

AD-A200 422

DTIC FILE COPY ②

OFFICE OF NAVAL RESEARCH

Contract N00014-83-K-0470-P00003

R&T Code NR 33359-718

Technical Report No. 113

The Behavior of Microdisk and Microring Electrodes.
Mass Transport to the Disk in the Unsteady State:
Coupled Chemical Reactions

by

M. Fleischmann and S. Pons

Prepared for publication in J. Electroanal. Chem.

Department of Chemistry
University of Utah
Salt Lake City, UT 84112

July 15, 1988

DTIC
FILE
NOV 1 1988
CSE

Reproduction in whole, or in part, is permitted for
any purpose of the United States Government

88 11 10 081

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release and sale. Distribution unlimited.		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION REPORT NUMBER(S) ONR Technical Report No. 113		5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION University of Utah	6d. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) Department of Chemistry Henry Eyring Building Salt Lake City, UT 84112		7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Office of Naval Research	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-83-K-0470-P00003		
8c. ADDRESS (City, State, and ZIP Code) Chemistry Program, Code 1113 800 N. Quincy Street Arlington, VA 22217		10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
11. TITLE (Include Security Classification) The Behavior of Microdisk and Microring Electrodes. Mass Transport to the Disk in the Unsteady State: Coupled Chemical Reactions				
12. PERSONAL AUTHOR(S) M. Fleischmann and S. Pons				
13a. TYPE OF REPORT Technical	13b. TIME COVERED FROM 9/87 TO 7/88	14. DATE OF REPORT, 1988, Month, Day July 15, 1988	15. PAGE COUNT 24	
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) microelectrodes , mass transport		
FIELD	GROUP			SUB-GROUP
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Attached.				
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USE ONLY		21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Stanley Pons		22b. TELEPHONE (Include Area Code) (801)581-4760	22c. OFFICE SYMBOL	

ABSTRACT

In this work, we discuss the solution of the differential equations in the cylindrical coordinate system for the case of a coupled CE reaction mechanism at a finite disk electrode. We use the properties of discontinuous integrals of Bessel functions to treat the mixed boundary conditions at the electrode surface and the surrounding insulator. The results are compared to previous analyses and we also make comparisons of various estimates of the chronoamperometric response for constant surface concentration conditions.

Accession For	
NTIS	<input checked="" type="checkbox"/>
DTIC	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist Special	
A-1	



The behavior of microdisk and microring electrodes. Mass transport to the disk in the unsteady state

The effects of coupled chemical reactions: the CE mechanism

Martin Fleischmann

Department of Chemistry, The University, Southampton, Hants. SO9 5NH (Great Britain)

Stanley Pons

Department of Chemistry, University of Utah, Salt Lake City, UT 84119 (U.S.A.)

(Received 18th February 1988; in revised form 3rd May 1988)

ABSTRACT

In this work, we discuss the solution of the differential equations in the cylindrical coordinate system for the case of a coupled CE reaction mechanism at a finite disk electrode. We use the properties of discontinuous integrals of Bessel functions to treat the mixed boundary conditions at the electrode surface and the surrounding insulator. The results are compared to previous analyses and we also make comparisons of various estimates of the chronoamperometric response for constant surface concentration conditions.

INTRODUCTION

The application of microdisk electrodes to the investigation of the kinetics of chemical reactions in solution coupled to the electrode reactions (CE, ECE, and DISP reactions) has been investigated recently [1,2]. It was shown that the dimensions of the electrode become a parameter of the investigation, these dimensions in effect probing the reaction layer at the electrode surface. An interesting aspect of these measurements is that it becomes possible to differentiate between alternative reaction paths such as the ECE and DISP1 mechanism by combining measurements using microelectrodes with those using conventional planar electrodes; rate parameters can be derived from "working curves", e.g. of the effective number of electrons transferred as a function of the inverse of the radius of the electrode.

An approximate method of data analysis was used in these investigations. For example, for the CE mechanism



the flux of B to the surface was obtained from the solution of the differential equation in the spherical coordinate system in the steady state

$$D \frac{d^2c}{dr^2} + \frac{2D}{r} \frac{dc}{dr} + k_1 - k_2c = 0 \quad (1)$$

rather than that for the cylindrical coordinate system appropriate to the microdisk electrode

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial r^2} + \frac{D}{r} \frac{\partial c}{\partial r} + D \frac{\partial^2 c}{\partial z^2} + k_1 - k_2c = 0 \quad (2)$$

in the steady state. The solutions obtained for a microsphere were then corrected to those for a microdisk by assuming that the same scale factor holds in these experiments as for the measurements of the voltammetric curve for a reversible electrode reaction, viz.

$$a_{\text{disk}} = \frac{4}{\pi} a_{\text{sphere}} \quad (3)$$

where a_{disk} and a_{sphere} are the relevant electrode radii.

