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New analytical strategies for gold interdigitated filar microelectrodes

Harrington, Michael Smith, Ph.D.
The Ohio State University, 1990
NEW ANALYTICAL STRATEGIES FOR GOLD INTERDIGITATED
FILAR MICROELECTRODES

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the
Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Michael Smith Harrington, B.A., B.S.
The Ohio State University
1990

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Advisor
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To my wife, Tina Scott.
ACKNOWLEDGEMENTS

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<td>Ag/Ag⁺</td>
<td>Silver/silver ion reference electrode</td>
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<td>BHMF</td>
<td>1,1'-bis(hydroxymethyl) ferrocene</td>
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<tr>
<td>b</td>
<td>Length of electrode filaments</td>
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<tr>
<td>Cᵢ</td>
<td>Concentration of species i</td>
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<td>COL</td>
<td>Collector electrode</td>
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<tr>
<td>Dᵢ</td>
<td>Diffusion coefficient of species i</td>
</tr>
<tr>
<td>Dᵢᵢ</td>
<td>Dimensionless diffusion coefficient of species i</td>
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<tr>
<td>E</td>
<td>Potential</td>
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<td>E&quot;&quot;</td>
<td>Formal potential of redox couple</td>
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<td>Eₛ</td>
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<td>fᵢ</td>
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<td>i</td>
<td>Current</td>
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<td>iₛₛ</td>
<td>Steady-state current</td>
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INTRODUCTION

Electroanalytical techniques traditionally have employed a single working electrode to extract the analytical information of interest from a chemical system. Appropriate choice of experimental conditions enables a variety of chemical information to be determined. For example, electroanalytical methods have been used to determine solution composition, thermodynamic properties, and kinetic information (13).

The information content of an electroanalytical technique may be increased by employing a device constructed of multiple, independent working electrodes. For example, twin intercommunicating electrodes have been used to monitor the products of electrochemical reactions (1, 6, 15). The rotating ring-disc electrode (1) and the thin-layer cofacial twin electrode (6) are particular examples of twin intercommunicating electrodes.

For the cofacial twin electrode (Figure 1-A), the potential of one electrode (the collector) is held at a fixed value for a minimum background signal, while the potential of the facing electrode (the generator) undergoes a potential excitation program. The products of electrolysis at the
Figure 1. Twin electrode designs: A) Cofacial twin electrode; B) Coplanar twin disc electrode; C) Coplanar disc and horseshoe electrodes; D) Coplanar twin interdigitated filar electrode.
Figure 1
generator electrode diffuse across the small gap, about 100 μm, to the collector, where they are detected and reconverted to their initial state. Although both currents are monitored during an experiment, the collector current is used most commonly for analytical purposes (41) because the faradaic response at this fixed-potential electrode is not corrupted by charging and background currents present at the electrode undergoing potential change.

Under the appropriate experimental conditions, twin electrode methods provide steady-state currents (1,45). Cofacial twin electrodes exhibit steady-state currents which arise from diffusional feedback of chemical information through a quiescent thin layer of solution sandwiched between two electrodes (6,7). This continuous interconversion of analyte between the facing electrodes, called redox cycling, enhances the current signal at each electrode and causes the system to asymptotically approach a steady-state. Collection efficiencies for cofacial twin electrodes, defined as the ratio of the currents at the collector and generator (\(|i_{\text{COL}} / i_{\text{GEN}}| \times 100\%\)), approach 100% at steady-state. Under these circumstances, the sensitivity of the collector is at a maximum. However, cofacial twin electrodes suffer from edge effects, severe iR drop complications, and the mechanical difficulty associated with reproducibly placing the two macroscopic electrodes in close physical proximity (6).
Stationary coplanar twin electrodes provide the same advantages offered by other twin electrode techniques, while avoiding some of the mechanical complications. In parallel mode (41), the twin disc electrodes (Figure 1-B) are held at different potentials to provide independent information on different electroactive species. In serial mode, the same twin electrodes are used as a generator and collector pair similar to the cofacial twin electrode arrangement. Twin disc electrodes, although easy to manipulate, suffer from low collection efficiencies, generally less than 20%. In an effort to improve the collection properties, MacCrehan described a horseshoe shaped collector electrode surrounding a disc electrode (Figure 1-C) which provided collection efficiencies as high as 60% (43). Such macroscopic twin electrodes, however, offer no significant signal enhancement from redox cycling by diffusional feedback.

Signal enhancement from diffusional feedback is observed for coplanar twin interdigitated electrodes (Figure 1-D), which are easily constructed using standard photolithographic methods adapted from the microelectronics industry (33,46,50). Like their cofacial twin electrode counterparts, coplanar interdigitated twin electrodes, called filar electrodes for their thread-like geometry, can show high sensitivity and rapid response time by making the electrode filaments narrow and placing them close together. Although the filaments are several millimeters long and their projected areas are of
macroscopic size, their electrochemical behavior more closely resembles microelectrodes (60), because their smallest dimension, the filament width, is only a few microns.

Microelectrodes have a number of properties which are different from conventional macroscopic electrodes (21,42,58,60). Mass transport at microelectrodes is enhanced by cylindrical, or spherical diffusion which leads to quasi steady-state currents in a relatively short time. Their small physical size and rapid mass transport have been used to measure large heterogeneous electron transfer rate constants (23). Because the currents they produce are small, on the order of nA to fA, they do not produce a large iR drop even in highly resistive media. Bartlett has used microelectrode sensors in the absence of deliberately added supporting electrolyte (14). Brina and Pons have reported the use of microdisc electrodes to observe electrochemistry apparently occurring in the gas phase, although the mechanism of this reaction is not well understood (17).

Unfortunately, specialized instrumentation is required to measure subnanoampere currents observed at single microelectrodes (39). However, conventional electrochemical instrumentation can be employed if arrays of microelectrodes are used to increase the current magnitude (4,16,22). Hepel and Osteryoung have used arrays of over one million diffusionally isolated microdisc electrodes to obtain current sensitivity as large as 49 μA/mM (37). For this reason, each
electrode of a twin filar electrode commonly consists of an array of filaments.

Twin filar electrodes have been used in a variety of investigations including the study of redox electron conduction (19,27,29), an investigation of homogeneous chemical reactions coupled to electron transfer reactions (54), in a thin-layer spectroelectrochemical study of proteins (51,52), as a detector for high-performance liquid chromatography (30,31,35), in the construction of chemically-selective sensors (38), in the fabrication of chemical transistors (47), and in a study of non-aqueous electrochemistry (20). In order to improve response times of filar electrodes, much effort has been expended to reduce the filament width and gap dimensions below one micron (11,38,54). Stringent clean-room facilities and other semiconductor fabrication techniques inaccessible to most analytical laboratories are required to achieve linewidths below 10 μm. This is unfortunate, because these are significant advantages in having an electrode fabrication process that can be performed in the analytical laboratory.

Filar electrodes having linewidths of 10-200 μm have been constructed routinely on the benchtop using standard thin-film photolithographic techniques originally developed for industrial microcircuit fabrication. These techniques, adapted for use in the analytical laboratory, enable facile construction of microelectrode devices (20,35,57). It is
therefore important to identify the limits of application of filar electrodes having linewidths above 10 µm for analytical measurements.

There were three basic objectives for the research presented in this dissertation. The first goal was to develop a theoretical treatment for the transient current behavior of filar electrodes. The solution to the boundary value problem describing diffusion at filar electrodes was solved numerically using well-established methods of finite difference calculations by digital simulation. The results of the simulations were verified experimentally. In addition, using a coordinate transformation introduced by Aoki and coworkers (8), the validity of approximating the transient response of filar electrodes was examined for expressions derived from exact solutions for diffusion at cofacial twin electrodes.

The second goal of this study was to investigate the means of improving the response time and sensitivity of filar electrodes having characteristic dimensions above 10 µm by examining their mass transport properties. In this study, the majority of experiments were performed in a thin-layer cell (Figure 2). By placing a reflecting barrier at a distance \( l \) above the electrodes, species were confined to a thin layer of solution, which enabled the rapid establishment of true steady-state mass transport conditions (3,35). The characteristic dimension describing the electrode geometry was
Figure 2. Schematic of cell and interdigitated filar electrode. $W$: Center-line distance between adjacent electrode filaments. $l_2$: Depth of the thin layer.
Figure 2
$W$, the center-line distance between adjacent electrode filaments. Both $I_z$ and $W$ were typically ten to several hundred microns in size.

