a single polarographic wave refers to a process in which an electrochemical step involving electron transfer produces a species which then undergoes a chemical reaction to produce a product unstable at the potential, at which it is formed, and consequently rapidly reduced in a second electrochemical reaction.)

EXPERIMENTAL

Chemicals were obtained from the sources indicated: 2,4-dimethoxypyrimidine (Cyclo Chemical); 5-methylpyrimidine (Nutritional Biochemicals); 4-methylpyrimidine and pyrimidine-4-carboxylic acid (Calbiochem); bromobenzene (Eastman); bromobutane (J.T. Baker). 2-Aminopyrimidine (Eastman) was recrystallized once from water and twice from benzene. 2-Chloropyrimidine (K & K Laboratories) was recrystallized from isopentane four times to give white crystals: m.p. $63.5-64.5^{\circ}\text{C}$ (literature [10]: $64.5-65.5^{\circ}\text{C}$) (anal. calc. for $\text{C}_4\text{H}_3\text{N}_2\text{Cl}$: C, 41.95; H, 2.64; N, 24.46; Cl, 30.95; found: C, 41.80; H, 2.67; N, 24.39; Cl, 31.08). 2-Bromopyrimidine was prepared according to Bly and Mellon [11]: m.p. $53-54^{\circ}\text{C}$ (literature: $55.5-57^{\circ}\text{C}$) (anal. calc. for $\text{C}_4\text{H}_3\text{N}_2\text{Br}$: C, 30.22; H, 1.90; N, 17.63; Br, 50.26; found: C, 30.40; H, 1.94; N, 17.75; Br, 50.19). Concentrations of stock solutions of pyrimidines were checked by means of reported molar absorptivities [11,12].

Sources and purification of other chemicals, apparatus, and electrochemical procedures have been described [1,2,13].

All potentials were measured and, unless otherwise stated, are reported versus a $\text{Ag}/0.01\text{ M Ag}^+$, 0.1 M tetraethylammonium perchlorate (TEAP) in acetonitrile electrode, whose potential versus the aqueous SCE is 0.293 V [1,14]. Currents at the DME were measured as maximum currents on an undamped potentiostat; where necessary, as in the calculation of I_d values, maximum currents were multiplied by $6/7$ to convert them to average currents. The background electrolyte was 0.1 M TEAP.

RESULTS AND DISCUSSION

Pyrimidines, substituted with non-reducible groups such as amino or methyl, exhibit in acetonitrile polarographic properties very similar to those for pyrimidine itself [1,2], i.e., a single, 1e, diffusion-controlled wave (Table 1). Since methyl and amino groups are electron-donating relative to hydrogen, the half-wave potential ($E_{1/2}$) values are more negative than $E_{1/2}$ for pyrimidine itself. 4-Methylpyrimidine has a more negative $E_{1/2}$ than the 5-methyl derivative because of the closer proximity of the substituent to the reduction site (the 3,4 N=C double bond). In general, the cyclic voltammetric behavior of these compounds is much the same as that of pyrimidine itself.

2,4-Dimethoxypyrimidine, which is reduced at a quite negative potential, just prior to background discharge, has a diffusion current constant (I_d) equivalent to a 2e transfer, even though the wave slope is near that expected for a reversible 1e process. This probably indicates the presence of an ECE reaction; the initial, potential-determining, reversible 1e addition is followed by a fast chemical reaction (probably protonation) to produce a species that is immediately reduced in a second 1e process.

Pyrimidine-4-carboxylic acid

D.c. polarography. Pyrimidine-4-carboxylic acid in acetonitrile solution exhibits unusual polarograms at the DME, which essentially consist of three

TABLE 1

Polarographic behavior of substituted pyrimidines in acetonitrile ^a

Compound	$-E_{1/2}/V$ ^b	$E_{1/4}-E_{3/4}/mV$	I_d ^c	Slope of log plot ^d
Pyrimidine	2.630	54(5)	3.39(7)	0.53
2-Amino-	2.75	58(3)	3.78(12)	0.52
4-Methyl-	2.74	55(4)	3.71(9)	0.53
5-Methyl-	2.64	54(3)	3.71(9)	0.57
2,4-Dimethoxy-	2.91	54(8)	6.55(10)	0.65
4-Carboxyl- ^e I	1.29	<i>f</i>	2.17(16)	0.6
II	2.41	60(10)	0.42(4)	1
III	2.57	54(6)	3.05(14)	0.52

^a 0.1 M TEAP background electrolyte. The numbers in parentheses are the uncertainties (standard deviations) of the last digit(s).

^b Potential vs. Ag/Ag⁺. Standard deviations are less than 10 mV.

^c $I_d = 6 i_{max} / 7 cm^{2/3} t^{1/6}$.