We have shown recently that it is possible to develop systematic algebraic analyses of a variety of the usual types of electrochemical experiments (chronopotentiometry [3], chronoamperometry [4], ac impedance [5]) by appropriate solutions of the differential equations in the cylindrical coordinate system. In the derivation of these solutions we have made use of the properties of discontinuous integrals of Bessel functions to take account of the mixed boundary conditions at the electrode surface, viz. prescribed concentration or flux over the electrode surface, zero flux over the surrounding insulator surface. In this paper we explore the application of the same approach to the analysis of the kinetics of chemical reactions coupled to electrode reactions using the CE process (i) and (ii) to illustrate the method of calculation.

THEORETICAL CONSIDERATIONS

In the simplest method of investigating the kinetics of the coupled chemical reactions (i) and (ii), a sufficiently high overpotential is applied to the electrode surface to reduce the surface concentration of B to zero. The rate of the reaction then becomes controlled by the kinetics of reaction (i); species A is assumed to be present at sufficiently high concentrations that we need only consider the concentra-

tion distribution of species B, eqn. (2). It should be noted that it is relatively straightforward to achieve such conditions with microelectrodes (and of pseudo-first-order reaction conditions in second-order reactions) in view of the high rates of steady state mass transfer to the electrode surface [1,2].

We therefore require the solution of eqn. (2) subject to the condition

$$c = c^\infty = k_1/k_2 \quad r = \infty, z = \infty, \text{ all } t \quad (4)$$

and with

$$c = 0 \quad 0 < r < a, z = 0, t > 0 \quad (5)$$

$$\partial c / \partial z = 0 \quad r > a, z = 0, t > 0 \quad (6)$$

We have pointed out that the application of condition (5) to the solution of the mass transfer problem for the chronoamperometric response is difficult and these difficulties also apply to the present case. Instead we consider that the electrode is subjected to a constant uniform flux $-Q$, i.e.,

$$D \partial c / \partial z = -Q \quad 0 < r < a, z = 0, t > 0 \quad (7)$$

and we evaluate the average concentration of B over the electrode surface and then determine the strength of Q required to make this average concentration zero. It should be noted that the constant surface flux condition is in fact likely to be a very good approximation for the investigation of coupled chemical reactions since the rate will be controlled by step (i). Provided the concentration of A is uniform over the surface, Q will be uniform over the surface.

Laplace transformation of eqn. (2) subject to condition (4) gives

$$\frac{\partial^2 \bar{c}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{c}}{\partial r} + \frac{\partial^2 \bar{c}}{\partial z^2} - \left(q^2 + \frac{k_2}{D} \right) \bar{c} + \frac{k_1}{D} \left[\frac{1}{k_2} + \frac{1}{s} \right] = 0 \quad (8)$$

where $q = (s/D)^{1/2}$.

The solution of eqn. (8) consists of the Particular Integral $k_1/k_2 s$ and the Complementary Function which must be found from

$$\frac{\partial^2 \bar{c}_{CF}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{c}_{CF}}{\partial r} - \left(q^2 + \frac{k_2}{D} \right) \bar{c}_{CF} = 0 \quad (9)$$

By analogy to the discussion of the previous examples of electrochemical experiments at microdisk electrodes [3-5], we note that the substitution

$$\bar{c}_{CF} = \bar{v} \left[-f \left(\lambda, q, \frac{k_2}{D} \right) z \right] \quad (10)$$

converts eqn. (9) into

$$\frac{\partial^2 \bar{v}}{\partial r^2} + \frac{1}{r} \frac{\partial \bar{v}}{\partial r} + \alpha^2 \bar{v} = 0 \quad (11)$$

with

$$\alpha^2 = \left[f\left(\lambda, q, \frac{k_2}{D}\right)z \right]^2 - \left(q^2 + \frac{k_2}{D} \right) \quad (12)$$