The separation of analytical signals from one another, as well as the separation of signals from background and noise was illustrated by computing the difference and summation of the measured currents. This analysis technique was shown to lead to a four-fold increase in the rate of convergence of the difference current to a steady-state value, causing the electrodes to behave as though the mean distance between them had been halved. In addition, the removal of correlated noise was demonstrated using a self-correction method based upon the difference current analysis.

The third and final goal of this investigation was to examine the information content of multiple intercommunicating electrodes. By employing a device constructed of multiple independent electrodes, many experiments could be performed simultaneously. An early example of this was the split ring-disc electrode (1) which provided a method of monitoring the products of the disc reaction at the two half-ring electrodes held at different potentials. Multiple electrode strategies employing many independent working electrodes have been reported recently due to the progress made in the microelectronics fabrication process (33). Tobias and coworkers, for example, have reported the use of an array of 100 independent microsquare electrodes (92 μm on a side
separated by a gap of 2 μm in a 10 by 10 array geometry) to study natural convection phenomena in open solution (24,59).

Experiments were carried out in this study to determine the utility of filar electrodes comprised of many independent filaments. An array of twenty independent electrodes were employed as a multichannel sensor to generate steady-state voltammograms by simultaneously monitoring the currents at electrodes which experienced different magnitudes in potential-step excitations. In addition to this multichannel detection method, a common collector electrode detection technique was examined to determine the feasibility of performing a multiplex electrochemical experiment analogous to the Hadamard-transform multiplex spectroscopic method. This approach was shown to be severely limited in practice by the poor between-run reproducibility of these solid electrodes.
CHAPTER I
EXPERIMENTAL

The Electrodes

The electrodes used in this study consisted of interdigitated gold filaments having equal widths and gap sizes between adjacent filaments. Three different electrode arrangements were examined. A twin filar electrode (or 1x1 electrode) consisted of a single array of filaments which was interdigitated with a second array of filaments. This electrode geometry (Plate IA) has been employed by several research groups (11,16,19,20,35,51). The twin filar configuration was used in this study to examine the current transients under potentiostatic conditions, as well as for performing generation/collection cyclic voltammetry. A second arrangement (called a 10x1 electrode, Plate IB), had ten independent pairs of filaments, each interdigitated with a common array of filaments. This configuration was used to test multiplex electrochemical methods under potentiostatic conditions at steady-state. The final electrode arrangement examined (Plate IC) was a 10x10 geometry containing ten adjacent electrode pairs, each consisting of two generator filaments interdigitated with an array of three collector
Plate I. Interdigitated filar microelectrode arrays. A) Twin filar electrode with one generator electrode of 20 filaments and one collector electrode of 21 filaments; B) 10x1 electrode with ten generator electrodes, each having two filaments, and one collector electrode of 21 filaments; C) 10x10 electrode consisting of 10 adjacent twin filar electrode units, each unit having 1 generator electrode of 2 filaments, and one collector electrode of 3 filaments.
Plate I
filaments. This electrode was used to generate steady-state voltammograms under multichannel potentiostatic conditions.

**Artwork:** The original artwork for each electrode was prepared in one of two ways. In the first method, the electrode design was prepared using matte finish white graphics tape (1/16" width) on a matte finish black poster board surface. The electrode was constructed in the appropriate proportions on an enlarged scale for subsequent photographic reduction to a 35 mm slide negative. In the second method, artwork was generated using a Hewlett-Packard 7475A six-pen plotter (Hewlett-Packard Corporation, Cupertino, CA (63)), which had a minimum critical step movement of 25 μm. Under these circumstances, black felt pens of the appropriate tip diameter were used to draw the lines on high gloss white plotter film. The plotter was manipulated under computer control by the simple CAD-CAM program provided in Appendix A.

**Photography:** The negative photolithographic masks were produced on Kodak LPD-4 precision line film (Eastman Kodak Co., Rochester, NY, ASA 6) with a 35 mm camera following a procedure described by Clough for artwork produced on a matte finish black background (20). Proper photographic exposure of the extensive white areas in the artwork, which define the electrical contact pads for each filament, often caused improper exposure of the finer filament structures. More uniform exposure could be obtained by "dodging," which consists of covering the pads of the artwork with matte-finish
black construction paper for approximately one third of the total exposure time. The best total exposure time was determined empirically to be approximately 30 seconds at an optical aperture (f-stop) of f/22. Plotter-produced artwork was photographed with Kodak HCS-135 high contrast slide film (ASA 25) for an exposure time of only 1 second. The HCS-135 film was developed by the same method used for the LPD-4 film as described by Clough (20).

LPD-4 film has a resolution of 800 lines/mm, compared to 400 lines/mm for HCS-135 film, and should therefore be used to produce masks having electrode filament widths of 25 µm or below. A 25 µm-wide filament on LPD-4 film is defined by 20 lines, while for the HCS-135 film, only 10 lines define the filament, approaching the limit of the film. LPD-4 film is only available in bulk quantities and requires the use of a daylight bulk film loader for preparing the film in cartridge form. HCS-135 film, however, may be purchased in cartridge form, and is therefore more convenient when electrode masks with large filament widths (50+ µm) are to be produced.

Production of both the 10x1 and 10x10 electrodes having a center-line distance of approximately 40-50 µm required a two-step photoreduction process. The original artwork was reduced 1:10, as a 5" by 7" positive print photograph. This photograph was then remounted and photographically reduced 1:8, to produce a 35 mm positive photolithographic mask (a total reduction of 80 times).
Photolithography: The electrodes were fabricated on one inch square Superstrates (Materials Research Corp., Pearl River, NY) as described by Clough (20), with several modifications described below. An additional step was added after the development of the photoresist image to aid in the examination of the pattern. Following development, the Superstrate was rinsed with reagent grade isopropanol and immersed in KPR Blue Dye (Eastman Kodak Co., Rochester, NY) for approximately 5 seconds. The Superstrate was then gently rinsed with isopropanol, air dried, and examined using a light microscope at a magnification of 60x to determine the integrity of the photoresist image. Superstrates having unsuitable resist patterns were sonicated in Stripper #400 (Photofabrication Chemical and Equipment Co., Frazer, PA) to remove the polymerized photoresist so the lithography could be repeated with the same Superstrate. Using two 350 nm blacklights, typical exposure times were 80 and 30 seconds for filar electrodes having a 50 and 100 μm center-line distances respectively. After the etching step, the polymerized photoresist was removed by sonication in Stripper #400 for approximately 5 minutes, followed by rinsing with methanol.

Electrodes were deemed acceptable if the resistance between adjacent filaments on a dry substrate exceeded 32 megohms, as determined by a Fluke 73 digital multimeter (John Fluke MFG. Co., Everett, WA). Success rates were highest when the following precautions were observed: contact of the
Superstrate with dust and grease was avoided; KPR photoresist was filtered just prior to use through a 5 mL syringe with a Milllex-SR 0.5 μm Teflon filter unit (Millipore Corp., Bedford, MA); Scotch brand Magic tape (3M Co., St. Paul, MN) was employed rather than vinyl electrical tape to protect the unused side of the Superstrate; and freshly prepared etchant solutions (prepared according to Glang et. al. (32)) were used by diluting the stock solutions in a ratio of one to three with distilled water to provide a relatively mild etch rate.

As with all solid electrodes, these filar electrodes required a method of regenerating their electroactivity after each experiment. Although a wide variety of methods have been developed to regenerate a "clean" surface of a macroscopic electrode (49), none of these methods could be applied satisfactorily to the electrodes employed in this study. The gold electrodes were approximately 0.2 μm thick, which precluded any mechanical form of polishing or chemical etching. Vacuum heat treatment above 350°C causes the 200 Å underlayer of chromium to diffuse into the gold material. Electrochemical pretreatment methods, such as cycling the potential of the electrode in an acid solution between -0.3 V and +1 V vs. SCE, invariably weakened the contact of the filaments with the alumina surface of the Superstrate, often causing them to fracture.