^d The slope of a plot of log *i* vs. log h_{Hg} . The theoretical value expected for a diffusion-controlled wave is 0.50; that is, the current is proportional to the square root of the mercury column height.

^e I, II, and III refer to results for three separate polarographic waves.

^f Very drawn-out, irregularly shaped wave; cf. text for description.

reduction waves. The first wave at -1.29 V is due to a highly irreversible, $1e$ acid (proton) reduction. The second wave is a small prewave (-2.41 V) antecedent to the third wave (-2.57 V); both correspond to $1e$ reduction of the pyrimidine moiety. At longer drop-times, the prewave current is linear with the first power of mercury column height (h), possibly indicating an adsorption-controlled current. Occurrence of the small prewave between two much larger waves makes evaluation of its current magnitude difficult. Since there are indications that strong adsorption may occur during the acid reduction wave and since electron transfer is already taking place at the solution/electrode interface, the prewave may correspond to the reduction of an adsorbed species or of some molecules in a preferred orientation at the interface.

Although there is no clear correlation for acids between aqueous pK_a and reduction $E_{1/2}$ in acetonitrile [15], stronger acids generally have more positive $E_{1/2}$ values; thus, the first acidic hydrogen wave indicates that pyrimidine-4-carboxylic acid is moderately strong for a carboxylic acid. The wave is complex in nature, e.g., about half-way up the wave, the slope changes and becomes less steep. Polarography of a saturated solution (ca. 4 mM) of the acid shows that this is due to two incompletely resolved waves (Fig. 1). At long drop-times (low h), the two waves are well resolved and can be relatively easily evaluated. With increase in h , the first wave shifts very slightly to more negative potential but remains approximately constant in slope; the second wave shifts to more positive potential and decreases markedly in slope. The net effect at fast drop-times (and at lower concentrations) is to make the acid reduction wave appear to be "bent" in the middle.

The causes for the two waves must, at this point, remain hypothetical; there are at least four possibilities:

(a) A coupled chemical reaction involving reduction of bonded acid (HA) and of dissociated proton (H^+) may occur at the interface. The drop-time dependence of the two waves could be interpreted to indicate a slow coupled reaction.

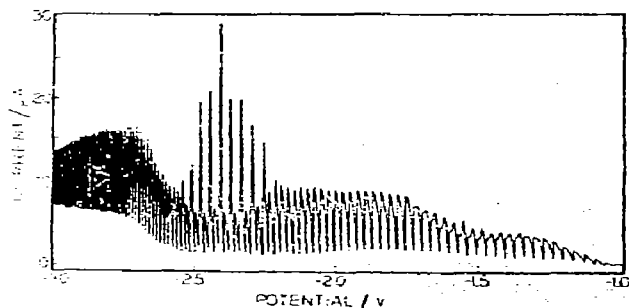


Fig. 1. Polarogram of saturated (ca. 4 mM) pyrimidine-4-carboxylic acid in acetonitrile. Mercury column height = 38 cm.

(b) A substantial fraction of hydrogen-bonded dimer, in addition to the monomer, may be present. Dimeric carboxylic acids are known to persist even in the vapor state and in dilute solution in hydrocarbon solvents [16]. The dielectric constant of acetonitrile ($\epsilon = 35$), while not very small, may be sufficiently low to permit substantial dimerization at the interface. The fact that the "bent" acid-reduction wave does not appear to be general (e.g., solutions of benzoic and chloroacetic acids exhibit drawn-out waves but of normal shape, and Coetzee and Kolthoff [15] report very drawn-out waves for fluorovaleric and phosphoric acids, but no unusual wave shapes for nine Bronsted acids studied), would seem to indicate that explanations (a) and (b) are either incorrect or insufficient.

(c) A zwitterionic or internally hydrogen-bonded form may be reduced as well as the normal carboxylic acid. Such a form, stabilized by hydrogen bonding, should be more difficult to reduce.

(d) The acid reduction may involve strong surface or adsorption phenomena. The distorted shape of the $i-t$ curves between -1.3 and -1.7 V may indicate film formation; during the course of the drop-life, the current reaches a maximum and then decreases, as though reduction during the early part of the drop-life were producing a film about the drop which hinders further diffusion of the electroactive species to the electrode surface.

In saturated solution of the acid, the mercury droplets falling during the rising part of the wave and for some distance on the wave plateau do not coalesce on the cell bottom; once the potential corresponding to reduction of pyrimidine moiety is reached, however, the falling mercury droplets again coalesce. On the acid reduction wave plateau from -2.2 to -2.6 V, alternating drops of high and of low current occur, the only adequate explanation for which is some type of film formation. In the relatively concentrated solution, streaming of the solution past the electrode surface may occur, resulting in an enhanced supply of depolarizer at the electrode surface with a concomitant increase in current. When the mercury drop falls, a film of the less soluble pyrimidine carboxylate anion remains around the new growing drop, thereby retarding diffusion of more depolarizer to the electrode surface and resulting in a lowered current for the second drop. When this drop falls, it either disrupts this film or pulls it through the solution, thus allowing an increased current for the following drop.