The solution is then

$$\bar{c} = \frac{k_1}{k_2 s} - \int_0^\infty g\left(\lambda, q, \frac{k_2}{D}\right) \exp\left[f\left(\lambda, q, \frac{k_2}{D}\right)z \right]^2 J_0(\alpha r) d\alpha \quad (13)$$

where the function $g(\lambda, q, k_2/D)$ must be chosen to satisfy the Laplace transforms of eqns. (6) and (7).

$$\frac{d\bar{c}}{dz} = 0, \quad r > a, z = 0 \quad (14)$$

$$\frac{d\bar{c}}{dz} = -\frac{Q(s)}{D} \quad 0 < r < a, z = 0 \quad (15)$$

We again make use of the discontinuous integral

$$\int_0^\infty J_0(\alpha r) J_1(\alpha a) d\alpha = \begin{cases} 0 & r > a \\ 1/2a & r = a \\ 1/a & r < a \end{cases} \quad (16)$$

and with the particular form

$$\left[f\left(\lambda, q, \frac{k_2}{D}\right)z \right]^2 = \alpha^2 + q^2 + \frac{k_2}{D} \quad (17)$$

We obtain

$$\bar{c} = \frac{k_1}{k_2 s} - \frac{Q(s)a}{D} \int_0^\infty \exp\left[-\left(\alpha^2 + q^2 + \frac{k_2}{D} \right)z^{1/2} \right] J_0(\alpha r) J_1(\alpha a) \times \frac{d\alpha}{\left(\alpha^2 + q^2 + \frac{k_2}{D} \right)^{1/2}} \quad (18)$$

and, at $z = 0$,

$$\bar{c} = \frac{k_1}{k_2 s} - \frac{Q(s)a}{D} \int_0^\infty J_0(\alpha r) J_1(\alpha a) \frac{d\alpha}{\left(\alpha^2 + q^2 + \frac{k_2}{D} \right)^{1/2}} \quad (19)$$

We derive the average surface concentration over the surface of the disk

$$\begin{aligned} \bar{c}_{Av} &= \frac{k_1}{k_2 s} - \frac{Q(s)a}{D} \int_0^a \int_0^\infty J_0(\alpha r) J_1(\alpha a) \frac{r dr d\alpha}{\left(\alpha^2 + q^2 + \frac{k_2}{D} \right)^{1/2}} \\ &= \frac{k_1}{k_2 s} - \frac{2Q(s)}{D} \int_0^\infty [J_1(\alpha a)]^2 \frac{d\alpha}{\alpha \left(\alpha^2 + q^2 + \frac{k_2}{D} \right)^{1/2}} \end{aligned} \quad (20)$$

and, on setting the average concentration at the surface equal to zero, we obtain

$$Q(s) = \frac{k_1 D / 2k_2 s}{\int_0^\infty [J_1(\alpha a)]^2 \frac{d\alpha}{\alpha(\alpha^2 + s^2 + k_2/D)^{1/2}}} \quad (21)$$

If we define

$$\beta = \frac{D^{1/2} \alpha}{(s + k_2)^{1/2}} \quad (22)$$

eqn. (21) can be written

$$Q(s) = \frac{\frac{k_1 a}{2k_2} \cdot a \left(\frac{s + k_2}{D} \right)^{1/2}}{\frac{a^2 s}{D} \int_0^\infty \left[J_1 \left(\beta a \left(\frac{s + k_2}{D} \right)^{1/2} \right) \right]^2 \frac{d\beta}{\beta(\beta^2 + 1)^{1/2}}} \quad (23)$$

We therefore obtain a family of curves in the s -domain of $Q(s)$ as a function of $(a^2 s/D)$ each determined by the given value of the parameter $(a^2 k_2/D)$. Numerical inversion gives the responses in the t -domain. Here we restrict attention to the steady state limit

$$Q_{t \rightarrow \infty} = \frac{\frac{k_1 a}{2} \cdot \left(\frac{D}{a^2 k_2} \right)^{1/2}}{\int_0^\infty \left[J_1 \left(\beta \left(\frac{a k_2^{1/2}}{D^{1/2}} \right) \right) \right]^2 \frac{d\beta}{\beta(\beta^2 + 1)^{1/2}}} \quad (24)$$