The most effective method we have used consists of sonicating the Superstrate in Stripper #400 for approximately
5 minutes (to remove organics and loosely attached materials from the surface), followed by rinsing in reagent grade methanol. This method could be applied repeatedly over the life of an electrode, and in many cases, satisfactorily regenerates electrochemical activity. Electrodes could be used repeatedly for several hundred experiments when mild potential excitation conditions were employed (-0.3 < E vs. SCE < +0.8). A gradual reduction of the filament width was usually observed, however, over the course of several weeks use, usually resulting in the eventual fracture of the electrode filaments.

Reagents

Hydroxymethylferrocene, 1,1'-bis(hydroxymethyl)-ferrocene (Strem, Newburyport, MA), ferrocene, ferrocene dicarboxylic acid (Aldrich Chemical Co., Milwaukee, WI), and sodium perchlorate (G. Frederick Smith, Columbus, OH) were used as received. Acetonitrile (certified A.C.S. grade, Fisher Scientific, Fair Lawn, NJ) was dried prior to use over 4 Å molecular sieves (Fisher Scientific) which had been activated by heating to 450 °C in a muffle furnace for approximately 6 hours. Aqueous solutions were prepared with distilled deionized water which had been passed through a Nanopure II filtration system (SYBRON Barnstead, Boston, MA). The aqueous supporting electrolyte was a 0.1 M phosphate buffer solution (from reagent grade KH₂PO₄) adjusted to pH 7.0 by addition of
concentrated ammonium hydroxide. Prepurified nitrogen (Burdox, Cleveland, OH) was used to deaerate all solutions for approximately 10 minutes prior to use.

**Electrochemical Cells**

Thin-layer experiments were performed in a modified BAS flow cell (Bioanalytical Systems, West Lafayette, IN) illustrated in Figure 3-1. The cell had been modified to accommodate a one inch square Superstrate upon which the filar electrode had been fabricated. The depth of the thin layer was adjusted by appropriate choice of a Teflon gasket having a thickness of 51, 127, or 380 μm, providing approximate solution volumes of 4.6, 11, and 34 μL respectively. The top barrier, defining the thin layer of analyte solution contacting the electrode surfaces, was either a stainless steel or Macor (machinable ceramic) cell cap (D in Figure 3-1). All experiments were performed in a quiescent solution with sample introduction provided by direct injection from a 5 mL disposable syringe (Becton Dickinson & Co., Rutherford, NJ) through the sample inlet tube. Semi-infinite diffusion experiments were performed in a beaker of the analyte solution employing a dip-type probe illustrated in Figure 3-2 which had been designed originally for electroanalysis in a vacuum line cell (20).

A BAS Ag/AgCl or SCE reference electrode was used for aqueous studies. A nonaqueous reference electrode for studies
Figure 3. Schematic diagram of the two electrochemical cells employing interdigitated filar electrodes. 1: Thin layer cell; A) Sample inlet; B) Reference electrode; C) Stainless-steel retaining plate; D) Reflecting barrier/cell cap; E) Teflon gasket; F) Superstrate; G) Teflon support; H) Cell body; I) Waste outlet. 2: Open-solution twin electrode probe (after Figure 7 of Reference 20); A) Copper wire; B) Heat-shrink tubing; C) Silver epoxy cement; D) Superstrate; E) 'Torr seal' epoxy; F) Gold wire; G) Glass tube.
Figure 3
in acetonitrile was constructed from the body of a BAS Ag/AgCl reference electrode. The reference electrode consisted of a silver wire suspended in a solution of 0.01 M silver nitrate (Allied Chemical, Morristown, NJ) and 0.1 M tetrabutylammonium tetrafluoroborate (anhydrous electrochemical grade) prepared in dry acetonitrile. The potential of the non-aqueous reference electrode was determined in the following manner. An aqueous SCE reference was placed in a glass tube with a fritted terminus, filled with a 1 M NaCl (certified A.C.S. grade, Fisher Scientific, Fair Lawn, NJ) aqueous solution. This tube was then placed into a solution of acetonitrile containing 0.1 M NaClO₄ and the Ag/Ag⁺ reference electrode. The potential difference between the two reference electrodes was measured to be 183 mV with a Fluke model 73 digital multimeter.

Experiments involving filar electrodes with center-line distances of 50 μm or less were carried out in a Faraday cage, which was grounded to the potentiostat common to reduce environmental noise.

Instrumentation

Multiple Electrode Potentiostat: Electrochemical experiments using more than one working electrode were performed with a multiple electrode potentiostat which was designed and constructed by the Chemical Instrumentation Support Group of the Department of Chemistry of The Ohio State
University (34). The general purpose potentiostat was capable of independently controlling the potentials (stepped or scanned programs) and measuring the currents at up to eleven working electrodes using a single auxiliary electrode and a single reference electrode. It was designed for either stand-alone operation or for performance under the direction of a computerized data acquisition and control system. Current sensitivities of 1 mA/V to 100 nA/V in five ranges were selectable with additional sensitivities of 10 nA/V, 1 nA/V and 100 pA/V available through the use of a single channel preamplifier.

The multiple electrode potentiostat, shown schematically in Figure 4, consisted of a base working electrode unit, ten offset working electrode units, and a serial mode data acquisition and control unit housed in a common backplane/power supply assembly. A two channel sample and hold circuit was provided on the base and on each offset working electrode unit, the outputs of which were bused through the backplane to the data acquisition unit for presentation to an external data acquisition system.

A combination of five inverted transistor-transistor logic (TTL) selector inputs from the 9-pin front panel connector of the data acquisition unit acted to connect the appropriate operational amplifier circuitry to the bus signal line. The Cell/DummyNot control line was routed out this 9-pin connector as well for access by the external data
Figure 4. Multiple electrode potentiostat schematic.
Figure 4
acquisition and control system. Upon selecting channel zero, the hold signal was maintained at a false value to allow continuous data collection by the sample and hold circuitry on each unit. The selection of any other channel asserted the hold signal, subsequently allowing the external data acquisition system to examine sequentially all channels at a fixed point in time. The data bus signal was then buffered, scaled and power boosted before being delivered to the BNC connector on the front panel. The backplane bus channel address assignments for the multiple electrode potentiostat are provided in Appendix B.

**Electrical Connections:** Electrical contact to each of the twin filar electrode, the auxiliary electrode, and to the reference electrode was provided by a separate coaxial cable with a patch-clamp connector at one end and a male BNC connector at the other for direct attachment to the potentiostat. Ten element contact clamps (TRW #8533-255-10, TRW Corp., Chicago, IL) were used to make electrical connection with the ten pads of one side of the 10x1 electrode, and to both sides of the 10x10 electrode. The spacing of the ten leads on the clamp was fixed, so it was necessary to design the ten pads on the electrodes with an appropriate spacing and width. Two cables were prepared by connecting the ten element contact clamp to a twisted pair cable, which terminated in a 25-pin male connector.
One of these cables was joined to a 25-pin female connector which was attached to ten coaxial cables, each terminating in a male BNC connector for direct attachment to the potentiostat. For the 10x10 electrode configuration, ten electrodes on one side of the electrode were controlled by the potentiostat while the ten electrodes of the other side were under the control of a linear voltage divider circuit. The voltage divider (Figure 5) provided ten independent, equally spaced potentials. A variable offset and variable potential spacing was provided by precision ten-turn potentiometers, each connected to a 1.5 volt dry cell (Eveready No. IS6, Union Carbide Corp., New York, NY). Connection to the voltage divider was provided by the other ten element contact clamp cable via a 25-pin female connector.

**Computer Data Acquisition and Control:** For automated data acquisition and control, the multiple electrode potentiostat was interfaced to a PC-Designs GV-286 microcomputer (PC-Designs, Broken Arrow, OK). All control lines between the microcomputer and the potentiostat were provided by the digital input/output lines of an 8255A parallel port of a LabMaster DMA multifunction data acquisition and control unit (Scientific Solutions, Solon, OH (64)). The data acquisition unit's channel selection function was provided by the five output bits B2 (most significant bit) to B6 (least significant bit) of the 8255A's port B. The Cell/DummyNot control signal was coupled to input bit 5 of the
Figure 5. Voltage divider circuit.
8255A's port A. Each of these control lines was easily addressable from the software environment as a memory address.