The unusual pattern of droplets of alternating high and low current magnitude is also observed when the DME potential is held constant at several values between -2.3 and -2.5 V (and at several mercury column heights), although the current magnitude differences are not quite as large as those observed during a polarogram.

Drop time curves. Since the most plausible explanation for the unusual acid-reduction wave for pyrimidine-4-carboxylic acid would seem to be a strong surface or interfacial effect such as adsorption or film formation, drop time curves were obtained.

Drop time curves for 1 and 5 mM pyrimidine are essentially identical with that for the background electrolyte alone, indicating little or no specific adsorption of pyrimidine.

Except for the sharp depressions at +0.2 and +0.1 V, the drop time curve for saturated (ca. 4 mM) pyrimidine-4-carboxylic acid solution (Fig. 2) is quite close (within 0.10 s) to that for the background electrolyte alone. Since small changes in the residual water content of the solvent seem to increase slightly the drop-time in the vicinity of the electrocapillary maximum (−0.4 to −1.1 V) and in the range of −2.0 to −2.6 V, it is difficult to say if the small drop-time differences in these two regions are due to water or to the surface effect of pyrimidine-4-carboxylic acid. What is evident, however, is that the unusual current behavior between −2.0 and −2.5 V does not have an appreciable effect on the drop time curve, as would be expected if strong specific adsorption were occurring.

The two sharp depressions at positive potential are probably adsorption prewaves just prior to anodic mercury dissolution. Pyrimidine-4-carboxylic acid has the molecular configuration suitable for forming a stable 5-member chelate ring with mercury cations involving the carboxylate oxygen and N(3) of the ring. The potential and depth of the incision at +0.19 V (Fig. 2) are dependent on the concentration of the acid. The potential becomes more

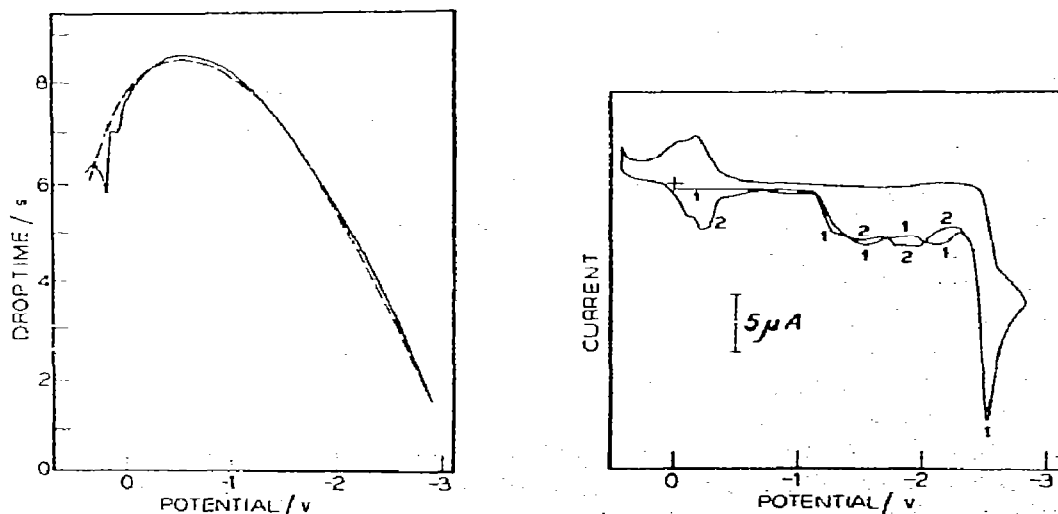


Fig. 2. Electrocapillary curves for saturated (ca. 4 mM) pyrimidine-4-carboxylic acid in acetonitrile (solid line) and for background electrolyte alone (0.1 M TEAP); mercury column height = 38 cm.

Fig. 3. Cyclic voltammogram of 0.85 mM pyrimidine-4-carboxylic acid in acetonitrile at the HMDE. Scan rate = 200 mV s^{-1} ; arabic numerals refer to the numbers of the scan on successive cycles.

negative with increasing concentration: +0.30, +0.25, and +0.19 V for 0.15, 0.76, and 4 mM solutions, respectively. The depth, as expected, increases with concentration; for the same solutions, the change in drop-time, Δt , is 0.40, 0.82, and 1.18 s. The smaller incision at ca. 0.1 V is not visible, at least within experimental accuracy, at 0.15 and 0.76 mM concentration.