It is readily confirmed that this result also follows directly from eqn. (2) in the steady state provided we use the substitutions

$$c = v \exp \left[- \left(\alpha^2 + \frac{k_2}{D} \right)^{1/2} z \right] \quad (25)$$

and

$$\beta = D^{1/2} \alpha / k_2^{1/2} \quad (26)$$

Equation (24) is identical to the chronoamperometric response [4] provided we replace $(c^\infty - c_{Av})$ by k_1 and $s^{1/2}$, by $k_2^{1/2}$, i.e. we obtain

$$Q^{1/2} = \frac{k_1 a}{2} \Phi_2 \left(\frac{a k_2}{D^{1/2}} \right) \quad (27)$$

The result of the approximate method of analysis (see above) can be written in the form

$$Q = \frac{k_1 a}{2} \cdot \frac{8}{\pi} \left(\frac{D}{a^2 k_2} \right) \left\{ 1 + \frac{\pi}{4} \left(\frac{a^2 k_2}{D} \right)^{1/2} \right\} \quad (28)$$

TABLE 1

Comparisons of the various results for the CE flux and diffusion limited current flux

$\frac{a^2 k_2}{D}$	Exact eqn. (27)	Equation (28)	Equation (29)	(eqn. 29) - (eqn. 27) (eqn. 27)	(SS) ^a - (eqn. 27) (eqn. 27)
0.01	23701	25664	23747	0.001943	0.000834
0.015	10564	11451	10595	0.002901	0.001248
0.02	5960.1	6466.2	5983.0	0.003849	0.001660
0.03	2664.1	2896.1	2679.1	0.005717	0.002476
0.04	1507.5	1641.5	1518.9	0.007547	0.003284
0.05	970.42	1058.6	979.49	0.009341	0.004082
0.06	677.82	740.69	685.34	0.011098	0.004872
0.07	500.87	548.26	507.29	0.012821	0.005653
0.08	385.69	422.89	391.29	0.014508	0.006425
0.09	306.50	336.60	311.45	0.016162	0.007189
0.1	249.69	274.65	254.12	0.017781	0.007945
0.2	66.028	73.662	68.158	0.032251	0.015056
0.3	30.987	34.961	32.348	0.043929	0.021421
0.4	18.374	20.915	19.353	0.053256	0.027117
0.5	12.376	14.186	13.126	0.060606	0.032211
0.6	9.0306	10.407	9.6292	0.066293	0.036765
0.7	6.9609	8.0540	7.4522	0.070585	0.040833
0.8	5.5832	6.4789	5.9947	0.073709	0.044462
0.9	4.6150	5.3660	4.9650	0.075854	0.047696
1.0	3.9053	4.5465	4.2067	0.077185	0.050573
2.0	1.4186	1.6366	1.5143	0.067456	0.065799
3.0	0.83920	0.94961	0.87862	0.046943	0.067957
4.0	0.59278	0.65915	0.60990	0.028887	0.063204
5.0	0.45767	0.50186	0.46436	0.014619	0.060779
6.0	0.37258	0.40407	0.37387	0.003464	0.056015
7.0	0.31414	0.33768	0.31245	-0.005360	0.051451
8.0	0.27152	0.28979	0.26813	-0.012472	0.047287
9.0	0.23908	0.25366	0.23470	-0.018303	0.043569
10.0	0.21356	0.22546	0.20862	-0.023153	0.040282
12.0	0.17599	0.18435	0.17058	-0.030741	0.034831

^a Simulation result from Shoup and Szabo, reference (7).

The result, however, applies for constant surface concentration whereas eqn. (27) assumes a constant surface flux. The correction to the latter condition will be of the order of the ratio of the mass transfer coefficients for constant flux and constant concentration, $3\pi^2/32$, i.e. we predict the relation

$$Q = \frac{k_1 a}{2} \cdot \frac{3\pi}{4} \left(\frac{D}{a^2 k_2} \right) \left(1 + \frac{\pi}{4} \left(\frac{a^2 k_2}{D} \right)^{1/2} \right) \quad (29)$$

Table 1 compares values of $2Q/k_1 a$ for the various predictions (27)–(29) while Fig. 1 plots the percentage deviation between the predictions (29) and (27). It can be