The voltage furnished by the analog output BNC connector of the data acquisition unit was translated by the LabMaster to the digital domain by a single ended bipolar twelve bit successive approximation analog to digital converter operating at a fixed gain of one. Autoranging was not implemented due to calibration problems which occurred upon changing the gain. For all desired voltages to be sampled, it was necessary to sequentially address and monitor each channel. The sample and hold hardware incorporated into the potentiostat conveniently enabled the software to determine multiple voltages which had been sampled simultaneously.

The software support of the data acquisition and control system was implemented using Turbo PASCAL version 4.0 (Borland International, Scotts Valley, CA (67)). Supervisory programs were written in PASCAL with the data acquisition routine having been encoded as 8086 assembly language instructions (Microsoft Macro Assembler, Microsoft Corp., Redmond, WA (65,66)) for rapid execution. The menu driven software package included routines which performed experiments, archived data to and retrieved data from disk storage, displayed data graphically and in raw format to the screen or printer, and managed system parameters. The software was designed to be flexible and easy to use with a minimum amount of training.
Up to 100 sets of data points (each set containing a data point from eleven channels; i.e., the eleven currents) were acquired during an experiment. Prior to the experiment, the time between acquisition of each set was entered in milliseconds from the Parameter Menu. An experiment was initiated from the Run Experiment Menu by selecting the Experiment option. A prompt was then issued to allow last-minute modification of the system parameters. Data collection commenced upon engaging the Cell/Dummy switch to CELL. Upon completion, experimental data were examined using the Plot option, and could be archived to disk from the File Maintenance Menu. The procedures used to perform an experiment are described by the flow charts of Figures 6-8. The complete source code for the software system is presented in Appendix C.

Procedure

Single Electrode Experiments: Conventional cyclic voltammetry was performed on analyte solutions using a 4 mm diameter BAS gold disk electrode in open solution with a platinum auxiliary electrode and the appropriate reference electrode. Potential control and current measurement were provided by a BAS CV-1B potentiostat with a 0.001 second RC time constant filter. Currents were plotted as a function of applied potential using an XY recorder (Moseley Model 2D-2M or 7001 AM, Hewlett-Packard, Pasadena, CA). Prior to each
Figure 6. Flow chart of multiple electrode potentiostat software—Main module.
Figure 6
Figure 7. Flow chart of multiple electrode potentiostat software—Run Experiment module.
Figure 7

RUN EXPT

RUN MENU
CHOOSE OPTION

SET A-TO-D
GAIN = 1
CHANNEL 0

INITIALIZE
MEMORY ARRAYS
TO ZEROS

CHANGE
PARAMETER
OPTIONS?

YES

SYSTEM
PARAMETER
MENU

NO

PROMPT
TO ACTIVATE
CELL

GETCURR
(80286
MODULE)

PROMPT
TO DEACTIVATE
CELL

COMPUTE
2s COMPLEMENT
OF RAW DATA
Figure 8. Flow chart of multiple electrode potentiostat software--GETCURR assembly language module.
GETCURR

CONFIGURE 8255A PORTS A,C=IN B=OUT

INITIALIZE COUNTERS

ASSERT HOLD CHANNEL 0 OF PORT B SET

SELECT NEXT CHANNEL ON PORT B

START A-TO-D CONVERSION

NO TO D COMPLETE?

NO

YES

SET LOW BYTE AND HIGH BYTE OF DATA

MASK OFF HIGH NIBBLE OF HIGH BYTE

STORE VALUE IN MEMORY ARRAY

ALL CHANNELS READ?

NO

YES

RELEASE HOLD CHANNEL 0 OF PORT B SET

DELAY X msec

MEMORY ARRAY FULL?

NO

YES

RETURN

Figure 8
experiment, the gold disk electrode was cleaned by polishing with 0.05 μm alumina slurry on microcloth polishing fabric (Buehler LTD., Lake Bluff, IL) followed by thorough rinsing with distilled water. Cyclic voltammograms from this instrumentation were used to determine the half-wave potentials of the analyte redox couples of interest.

**Twin Electrode Chronoamperometry:** Twin filar electrode chronoamperometric experiments were performed with the multiple electrode potentiostat by first determining the potential of minimum background current. With the generator electrode at open circuit, the potential of the collector electrode (connected to the base working electrode unit of the potentiostat) was stepped to different values to determine the potential at which the current rapidly decayed to a minimum value. In addition, the chosen potential was removed from the standard potential of the analyte redox couple sufficiently that no electrolysis occurred. With the potential of the collector electrode held at this predetermined value, the potential of the generator electrode (connected to an offset working electrode unit) was stepped to a region where the analyte was electrolyzed at the diffusion limited rate. Current transients for the two electrodes were monitored on separate XY recorders, or were sampled directly by the data acquisition and control program.

**Twin Electrode Cyclic Voltammetry:** Generation / collection cyclic voltammetry (G/C-CV) at twin filar
electrodes was performed by applying a cyclic triangular waveform to the generator electrode while the potential of the collector electrode was maintained at a fixed value. In order to perform G/C-CV using the multiple electrode potentiostat, the offset voltage follower operational amplifier chip (see Figure 4) was gently removed from the offset working electrode unit. The cyclic triangular waveform was provided by a function generator (Krohn-Hite Corp., Avon, MA) through the offset output BNC connector on the front panel of the potentiostat which then directly controlled the potential of the electrode connected to the modified unit. The potential of the collector electrode was selected for minimum background current as described previously. The potential of the generator electrode, connected to the modified offset working electrode unit, was then swept for one cycle through the potential region of interest. Currents were recorded as a function of the generator potential on separate XY recorders. Data collection under computer control was also possible by a simple modification of the computer software to enable the monitoring of the generator electrode potential.

10x1 Multichannel Chronoamperometry: Potential-step chronoamperometric experiments were performed at 10x1 electrodes in the thin-layer cell. The potential of the collector electrode was set for a minimum background current. The potentials of the ten generator electrodes were then poised at approximately equal intervals across the potential
region of interest. Multichannel (multiple potential) experiments were performed on analyte solutions and on solutions of supporting electrolyte alone for background subtraction. An initial experiment on a standard solution was performed to determine the relative active areas of the ten generator electrodes by poising all of them at a potential where the analyte was electrolyzed at the diffusion limited rate, while maintaining the potential of the collector electrode in the region of minimum background. The steady-state values of the generator electrode currents were recorded and normalized by dividing each current by the largest value. These normalization values were then multiplied by the respective background-corrected multichannel steady-state currents of subsequent experiments. Steady-state voltammograms were constructed by plotting these corrected generator currents as a function of the applied potential.

**Multiplex Chronoamperometry:** Multiplex chronoamperometric experiments, employing a Hadamard-type mask sequence, were performed at 10×1 electrodes in the thin-layer cell. The potential of the collector electrode was determined as above for a minimum background current. The potentials of the ten generator electrodes were poised at approximately equal intervals across the region of interest. The multiplex experiment consisted of performing ten chronoamperometric trials, each with a different combination of active generators. To obtain maximum current signals for each trial,
all but one of the generator electrodes were active; trials differed by the choice of the inactive electrode. The collector current was monitored digitally and a steady-state value was calculated for each of ten trials. These ten collector currents were then used to compute the expected generator electrode currents by solving the system of linearly independent equations, using the method of gaussian elimination performed with the equation-solving software package Eureka: The Solver (Borland International (62)). Steady-state voltammograms were constructed by plotting the calculated generator currents (corrected for differences in electroactive area) as a function of their applied potentials.

10x10 Multichannel Chronoamperometry: Potential-step chronoamperometric experiments were performed at 10x10 electrodes in the thin-layer cell. The potential for the ten collector electrodes was determined by the same method employed above. This potential was applied to each of the collectors by the multiple electrode potentiostat. The relative active areas of the ten collectors were computed by performing a preliminary experiment where the potentials of all ten generator electrodes were stepped to a diffusion limited value while maintaining the potential of all collectors near minimum background. The steady-state collector electrode currents were computed and normalized by dividing each current by the largest current observed. These values were then used to correct the collector electrode
currents of subsequent experiments for differences in electroactive area. For the multipotential experiments, the potentials of the ten generator electrodes (controlled by the voltage divider circuit described previously) were uniformly spaced across the region of interest. Steady-state collector currents were recorded, corrected, and plotted as a function of the corresponding generator potentials.
CHAPTER II
THEORY

Digital Simulation

Filar Electrode Unit Cell: Theoretical solutions of the mass-transport problem for filar electrodes were obtained using standard digital simulation procedures (13,18,28,44) involving a numerical model which was implemented through the method of finite differences. All simulations were performed in a discrete two-dimensional cartesian space as shown in Figure 9 for a unit cell representing a portion of the interior of an interdigitated filar electrode.