Current magnitude at the DME. The diffusion current constant, I_d , for the acid reduction wave of 2.17 is somewhat low for an expected 1e reduction, e.g., values of 3.4 to 3.7 are obtained for 1e reduction of other pyrimidines.

Low I_d values have been reported for the irreversible reduction of acids in acetonitrile. For nine acids, I_d generally ranged from 1.9 to 2.8 with extremes of 1.47 (phosphoric acid) and 3.04 (perchloric acid) [15]. While the latter values may be partially explained on the basis of differences in diffusion coefficient (perchloric acid, essentially completely dissociated, diffuses as a solvated proton, whereas phosphoric acid may quite possibly exist in solution as long-chain or cyclic hydrogen-bonded oligomers undergoing relatively slow diffusion), other factors must certainly be operative to explain a two-fold change in I_d in what would seem to be superficially similar reactions, i.e., 1e reduction of an acid to form hydrogen gas. These other factors may involve reversibility or mechanistic considerations, which may tend to lower currents in acetonitrile media below expected levels, e.g., the aging effect [17] observed for solutions of acids in acetonitrile, in which the dissociation of weak acids increases with time.

Cyclic voltammetry. Cyclic voltammograms (Fig. 3) show several peaks for reduction of the acid hydrogen, beginning at about -1.2 V, and the adsorption prewave at about -2.2 V just prior to the large peak at -2.5 V, which corresponds to 1e reduction of the pyrimidine moiety. The rather unusual shape of this series of peaks and the fact that the current does not decay appreciably over nearly a one-volt range are further indications of the multiplicity of processes, including probably adsorption and irreversible reduction, involved in the acid-reduction wave for pyrimidine-4-carboxylic acid.

An erratically shaped peak pair at about -0.2 to -0.5 V appears to be due to proton reduction, e.g., clipping the cathodic scan before the prewave results in the appearance of these peaks being only slightly altered in shape and magnitude. These peaks correspond to peaks Va and Vc produced on cyclic voltammetry of solutions of benzoic acid and benzoic acid plus pyrimidine, which peaks have been attributed to reduction of acids in acetonitrile [1].

Repeated attempts to prepare a dry crystalline tetraethylammonium salt of pyrimidine-4-carboxylic acid, in order to study the electrochemical behavior of the carboxylate in the absence of the acid-reduction wave, were unsuccessful.

Chloro- and bromoazines

Since preliminary results indicated that the polarographic reduction of 2-chloropyrimidine exhibited some rather unusual phenomena and since the

results might shed further light on the widely studied carbon-halogen bond fission process [6,18,19], the electrochemical behavior of 2-bromopyrimidine, and model haloazines was also investigated.

Model compounds. The polarographic behavior (Table 2) of n-bromobutane (BuBr) and bromobenzene (PhBr), which are typical model compounds for the carbon-halogen bond-fission process, is similar to that previously reported for these compounds in nonaqueous media [20–22]: a highly irreversible, diffusion-controlled $2e$ wave. $E_{1/2}$ for BuBr in acetonitrile, however, is approximately 0.18 V more negative than that reported for DMF solution [21], the most valid explanation for which appears to be differences in the irreversibility of the electron-transfer process.

The polarographic behavior of 2-bromopyridine also appears to be straightforward: a $2e$ irreversible scission of the C–Br bond (–2.47 V, wave I), consequent generation of pyridine itself via protonation, and $2e$ reduction of the pyridine (–2.9 V, wave II). $E_{1/2}$ for wave II is identical, within experimental error, with that for pyridine itself [2]. On increasing the pyridine concentration from 0.07 to 1.5 mM, however, I_d for wave II steadily decreases to that expected for an overall 1.5-electron process, possibly indicating partial change of the mechanism to an overall $1e$ process to produce a free radical, which dimerizes. Previous reports have indicated an overall $2e$ reduction of pyridine in acetonitrile [23] at 0.6 mM concentration and in DMF [24] at 1 mM concentration. ESR investigations [25–27], however, have indicated that pyridine radical anions can dimerize and rearomatize oxidatively to form 4,4'-bipyridine, which then can be reduced to a radical anion.

Coulometric electrolyses at controlled electrode potential of solutions of BuBr, PhBr, and 2-bromopyridine confirmed the $2e$ nature of the C–Br fission process (Table 3). Plots of log (electrolysis current) vs. time were linear over nearly 3 orders of current magnitude, indicating the absence of slow intervening chemical steps in the overall process.

The electrolyzed solutions were brownish; the most characteristic feature of their absorption spectra was a strong, broad absorption band with $\lambda_{\max} \approx 253$ nm (ϵ : (7 to 13) $\times 10^3$ l mol⁻¹ cm⁻¹, based on the original concentration of the electroactive compound). Flash distillation of these solutions through a short column produced a clear distillate with an ultraviolet absorption spectrum characteristic of a quantitative yield of the parent compound for the benzene and pyridine derivatives. There was no spectrophotometric evidence for the formation of bipyridine in the electrolyzed solutions, either before or after distillation. The brownish color of the electrolyzed solutions and the strong absorption at 253 nm are undoubtedly due to polymeric or other non-volatile products from decomposition of solvent and/or background electrolyte during electrolysis.