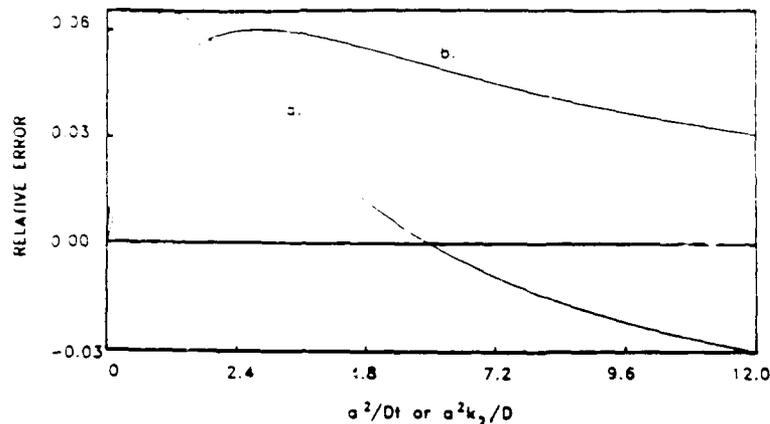


Fig. 1. Plot of the relative errors with respect to the exact CE result (27) or the exact chronoamperometric result (7) for (a) the CE approximation in eqn. (29) and (b) for the chronoamperometric approximation in eqn. (33).

seen that the approximate method gives results which are in fact very close to the result (27).

CONCLUSION

The present series of papers (see also refs. 3-5) has shown that it is possible to analyze a wide range of electrochemical experiments at microdisk electrodes by making use of the properties of discontinuous integrals of Bessel functions. In this analysis we have made extensive use of the average concentration over the surface of the microdisk rather than solving the problems for controlled uniform concentrations over the surface. The latter approach (although possible) leads to considerable mathematical complications and results which frequently have to be approximated. It is of interest therefore, that the approximate procedure used previously for the discussion of coupled reactions in solution (in which the exact result for the problem for a microspherical electrode is scaled to that for the disk using eqn. (3) [3]) gives results which are close to those using the procedure developed in this series of papers. As a further illustration of this procedure, we note that the diffusion limited current density to a sphere (a special case of constant surface concentration)

$$I = nFDc^\infty/a_{\text{sphere}} + nFD^{11/2}c^\infty/\pi^{1/2}t^{1/2} \quad (30)$$

can be rescaled to that at the disk using eqn. (3).

$$I = 4nFDc^\infty/\pi a_{\text{disk}} + nFD^{11/2}c^\infty/\pi^{1/2}t^{1/2} \quad (31)$$

We therefore obtain the actual current at a disk of radius a_{disk} as

$$\pi a_{\text{disk}}^2 I = 4nFDc^\infty a_{\text{disk}} + nF\pi^{1/2} D^{1/2} c^\infty a_{\text{disk}} / t^{1/2} \quad (32)$$

The current transient normalized by the steady state current is

$$\frac{\pi I a_{\text{disk}}}{4nFDc^\infty} = 1 + \frac{\pi^{1/2}}{4} \left(\frac{a_{\text{disk}}}{D^{1/2} t^{1/2}} \right) \quad (33)$$

We note that eqn. (33) is close to the values predicted algebraically [6] or by simulation [7] the maximum deviation being +6.8% at $a_{\text{disk}}/D^{1/2}t^{1/2} \approx 3$ this deviation decreasing at both high and low values of $a/D^{1/2}t^{1/2}$. Table 1 and Fig. 1. We note that a wide range of problems has already been analyzed in the spherical coordinate system and that, when solutions are not available, these are easy to obtain in view of the uniform accessibility of the surface of spherical electrodes. The approximate procedure may therefore prove to be generally useful.

ACKNOWLEDGEMENT

We thank the Office of Naval Research for support of this work.

GLOSSARY OF ADDITIONAL SYMBOLS USED (see also ref. 4)

- I Current density, $A\text{ cm}^{-2}$
 k_1, k_2 Homogeneous rate constants, s^{-1}
 β Parameter $D^{1/2}\alpha/(s+k_2)^{1/2}$

$$\Phi_2 = \frac{\left(\frac{D}{a^2 k_2} \right)^{1/2}}{\int_0^\infty \left[J_1 \left(\beta \left(\frac{ak_2^{1/2}}{D^{1/2}} \right) \right) \right]^2 \frac{d\beta}{\beta(\beta^2+1)^{1/2}}}$$

REFERENCES

- 1 M. Fleischmann, F. Lasserre, J. Robinson and D. Swan, *J. Electroanal. Chem.*, 177 (1984) 97.
- 2 M. Fleischmann, F. Lasserre and J. Robinson, *J. Electroanal. Chem.* 177 (1984) 117.
- 3 M. Fleischmann, J. Daschbach and S. Pons, *J. Electroanal. Chem.*, JEC9788, 1979
- 4 M. Fleischmann and S. Pons, *J. Electroanal. Chem.*, JEC9789, 1979
- 5 M. Fleischmann and S. Pons, *J. Electroanal. Chem.*, JEC9787.
- 6 K. Aoki and J. Osteryoung, *J. Electroanal. Chem.*, 122 (1981) 19.
- 7 D. Shoup and A. Szabo, *J. Electroanal. Chem.*, 140 (1982) 237.