Mass transport of species is described by Fick's laws of diffusion in the absence of migration and convection. Fick's laws of diffusion for a species \( i \) may be represented by the following equations if one assumes that the diffusion coefficient, \( D_i \), is isotropic (i.e. \( D_i(x) = D_i(y) = D_i(z) \)).

Fick's First Law:
\[- J_i = \frac{i}{(nFA)} = D_i \nabla C_i \quad (1)\]

Fick's Second Law:
\[( \frac{C_i}{t} ) = D_i \nabla^2 C_i \quad (2)\]
Figure 9. Diagram of two-dimensional space grid for digital simulation: Unit cell representation of filar electrode geometry.
Figure 9
Employing cartesian coordinates with the simplifying assumption that the filaments are much longer than they are wide, and thus that there is symmetry in the y dimension:

$$\frac{\partial C_i(x, y, z, t)}{\partial y} = \frac{\partial^2 C_i(x, y, z, t)}{\partial y^2} \approx 0$$  \hspace{1cm} (3)

Thus, any end effects where filaments are connected to contact pads will be neglected, and the diffusion equations can be cast into a two-dimensional form:

$$\frac{\partial C_i(x, z, t)}{\partial t} = D_i \left[ \frac{\partial^2 C_i(x, z, t)}{\partial x^2} + \frac{\partial^2 C_i(x, z, t)}{\partial z^2} \right]$$  \hspace{1cm} (4)

$$- J_i(z, t) = \frac{i}{(nF)A} = D_i \frac{\partial C_i(x, z, t)}{\partial z}$$  \hspace{1cm} (5)

$$- J_i(x, t) = D_i \frac{\partial C_i(x, z, t)}{\partial x}$$  \hspace{1cm} (6)

Transformation of these equations into a discrete form allows solution by finite difference methods that can be easily mechanized (18). Thus, Fick's first law is transformed to the discrete domain as:

$$J_i(z, t) = \lim_{\Delta z \to 0} -D_i \frac{[C_i(x, z+\Delta z, t) - C_i(x, z, t)]}{\Delta z}$$

$$= (-D_i/\Delta z) [C_i(x, z+\Delta z, t) - C_i(x, z, t)]$$  \hspace{1cm} (7)

$$J_i(x, t) = \lim_{\Delta x \to 0} -D_i \frac{[C_i(x+\Delta x, z, t) - C_i(x, z, t)]}{\Delta x}$$

$$= (-D_i/\Delta x) [C_i(x+\Delta x, z, t) - C_i(x, z, t)]$$  \hspace{1cm} (8)

By using a one-half shift in coordinates (13), Fick's first law can be portrayed conveniently as:

$$J_i(z, t) = (-D_i/\Delta z) [C_i(x, z+\Delta z/2, t) - C_i(x, z-\Delta z/2, t)]$$  \hspace{1cm} (11)
\[ J_i(x,t) = (-D_i/\Delta x) \left[ C_i(x+\Delta x/2,z,t) - C_i(x-\Delta x/2,z,t) \right] \] (12)

Fick's Second Law can then be represented as:

\[-\partial C_i(x,z,t)/\partial t = \partial J_i(x,t)/\partial x + \partial J_i(z,t)/\partial z \] (13)

which may be cast into the following finite form, using the same one-half coordinate shift operation:

\[-\partial C_i(x,z,t)/\partial t = \lim_{\Delta t \to 0} -[C_i(x,z,t+\Delta t) - C_i(x,z,t)]/\Delta t \] (14)

\[ = [J_i(x+\Delta x/2,z,t) - J_i(x-\Delta x/2,z,t)]/\Delta x + [J_i(x,z+\Delta z/2,t) - J_i(x,z-\Delta z/2,t)]/\Delta z \] (15)

\[ = -D_i/\Delta x^2(C_i(x+\Delta x,z,t) - 2C_i(x,z,t) + C_i(x-\Delta x,z,t)) - D_i/\Delta z^2(C_i(x,z+\Delta z,t) - 2C_i(x,z,t) + C_i(x,z-\Delta z,t)) \] (16)

Assuming \( \Delta x = \Delta z \), terms can be combined to yield:

\[-[C_i(x,z,t+\Delta t) - C_i(x,z,t)]/\Delta t = -D_i/\Delta x^2(C_i(x+\Delta x,z,t) + C_i(x-\Delta x,z,t) + C_i(x,z+\Delta z,t) + C_i(x,z-\Delta z,t) - 4C_i(x,z,t)) \] (17)

This diagrammatically corresponds to the exchange of solute between a unit of volume (the center box in Figure 10-A) and the four units of volume immediately adjacent in the unit of time \( \Delta t \).

The boundary conditions for the solution are satisfied as follows. The change in concentration of species i in a box at the top left corner of the grid in Figure 9 (as represented in Figure 10-B) is described by:
Figure 10. Segments of the two-dimensional space grid. Four different spatial boundary conditions for determining the concentration change at: A) an interior box; B) a corner; C) a vertical edge; and D) a horizontal edge.
Figure 10
\[-\frac{C_i(x,z,t+\Delta t) - C_i(x,z,t)}{\Delta t} = - \frac{D_i}{\Delta z^2} (C_i(x+\Delta x,z,t) + C_i(x,z+\Delta z,t) + 2C_i(x,z,t)) \] (18)

The concentration change in a box at the left vertical boundary (Figure 10-C) is generated by summation of the three fluxes from adjacent boxes giving:

\[-\frac{C_i(x,z,t+\Delta t) - C_i(x,z,t)}{\Delta t} = - \frac{D_i}{\Delta z^2} (C_i(x+\Delta x,z,t) + C_i(x,z+\Delta z,t) + C_i(x,z-\Delta z,t) - 3C_i(x,z,t)) \] (19)

Finally, the concentration change in a box at the top horizontal boundary (Figure 10-D) is described as:

\[-\frac{C_i(x,z,t+\Delta t) - C_i(x,z,t)}{\Delta t} = - \frac{D_i}{\Delta z^2} (C_i(x+\Delta x,z,t) + C_i(x-\Delta x,z,t) + C_i(x,z-\Delta z,t) - 3C_i(x,z,t)) \] (20)

Note, in all of these computations, it is assumed that the discrete boxes do not communicate across the boundaries. Therefore, the concentration after one time unit—an iteration of a computational cycle—at a central region becomes:

\[C_i(x,z,t+\Delta t) = C_i(x,z,t) + \frac{D_i \Delta t}{\Delta z^2} (C_i(x+\Delta x,z,t) + C_i(x-\Delta x,z,t) + C_i(x,z+\Delta z,t) + C_i(x,z-\Delta z,t) - 4C_i(x,z,t)) \] (21)

In order for these difference equations to be digitized for solution on a computer, they must be cast into a dimensionless form. For this purpose, the following transformations will be employed:
Dimensionless Concentration:
\[ f_i = \frac{C_i(x,z,t)}{C_i^{\text{bulk}}(x,z,t)} \]  

Dimensionless Diffusion Coefficient:
\[ D_{m,1} = \frac{D_i \Delta t}{\Delta z^2} \]  

For computational stability in a two-dimensional model, the value for the dimensionless diffusion coefficient, \( D_{m,1} \), must be less than or equal to 0.25. A value larger than this will cause the calculation to oscillate, preventing the simulation from converging to a solution. In addition, the following relationship holds for the geometry defined by the unit cell used in this study:
\[ W = L \Delta x \]  

where \( L \) is the number of discrete boxes in the \( x \) dimension which defines the quantity \( W \), the center-line distance between adjacent electrode filaments. For larger values of \( L \), the simulation exhibits greater spatial resolution and shorter time steps. The upper limiting value of \( L \) depends upon the amount of random access memory available on the computer as well as the time required to perform the simulation. This latter factor is apparent upon examining the following relationship:
\[ \Delta t = \frac{D_i \Delta z^2}{D_{m,1}} \]  

With \( \Delta z = W/L \), this becomes:
\[ \Delta t = \frac{D_i W^2}{D_{m,1} L^2} \]  

In essence, by using larger values of \( L \), the time required for one iteration spans successively shorter periods
of "real" time. Figure 11 illustrates the results for eight simulations using different values for \( L \) to calculate a value for the steady-state dimensionless current. A value of \( L=4 \) gives the roughest estimate for the steady-state current. As \( L \) is increased, the time interval \( \Delta t \) decreases and the finite difference approximation of equation 14 is more valid, predicting a value for the dimensionless steady-state current which approaches the limiting value at \( L \to \infty \). Larger \( L \) values greatly increase the computation time, therefore the value of \( L=16 \) was chosen as a compromise between computation time and accuracy. Current accuracy of 5% could be expected at this dimensional resolution.