2-Bromo- and 2-chloropyrimidine. The electrochemical behavior of 2-bromo- and 2-chloropyrimidine is considerably more complex than that of the bromo-

TABLE 2

Polarographic behavior of organic halogen compounds at the DME^a

Compound	Concn./ mM ^b	h_{Hg} /cm	$-E_{1/2}/V$ ^c	$(E_{1/4}-E_{3/4})/$ mV	I_d ^d	Slope of log plot ^e	Number of polarograms
n-BuBr	0.09→2	25-50	2.713(8)	194(6)	5.31(9)	0.40	10
PhBr	0.06→2	25-60	2.640(11)	125(5)	5.90(12)	0.47	21
2-Br-pyridine	0.38	25-60	I 2.464(7)	85(3)	6.57(11)	0.48	10
			II 2.938(13)	51(2)	5.8	0.53	
2-Br-pyrimidine	0.07→1.5	40	I 2.468(5)	87(3)	6.35(19)	—	7
			II 2.93→3.00	51(6)	6.2→4.5	—	
2-Cl-pyrimidine	0.43	25-55	I 2.057(2)	56(2)	5.60(22)	0.52	7
			II 2.648(5)	49(3)	2.25(14)	0.70	
2-Cl-pyrimidine	0.04→1	40	I 2.058(2)	57(2)	7.9→4.3	—	6
			II 2.648(7)	47(6)	3.6→1.3	—	
RbClO ₄ ^f	0.50	25-60	I 2.167(5)	53(2)	5.95(16)	0.52	14
			II 2.646(7)	48(3)	2.44(8)	0.64	
RbClO ₄ ^f	0.07→1.5	40	I 2.168(5)	54(2)	7.3→4.7	—	8
			II 2.652(7)	46(4)	3.6→1.2	—	
RbClO ₄ ^f	0.5	40	2.260(6)	57(3)	3.11(16)	—	71

^a In acetonitrile/0.1 M TEAP. The numbers in parentheses are the uncertainties (standard deviations) of the last digit(s).^b For 2-bromopyridine, and 2-bromo- and 2-chloropyrimidine, the data have been divided into two parts: the first is a mercury column-height study at constant concentration, the second is a concentration study at constant column height to illustrate the effect of concentration on I_d values.^c Potential vs. Ag/Ag^+ , I and II refer to results for the first and second polarographic waves.^d $I_d = 6 i_{max}/7c m^{2/3} t^{1/6}$.^e The slope of a plot of $\log i$ vs. $\log h_{Hg}$. The theoretical value expected for a diffusion-controlled polarographic wave is 0.50, i.e., the current is proportional to the square root of the mercury column height.^f RbClO₄ standard solutions run over a period of two years.

TABLE 3
Coulometric analysis of bromo and chloro compounds

Compound	Electrolysis potential/V ^a	Shape of log <i>i</i> vs. <i>t</i> plot	Electrons transferred per molecule/ <i>n</i>	Yield of parent compound/% ^b	Number of electrolyses ^c
Bromobutane	-2.86	linear	1.98 ± 0.02	—	2
Bromobenzene	-2.46	linear	2.06 ± 0.04	100 ^d	3
2-Bromopyridine	-2.60	linear	2.00 ± 0.06	106 ^e	3
2-Bromopyrimidine	-2.15	linear	1.84 ± 0.03	60 ^f	6
2-Chloropyrimidine	-2.25	two linear segments	1.06 ± 0.04, 0.2 → 0.8 ^h	6 ^g	6

^a Potential vs. Ag/Ag⁺.

^b Yield of benzene, pyridine, or pyrimidine is based on u.v. spectrophotometric analysis of electrolyzed solutions that had been rapidly distilled through a short column. Comparison spectra were obtained on standard solutions of pure compounds in acetonitrile solvent.

^c Single electrolyses were performed on solutions of different concentrations, which generally ranged from about 0.2 to 2 mM.

^d Based on one electrolysis, 0.4 mM.

^e Based on two electrolyses, 0.4 and 0.8 mM.

^f Based on two electrolyses, 0.8 and 1.6 mM.

^g Yield of pyrimidine not determined.