DL/1113/87/2

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	<u>No. Copies</u>		<u>No. Copies</u>
Office of Naval Research Attn: Code 1113 800 N. Quincy Street Arlington, Virginia 22217-5000	2	Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Dr. Bernard Douda Naval Weapons Support Center Code 50C Crane, Indiana 47522-5050	1	Naval Weapons Center Attn: Dr. Ron Atkins Chemistry Division China Lake, California 93555	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko, Code LS2 Port Hueneme, California 93401	1	Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12 high quality	U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
DTNSRDC Attn: Dr. H. Singerman Applied Chemistry Division Annapolis, Maryland 21401	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375-5000	1	Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1

ABSTRACTS DISTRIBUTION LIST, SDIO/IST

Dr. Robert A. Osteryoung
Department of Chemistry
State University of New York
Buffalo, NY 14214

Dr. Douglas N. Bennion
Department of Chemical Engineering
Brigham Young University
Provo, UT 84602

~~Dr. Stanley Pons
Department of Chemistry
University of Utah
Salt Lake City, UT 84112~~

Dr. H. V. Venkatesetty
Honeywell, Inc.
10701 Lyndale Avenue South
Bloomington, MN 55420

Dr. J. Foos
EIC Labs Inc.
111 Downey St.
Norwood, MA 02062

Dr. Neill Weber
Ceramatec, Inc.
163 West 1700 South
Salt Lake City, UT 84115

Dr. Subhash C. Narang
SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

Dr. J. Paul Pemsler
Castle Technology Corporation
52 Dragon Ct.
Woburn, MA 01801

Dr. R. David Rauh
EIC Laboratory Inc.
111 Downey Street
Norwood, MA 02062

Dr. Joseph S. Foos
EIC Laboratories, Inc.
111 Downey Street
Norwood, Massachusetts 02062

Dr. Donald M. Schleich
Department of Chemistry
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 01

Dr. Stan Szpak
Code 633
Naval Ocean Systems Center
San Diego, CA 92152-5000

Dr. George Blomgren
Battery Products Division
Union Carbide Corporation
25225 Detroit Rd.
Westlake, OH 44145

Dr. Ernest Yeager
Case Center for Electrochemical
Science
Case Western Reserve University
Cleveland, OH 44106

Dr. Mel Miles
Code 3852
Naval Weapons Center
China Lake, CA 93555

Dr. Ashok V. Joshi
Ceramatec, Inc.
2425 South 900 West
Salt Lake City, Utah 84119

Dr. W. Anderson
Department of Electrical &
Computer Engineering
SUNY - Buffalo
Amherst, Massachusetts 14260

Dr. M. L. Gopikanth
Chemtech Systems, Inc.
P.O. Box 1067
Burlington, MA 01803

Dr. H. F. Gibbard
Power Conversion, Inc.
495 Boulevard
Elmwood Park, New Jersey 07407

DL/1113/87/2

ABSTRACTS DISTRIBUTION LIST, SDIO/IST

Dr. V. R. Koch
Covalent Associates
52 Dragon Court
Woburn, MA 01801

Dr. Randall B. Olsen
Chronos Research Laboratories, Inc.
4186 Sorrento Valley Blvd.
Suite H
San Diego, CA 92121

Dr. Alan Hooper
Applied Electrochemistry Centre
Harwell Laboratory
Oxfordshire, OX11 0RA UK

Dr. John S. Wilkes
Department of the Air Force
The Frank J. Seiler Research Lab.
United States Air Force Academy
Colorado Springs, CO 80840-6528

Dr. Gary Bullard
Pinnacle Research Institute, Inc.
10432 N. Tantan Avenue
Cupertino, CA 95014

Dr. J. O'M. Bockris
Ementech, Inc.
Route 5, Box 946
College Station, TX 77840

Dr. Michael Binder
Electrochemical Research Branch
Power Sources Division
U.S. Army Laboratory Command
Fort Monmouth, New Jersey 07703-5000

Professor Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton, Hants, S09 5NH UK