Selection of a specific experimental procedure defines the exact boundary conditions necessary to complete the solution of the mass-transport problem. All cases, nonetheless, include the following stipulations for boundary conditions which are easily cast into a dimensionless form. Assuming there is no net flux beyond the boundaries of the unit cell at the horizontal edges (at \( x=0 \) and \( x=W \)), we have:

\[
\left( \frac{\partial C_i(x,z,t)}{\partial x} \right)_{x=0} = \left( \frac{\partial C_i(x,z,t)}{\partial x} \right)_{x=W} = 0
\]  

(27)

Between the electrodes of the unit cell there is an insulating ceramic material, a "reflecting barrier" at \( z=0 \):

\[
\left( \frac{\partial C_i(x,z,t)}{\partial z} \right)_{z=0} = 0 \text{ for } \frac{W}{4} < x < \frac{3W}{4}
\]

(28)

For a reversible redox couple, the boundary conditions for the electrode surfaces will be determined by their potentials which will maintain the concentration ratio of the oxidized
Figure 11. Simulation resolution: Limiting steady-state dimensionless currents as a function of $W/\Delta x$. $I_z/W = 1.00$. Right Abscissa: Percent error in steady-state current from the limiting value at $W=64$ x. Time required to perform a single calculation are indicated for three spatial resolutions. Calculations were performed using a PC-Designs GV-286 microcomputer operating at 12 Mhz.
Figure 11

Dimensionless Steady-State Collector Current vs Error

% Error

0 10 20 30 40 50

W/x

0 0.04 0.08 0.12 0.16

15 min 1 hr 4 hr

Collector Current
and reduced forms of the analyte as determined by the Nernst equation:

\[ \frac{C_0(x,0,t)}{C_R(x,0,t)} = \exp\left[\frac{nF}{R_i T}(E - E')\right] \] (29)

Therefore, at \( z=0 \) for electrode I, \( 0 < x < W/4 \):

\[ \frac{C_0(x,0,t)}{C_R(x,0,t)} = \exp\left[\frac{nF}{R_i T}(E_I - E')\right] \] (30)

and at \( z=0 \) for electrode II, \( 3W/4 < x < W \):

\[ \frac{C_0(x,0,t)}{C_R(x,0,t)} = \exp\left[\frac{nF}{R_i T}(E_{II} - E')\right] \] (31)

and for both electrodes at \( z=0 \), \( 0 < x < W/4 \) and \( 3W/4 < x < W \):

\[ \left( \frac{\partial C_0(x,z,t)}{\partial z} \right)_{z=0} = - \left( \frac{\partial C_R(x,z,t)}{\partial z} \right)_{z=0} \] (32)

In the dimensionless domain, the concentration ratios may be represented by the quantity theta (\( \theta \)):

\[ \theta_1 = \frac{C_0(x,0,t)}{C_R(x,0,t)} \] (33)

\[ = \frac{f_0(x,0,t)}{f_R(x,0,t)} \] (34)

\[ = \exp\left[\frac{nF}{R_i T}(E_I - E')\right] \] (35)

\[ \theta_1' = \frac{f_0'(x,0,t+\Delta t)}{f_R'(x,0,t+\Delta t)} \] (36)

\[ = \frac{f_0(x,0,t)-\Delta f_0(x,0,t)}{(f_R(x,0,t)+\Delta f_0(x,0,t))} \] (37)

Thus,

\[ \Delta f_0(x,0,t) = f_0(x,0,t) - \theta_1' f_R(x,0,t)/(\theta_1' + 1) \] (38)

This last equation represents the quantity of dimensionless concentration of species O which is consumed (or produced) and of species R which is produced (or consumed).

The initial boundary condition in time is:

\[ C_0(x,z,t) = C_0^{\text{bulk}} \quad t < t_c \] (39)

\[ C_R(x,z,t) = C_R^{\text{bulk}} \quad t < t_c \] (40)

The solution to the boundary value problem requires two conditions in \( x \) at all times, two conditions in \( z \) at all
times, and one condition in time over all space. Each of these has been delineated above except for the final boundary condition in z. For this study, two different boundary conditions in z were examined: diffusion in a thin-layer cell defined by a reflecting barrier at \( z = l_z \), and semi-infinite diffusion in the z dimension. Diffusion to a reflecting barrier involves the boundary condition:

\[
\left( \frac{\partial C_i(x,z,t)}{\partial z} \right)_{z=l_z} = 0
\] (41)

Semi-infinite linear diffusion may be modelled approximately using this same criterion, by making the value of \( l_z \) arbitrarily large, so that the concentration of redox species will not change significantly at this limiting distance during the duration of the calculation.

The desired result of the digital simulation is to obtain a dimensioned function of current versus time, which can be compared subsequently with experimental data. In the calculation algorithm, simulated diffusional mass transport occurs, alternated with faradaic conversion of species at the electrode surfaces during each iteration of the calculation. In the simulation, the dimensionless current for one iteration is defined as the amount of analyte electrolyzed during that iteration. In general, the current into a unit segment of the electrode is taken as \( \Delta f_i(x,0,t) \) from equation 38. The dimensionless current density is then the sum of these currents for each electrode segment, divided by the "dimensionless area" of the electrode, \( L/4 \) (the number of
boxes used to define the electrode). A value for the real, dimensioned current may be calculated as follows:

\[ J_i(z,t) = \frac{i}{nFA} = D_i \left( \frac{\partial C_i(x,z,t)}{\partial z} \right)_{z=0} \]  

\[ = \lim_{\Delta z \to 0} D_i C_i^{\text{bulk}} \frac{L}{4} \sum_{j=1}^{L/4} \frac{(\Delta f_{i,j})}{(\Delta z)} \]

\[ i = 4nFAD_i C_i^{\text{bulk}} \sum_{j=1}^{L/4} \frac{\Delta f_{i,j}}{(\Delta z)} \]  

The area, A, is defined as the product of the number of filaments (m), the length of the filament (b), and the width of the filament (W/2); and substituting \( \Delta z = W/L \), the current is expressed as:

\[ i = 4nF(mbW/2) D_i C_i^{\text{bulk}} \sum_{j=1}^{L/4} \frac{\Delta f_{i,j}}{(W/L)} \]  

\[ = 2nFmbD_i C_i^{\text{bulk}} \sum_{j=1}^{L/4} \Delta f_{i,j} \]  

This current-time response (\( \Delta f_{i,j} \) is time-dependent), for a particular value of the dimensionless geometric factor, \( l_i/W \), can then be compared with experimental data.

As the active area of any given electrode can vary greatly during the lifetime of its use, calculated values for the current require adjustment to correct for the percent active area before agreement with experimental data is observed. The most convenient method available for a direct comparison of the experimental and calculated data is to normalize the transients to characteristic values for the current and time. The current can be normalized to the
steady-state current value \((i_{\text{ss}})\), while the time can be normalized to the time necessary for the collector current to reach one-half of its steady-state value \((t_{\text{1/2}})\).

**Entire Electrode Array Simulations:** In addition to the unit cell description given above, simulations of potential-step experiments for the entire twin filar electrode geometry were performed in an effort to examine edge effects and crosstalk. Additional diffusional space was provided for these cases at the extreme edges of the array to allow unimpeded expansion of "radial" diffusion profiles. Unit-cell calculations of the dimensionless current, and the current calculated at the interior of the twin filar electrode array model agreed to within 0.037%. Currents calculated for electrode filaments at the extreme edges of the array differed by a maximum of 5% (at an \(l_z/W\) of 3.0) with these same interior currents. Thus, the unit cell can be used to describe the behavior of twin filar electrodes to within 1%, as the currents at the edges of the array (in error by a maximum of 5%) contribute only 1/20 of the total current.