^h Number of electrons involved in each of the two linear *i* vs. *t* segments; the *n*-value for the second process increases as the concentration of the starting material decreases.

compounds just discussed. Under polarographic conditions at about 0.5 mM concentration, these two pyrimidines are reduced in two steps (Table 2): an initial apparent $2e$ process corresponding to the C—X cleavage (wave I), followed by a $1e$ reduction of the pyrimidine electrogenerated in the wave I process. $E_{1/2}$ for wave II is identical, within experimental error, with that for pyrimidine itself [2]; Although wave I seems to be an overall $2e$ process, its slope of about 55 mV is indicative of a reversible $1e$ potential-determining step. $E_{1/2}$ and I_d values are independent of h ; with increasing concentration (0.05 to 2 mM), I_d decreases and then levels off (Fig. 4).

Coulometry and spectroscopic studies. Coulometry of 2-chloropyrimidine solutions on electrolysis at potentials on the wave-I plateau indicate similar results (Fig. 4; Table 3). The coulometric n for concentrations greater than about 0.5 mM is roughly constant at 1.36 ± 0.07 electrons/molecule, increasing to nearly $2e$ as the concentration is decreased to 0.08 mM. Plots of log (electrolysis current) vs. time consist of two linear segments: a rapid 1.0 e -transfer, accounting for the first segment, and a slower process accounting for the excess fractional electron (Fig. 5). Potentiometric titration of an electrolyzed solution (originally 2.88 mM 2-chloropyrimidine) with AgNO_3 indicated a $97 \pm 5\%$ yield of Cl^- ion.

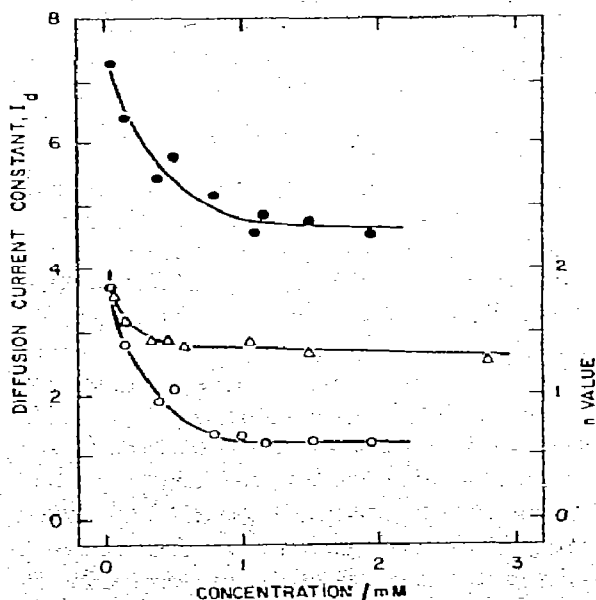


Fig. 4. Variation with concentration of the diffusion current constants for the two 2-chloropyrimidine reduction waves and of the coulometric n -values for the C—Cl bond fission process. (●) I_d for wave I at $E_{1/2} = -2.17$ V; (○) I_d for wave II at $E_{1/2} = -2.64$ V; mercury column height = 40 cm; (Δ) coulometric n -values for the wave I process; electrolysis potential = -2.25 V.

The exact electrolysis potential has little apparent effect on n ; for 0.58 mM 2-chloropyrimidine, $n = 1.35, 1.38, \text{ and } 1.40$ for $E = -2.18, -2.25, \text{ and } -2.40$ V, respectively.

Polarograms of electrolyzed solutions of 2-chloropyrimidine exhibit a reduction wave at -2.63 V due to electrogenerated pyrimidine, and two anodic waves at -0.15 and -0.45 V due to oxidation of mercury in the presence of chloride ion. Millimolar solutions of tetraethylammonium chloride in TEAP background exhibit very similar anodic waves at the same potentials. I_d values for all three waves decrease with increasing concentration in much the same manner as the I_d plots of Fig. 4. The $E_{1/2}$ values for the two anodic waves are also functions of concentration, as would be expected for anodic adsorption waves. Generally, the I_d values increase with decreasing concentration; simple dilution of solutions with acetonitrile results in increased I_d values for the two waves. The higher I_d values for the pyrimidine reduction wave for electrolyzed solutions of low concentration probably result from the ECE process in the reduction of pyrimidine [1], in which the electrogenerated pyrimidine radical anion is protonated by residual water and/or solvent and then further reduced in a second $1e$ process. Since the pyrimidine concentration is so low, the rate of the ECE process becomes competitive with the fast second-order dimerization reaction. There is no evidence for the formation of a neutral bipyrimidine compound in electrolyzed solutions as this should be reducible within the available potential range, e.g., $E_{1/2}$ for reduction of 2,2'-bipyridine in DMF is over 500 mV more positive than that of pyridine [24]; the only reduction wave observed is that due to pyrimidine itself, whose current magnitude indicates a more or less quantitative yield of pyrimidine.

Electrolyzed solutions of 2-chloropyrimidine exhibit a broad band near 310 nm ($\epsilon = 2700$ to $4700 \text{ l mol}^{-1} \text{ cm}^{-1}$), based on the original concentration), as well as the characteristic spectrum of pyrimidine itself in acetonitrile ($\lambda_{\text{max}}(\epsilon) = 233\text{s} (1610), 238 (2050), 242 (2020), 248\text{s} (1490)$). There is no ultraviolet indication of residual 2-chloropyrimidine ($\lambda_{\text{max}}(\epsilon) = 245\text{s} (2300), 251 (2600), 256\text{s} (1990)$) or of the formation of 2,2'-bipyrimidine ($\lambda_{\text{max}}(\epsilon) = 241 (15,900)$ in aqueous media [11]).

In contrast to the behavior of the 2-chloro compound, 2-bromopyrimidine exhibits linear $\log i$ vs. time electrolysis plots (Fig. 5) for solutions from 0.05 to 1.6 mM; n is constant at 1.34 ± 0.03 . Spectrophotometric analyses of flash-distilled electrolyzed solutions, however, indicate only a 60% yield of pyrimidine, as opposed to the 100% yield of the parent compound for BuBr and PhBr. Addition of water to electrolysis solutions has no effect on n values; for electrolysis of 0.80 mM solutions, $n = 1.36 \pm 0.01$ in nominally "dry" acetonitrile ($c_{\text{H}_2\text{O}} \approx 5 \text{ mM}$), or with 50 or 130 mM added water. Electrolyzed solutions are brownish. The most characteristic feature of the ultraviolet spectrum is a broad absorption band of $\lambda_{\text{max}} = 308 \text{ nm}$ ($\epsilon \approx 7000 \text{ l mol}^{-1} \text{ cm}^{-1}$, based on the original 2-bromopyrimidine concentration), which obscures the characteristic spectrum of pyrimidine itself until the solutions are

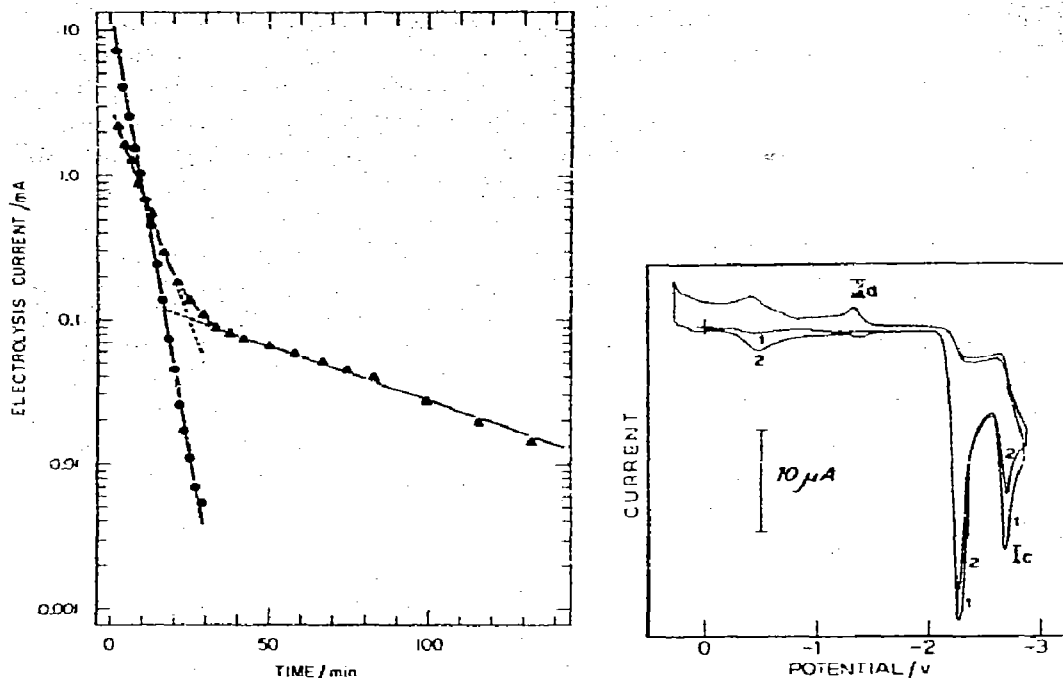


Fig. 5. Variation of current with time during the controlled potential electrolysis of 2-bromo- and 2-chloropyrimidine. (●) Electrolysis of 0.86 mM 2-bromopyrimidine at -2.25 V; $n_{\text{measured}} = 1.27 e/\text{molecule}$. (▲) Electrolysis of 0.46 mM 2-chloropyrimidine at -2.25 V; $n_{\text{measured}} = 1.42 e/\text{molecule}$.