**Cofacial Twin Electrode Model:** Electrochemical and diffusional events at a twin cofacial electrode were digitally simulated for comparison with thin-layer twin filar electrode simulations involving small values of the dimensionless geometric factor, \(l_z/W\). This one-dimensional problem is described in the digital domain analogous to equation 21 as:
\[ C_i(x,t+\Delta t) = C_i(x,t) + D_i \frac{\Delta t}{\Delta x^2}(C_i(x+\Delta x,t) + \]
\[ C_i(x-\Delta x,t) - 2C_i(x,t)) \]
\[ C_i(1,t+\Delta t) = C_i(1,t) + D_i \frac{\Delta t}{\Delta x^2}(C_i(2,t) - C_i(1,t)) \]
\[ C_i(l,t+\Delta t) = C_i(l,t) + \]
\[ D_i \frac{\Delta t}{\Delta x^2}(C_i(l-1,t) - C_i(l,t)) \]

The expression for the current is then:
\[ \frac{i_{x=a}}{nFA} = D_i \left( \frac{\partial C_i(x,t)}{\partial x} \right)_{x=a} \]
\[ = \lim_{\Delta x \to 0} D_i C_i^{\text{bulk}} \frac{\Delta f_{x=a}}{\Delta x} \]
\[ = D_i C_i^{\text{bulk}} \Delta f_{x=a} \frac{L}{l} \]

Or,
\[ i_{x=a} = nFAD_i C_i^{\text{bulk}} \Delta f_{x=a} \frac{L}{l} \]

where \( L \) in the number of elements used to define the cofacial twin electrode gap width, and \( a=0 \) or \( a=l \) depending upon which electrode is examined.

**Generation/Collection Cyclic Voltammetry:** Simulations for generation/collection cyclic voltammetry were also performed for the twin filar electrode geometry, using a unit cell model where the potential of the generator electrode was incremented after each time interval by a predefined amount:
\[ E = E_{\text{init}} + \Delta E \]
\[ \Delta E = (v \text{ mV/s}) \Delta t = v D_{o,i} \frac{W^2}{(DL^2)} \text{ mV} \]

Upon reaching the switching potential, the generator electrode potential was then decremented in the same fashion. The product of the scan rate \( (v) \) and the number of iterations in the simulation was defined to be equal to one, so that each simulation would comprise one full cycle. In this manner, an
increase in the scan rate acted to decrease the computational time.

Unit-cell simulation calculations were performed on a PC-Designs GV-286 microcomputer (PC-Designs, Inc.) with algorithms programmed in Turbo PASCAL (Borland, International). Large calculations were performed on an IBM 4341-2 mainframe computer with algorithms coded in IBM VS-PASCAL (IBM corp., Boca Raton, LA). Contour plots of the concentration profiles at steady-state were generated on an IBM 3081-D mainframe computer using DI-3000 graphics subroutines (Precision Visuals, Inc., Boulder, CO) from IBM VS2 FORTRAN programs. Simulation program source code listings are provided in Appendix D.

Analytic Solutions

Analytic solutions to the boundary value problem describing diffusion at twin filar electrodes are valuable for comparison of experimental data with theory. Several investigators have attempted to characterize the chronoamperometric behavior of interdigitated filar electrodes; however, no complete analytic solution to the boundary value problem has been reported to date. Steady-state current expressions, however, have been obtained by applying several simplifying assumptions.

Steady-State Expressions. Seddon and coworkers, for example, have derived a steady-state analytic solution for
semi-infinite diffusion to interdigitated filar electrodes in terms of the geometric parameters of bandwidth and bandgap (53). Sanderson and Anderson have described a semi-empirical analysis which quantitatively explains data from steady-state electrochemical and spectroelectrochemical experiments at twin filar electrodes (51). The steady-state current was defined as:

$$i_{ss} = \frac{2nFAD_{red} C_T}{kW}$$  \hspace{1cm} (56)

where $D_{red}$ is the reduced diffusion coefficient, $C_T$ is the total concentration of analyte, and the factor $k$ is a geometric constant which is determined empirically. This expression is analogous to the steady-state current equation for a cofacial twin electrode (6):

$$i_{ss} = \frac{nFADC}{l}$$  \hspace{1cm} (57)

where the value of $kW$ in equation 56 represents a mean path traveled by analyte between the adjacent coplanar electrodes, equivalent to the gap width, $l$, of the cofacial twin electrode.

This purely empirical approach was placed on a sound theoretical basis by Aoki and coworkers (8). For the special case of these interdigitated coplanar electrodes, Aoki and coworkers reduced the two-dimensional diffusion problem to an equivalent one-dimensional representation by a linear transformation. With the Schwarz-Christoffel transformation, a semi-infinite rectangle (Figure 12-A, the filar electrode pair) is mapped onto a line (for which there is apparently no
Figure 12. Coordinate transformations. The two-dimensional twin filar electrode geometry (A) is converted first to a line (B), then to the one-dimensional equivalent cofacial twin electrode arrangement (C).
physical meaning, Figure 12-B). A second coordinate transformation maps this line onto a plane consisting of a rectangular enclosure, with the twin electrodes facing one another across an intervening solution layer (Figure 12-C). The two transformations exactly map the coplanar twin electrode geometry onto a cofacial twin electrode geometry.

**Cofacial Transient Solution for Chronoamperometry.**

Analytic solutions to a variety of electrochemical boundary value problems at cofacial twin electrodes have been reported \(^{(7,40)}\), and these solutions may now be used to describe the electrochemical behavior of interdigitated filar electrodes. As an example of this insight, consider the exact solution for the transient current in chronoamperometry at twin cofacial electrodes, which has been solved in closed form \(^{(5,20)}\).

Referring to Figure 12-C and assuming that \(D_0 = D_r = D\), the expressions for the current transients at each electrode which converge rapidly at long times were shown to be:

\[
i_{\text{GEN}} = nFADC_0(x,0) \left[ 1 + 2 \sum_{k=1}^{\infty} \exp\left(-\frac{k^2 \pi^2 D t}{l^2}\right) \right] \quad (58)
\]

\[
i_{\text{COL}} = -nFADC_0(x,0) \left[ 1 + 2 \sum_{k=1}^{\infty} (-1)^k \exp\left(-\frac{k^2 \pi^2 D t}{l^2}\right) \right] \quad (59)
\]

These currents may also be expressed using expansions which are rapidly convergent at short times:

\[
i_{\text{GEN}} = \frac{nFADC_0(x,0)}{(\pi D t)^{3/2}} \left[ 1 + 2 \sum_{k=1}^{\infty} \exp\left(-\frac{k^2 l^2}{D t}\right) \right] \quad (60)
\]
\[ i_{\text{COL}} = -\frac{2nFADc_0(x,0)}{(\pi Dt)^\frac{3}{2}} \left[ \sum_{k=0}^{\infty} \exp\left(-\frac{(2k+1)^2\ell^2}{4Dt}\right) \right] \] (61)

**Semi-Empirical Expressions.** Clough has shown that truncation of the infinite series sums of these equations to a single term yields expressions which can be used to describe the twin filar electrode currents to within 5%. These semi-empirical expressions may be cast into the following form:

\[ \ln(i_{\text{COL}}t^\frac{3}{2}) \approx \ln(nFAD^*\ell^*/\pi^*) - (k_{st}W)^2/(4Dt) \] (62)

\[ \ln\left(\frac{1}{2} - i_{\text{COL}}/2i_{\text{COL,ss}}\right) \approx -\pi^2Dt/(k_{lt}W)^2 \] (63)

\[ i_{\text{GEN}} \approx nFAD^*\ell^*/(\pi t)^\frac{3}{2} \] (64)

\[ \ln(i_{\text{GEN}}/2i_{\text{GEN,ss}} - \frac{1}{2}) \approx -\pi^2DT/(k_{lt}W)^2 \] (65)

where \( k_{st}W \) and \( k_{lt}W \) represent a mean transport path of molecules at short and long times respectively between the two electrodes separated by the center-line distance \( W \). Clough used these approximations to fit experimental data at both short times (using equations 62 and 64) and long times (using equations 63 and 65). This type of semi-empirical approach provides a practical and convenient method of describing experimental current transients, particularly from experiments for which an accurate digital model is difficult to formulate, such as the case of adventitious convection (20). It is difficult to interpret such fits, however, in terms of the fundamental properties of the system, \( I_z, W, \) and \( t_k \).