Fig. 6. Cyclic voltammogram of 0.57 mM 2-chloropyrimidine at the HMDE. Scan rate = 200 mV s^{-1} ; arabic numerals refer to the number of the scan on successive cycles; peaks are identified in the text.

flash-distilled. The absorbance of electrolyzed solutions at 308 nm, however, is dependent on the water level of the solvent, increasing from about $\epsilon = 7000 \text{ l mol}^{-1} \text{ cm}^{-1}$ for nominally dry acetonitrile to about 12000 for 130 mM added water.

Cyclic voltammetry. Cyclic voltammograms of 2-chloropyrimidine (Fig. 6) show the reduction of the C—Cl bond prior to the peak corresponding to reduction of the pyrimidine moiety (Peak 1c). As would be expected for an electrode reaction involving C—Cl bond cleavage, the process is highly irreversible, e.g., no complementary anodic peak for the reoxidation appears even at high scan rates. With increase in scan rate, ν , from 0.2 to 140 V s^{-1} , the peak current function, $i_p/c\nu^{1/2}$, for the C—Cl scission peak decreases from about 95 to 10, whereas that for peak 1c remains constant at 37 ± 2 .

Peak 11a is due to the irreversible oxidation of a pyrimidine anionic dimer produced after $1e$ reduction of pyrimidine [1].

The peaks at about -0.5 V in Fig. 6 correspond to the anodic waves observed on polarography of electrolyzed solutions, i.e., are due to oxidation of mercury in the presence of chloride ion. Reversal of the scan at a potential just prior to peak Ic (about -2.5 V) produces these peaks essentially unchanged in appearance and magnitude, indicating that they appear as a result of the first electron transfer process, i.e., scission of the C-Cl bond.

Mechanism of carbon-halogen bond fission. The most reasonable explanation for the observed behavior of 2-bromo- and 2-chloropyrimidine in acetonitrile is that these two compounds are initially reduced in a reversible, $1e$ addition with a subsequent, fast scission to produce halide ion and pyrimidine free radical. The wave slope for the polarographic reduction (Table 2) is quite close to the theoretically expected 56 mV, as opposed to the more drawn-out, "irreversible" $2e$ waves for BuBr, PhBr, and 2-bromopyridine. This can be interpreted as being due to the initial addition of an electron to the lowest C-Br σ^* orbital in the three model compounds, but to the lowest π^* orbital in the pyrimidine compounds. Fukui et al. [28], for example, have correlated the $E_{1/2}$ values for reduction of haloalkanes and halobenzenes with the lowest σ^* C-X orbital; it is well known that substitution of N for CH in aromatics has the effect of lowering the energies of π^* orbitals.

The pyrimidine free radical thus generated must be a very transient species, as indicated by the non-appearance of a cyclic voltammetric peak that could be attributed to its oxidation. Most probably, it is deactivated by hydrogen atom abstraction from the solvent or background electrolyte to form pyrimidine which is then reduced at more negative potential (ca. -2.63 V). The preponderance of experimental evidence indicates quantitative formation of halide ion and pyrimidine in a $1e$ first step.

The "excess" electrons, i.e., that amount greater than $1e$ /molecule, must arise from secondary electrochemical reactions, probably involving the solvent, background electrolyte, and residual water. The presence of at least two such reactions is indicated by the data, e.g., the differing shapes for the $\log i$ vs. t electrolysis plots for bromo- and chloropyrimidine even when the electrolyses are performed at the same potential and the dependence on the "background" electrolysis reactions and products on the residual water level of the solvent as indicated by the variation in ultraviolet spectra of electrolyzed solutions of 2-bromopyrimidine with added water. BuBr and PhBr, which clearly involve $2e$ and proton abstraction, result in electrolyzed solutions with λ_{\max} at 253 nm, as compared to solutions with λ_{\max} at about 208 nm for the pyrimidine compounds.

The behavior for the 2-halopyrimidines is quite similar to that reported by Nadjo and Saveant [29] for bromo- and chloro-substituted benzophenone, in which the experimental observations are consistent with an expulsion of the halide ion from the anion radical initially formed, followed by abstraction of a hydrogen atom from the solvent. For example, coulometric analysis of 2 mM solutions with short electrolysis durations (about 15 min for 90% con-

sumption of the original compound; electrolysis conditions similar to ours) resulted in an n -value of about 1.2; with slower electrolysis conditions, i.e., $t_{90\%} \approx 3$ h, the n -value was close to two. Voltammetric studies on the benzophenones were apparently not performed on solutions as dilute as some of the ones in this study (down to 0.04 mM). Evidence for the existence of the intermediate benzophenone radical has been demonstrated by trapping with a nucleophilic reagent during the course of electrolysis [30].

Knowledge of the exact nature of the "background" reactions in acetonitrile must await further, more detailed studies, although there has already been considerable discussion of the solvent/electrolyte reactions in acetonitrile and DMF [2,31-36].

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