**Steady-State Expressions for Multiple Filar Electrodes.**
A general relation describing the steady-state current at a
given electrode in an array of multiple intercommunicating electrodes may be calculated as a sum of terms for the collection of signal from each of the other active electrodes. Using the approach developed by Sanderson and Anderson, the steady-state current between two electrodes, \( q \) and \( m \), is then formulated as:

\[
i_{ss}^q = \tau_{q,m} nFADC/(k_{q,m}W)
\]

(66)

where \( \tau_{q,m} \) represents the collection efficiency of electrode \( q \) for species generated at electrode \( m \), traveling a mean path between electrodes equal to \( k_{q,m}W \). Referring to Figure 13, an expression for the steady-state current at electrode 2, for example, may be given as:

\[
i_{ss}^2 = \tau_{2,1} nFADC/(k_{2,1}W) + \tau_{2,A} nFADC/(k_{2,A}W) + \tau_{2,B} nFADC/(k_{2,B}W) + \tau_{2,3} nFADC/(k_{2,3}W)
\]

(67)

In general, for an array of \( g \) independent electrodes, the expression for the steady-state current at a given electrode \( q \) takes the form:

\[
i_{ss}^q = \sum_{p=1}^{q-1} \tau_{q,p} nFADC/(k_{q,p}W) + \sum_{p=q+1}^{g} \tau_{q,p} nFADC/(k_{q,p}W)
\]

(68)

Such general expressions can be written to describe the steady-state current behavior of any given filament of a filar electrode.
Figure 13. Diagram of an array of 5 independent filar electrodes.
CHAPTER III
RESULTS AND DISCUSSION

Part I: Experimental Verification of Theory

Electrochemical and diffusional events occurring at filar electrodes can be described using theoretical models. In this section, the data from theoretical models using digital simulation and semi-empirical techniques are verified experimentally and evaluated for goodness of fit.

When a twin filar electrode undergoes a potential-step experiment in a quiescent solution, virtual steady-state conditions are eventually established. A reduction in the center-line distance between adjacent electrode filaments (W) monotonically reduces the time required to achieve this steady-state value (11). At values of 2-5 \( \mu m \) for the center-line distance, both Bard and Aoki have shown that virtual steady-state conditions are established after about 0.1 second (9,11). Fabrication of electrodes of this size requires clean-room facilities and other microcircuit fabrication techniques which are inaccessible to most analytical laboratories. Filar electrodes having bandwidths greater than 10 \( \mu m \), however, have been prepared on the benchtop using
conventional photolithographic techniques (20,35). It is therefore valuable to seek methods which improve the response and sensitivity of electrodes of this dimension.

By placing a barrier a short distance, $l_z$, above the electrode surfaces (Figure 14), analyte species are confined to a thin layer of solution. This barrier acts to enhance the diffusional feedback between adjacent electrodes by reflecting the $z$-axis transport of species back to the electrode surfaces, allowing the establishment of true steady-state conditions. The transient current behavior of a twin filar electrode may be described qualitatively by examining Figure 14, which illustrates a cross-sectional view of the electrode in the $x$-$z$ plane. The concentration gradient along the $y$-axis is uniform because the length of each filament is much greater than the width, and because of the symmetry associated with these interdigitated electrodes. Therefore, the two-dimensional slice of the cell geometry in Figure 14 can be used to characterize the filar electrode.

Figure 15 illustrates the potential excitation and current response for a chronoamperometric experiment at a twin filar electrode ($W=100 \ \mu m$, $l_z=380 \ \mu m$). The potential of one electrode, the collector, is held at a fixed value while the potential of the other electrode, the generator, is stepped to a value where electrolysis occurs. Upon application of the potential step, current instantaneously flows, and products of electrolysis at the generator electrode (black arrows in
Figure 14. Cross-sectional schematic view in the x-z plane of a section of a twin fila r electrode. White and black arrows schematically represent the flux of a hypothetical reduced and oxidized species respectively of an analyte redox couple.
Figure 14
Figure 15. Chronoamperometric experiment for a twin filar electrode. Potential excitation (A) and current response (B) for electrolysis of 0.4958 mM BHMF (W=100μm, Iz=380 μm).
Figure 15
Figure 14) can diffuse out to the reflecting barrier, or to adjacent collector electrode filaments where they are recycled. At the collector electrode, no current is initially observed until the generator's products diffuse across the interelectrode gap. These recycled species (the white arrows in Figure 14) can then diffuse back to the generator electrode filaments to be reelectrolyzed, or out to the reflecting barrier. A continuous process of interconversion of the analyte redox couple between its oxidized and reduced forms is established. This interconversion mechanism, called redox cycling, leads to the achievement of steady-state mass transport conditions, and both current transients asymptotically approach a steady-state value.

Steady-state currents are achieved after about ten seconds for a twin filar electrode \((W = 100 \mu m)\) when a 51 \(\mu m\) Teflon gasket is used to define the thin layer. Figure 16-A illustrates the transient behavior of the collector electrode current for a potential-step experiment at three different values for the depth of the thin layer, \(l_z\). As \(l_z\) becomes shallower, the current magnitude is enhanced and the transient approaches a steady-state value more rapidly.

Comparison of Experimental Data with Digital Simulation

The solution to the boundary value problem describing the behavior of filar electrodes can be solved numerically using standard methods of digital simulation. The
Figure 16. Collector electrode current transients. 
A) Raw data for diffusion-limited electrolysis of 0.5039 mM BHMF at a twin filar electrode (W=100 μm). $E_{\text{GEN}}=400$ mV, $E_{\text{COL}}=100$ mV vs. SCE. B) Data from A compared with theoretical curves determined by digital simulation. Current is normalized to the steady-state current ($i/i_{ss}$). Time is normalized to the time required for the current to reach one-half of the steady-state value, ($t/t_4$).
experimental currents of Figure 16-A are compared with the theoretical curves computed by digital simulation for the different values of \( l_z/W \) in Figure 16-B. The collector currents are normalized to the steady-state value, \( (i/i_s) \), while the time is normalized to the time required for the current to reach one-half of its steady-state value, \( (t/t_s) \). The agreement of the experimental data with the theoretical transients is within 5%.

This figure illustrates the behavior of the twin filar electrode in three geometric regimes. At values of \( l_z/W \leq 0.25 \), the normalized current transients coincide. At values of \( l_z/W \geq 3.0 \), another limiting region is encountered where the current transients cease to change as \( l_z/W \) is increased. This region may be described as an open solution or semi-infinite diffusional region. The shape of the normalized transient current changes significantly in the intermediate region of \( 0.25 < l_z/W < 3.0 \).

**Effect of Differing Barriers**

When current transients from initial experiments were compared to the theoretical response predicted by digital simulation, no acceptable match was observed—particularly for the 51 \( \mu \)m spacing. While the digital model incorporated an inert reflecting barrier, experiments were performed with a stainless steel auxiliary electrode acting as the opposing wall for the thin-layer cell. Electrolysis at this auxiliary
electrode had produced a strong effect on the concentration profiles of the analyte.

When experiments were repeated using an external auxiliary electrode, the experimental current transients still failed to agree with the theoretical curves. In this case, the stainless steel barrier was an equipotential surface which served as a conduit for electron conduction between analyte species at its surface. The barrier provided a parallel path to ionic conduction in solution by rapid electron exchange between the oxidized and reduced forms of the analyte redox couple which could be far apart. This parallel path of instantaneous electron conduction caused the transient current response to behave as though mass transport had been accelerated. Agreement of the experimental current transients with theoretical data was finally achieved when the stainless steel barrier was replaced with one constructed of Macor (a nonconducting, machinable ceramic).

The effects of differing reflecting barriers were examined in a quantitative manner by examining the feedback factor, FB, as defined by Bard for interdigitated electrodes in open solution (11):

\[
FB = [1 - (i_{g,0} / i_{g,c})] \times 100\% \tag{69}
\]

where \(i_{g,c}\) and \(i_{g,0}\) represent the steady-state generator current with and without collection at the adjacent collector electrodes respectively. For the experiments of this study, the feedback factor is a measure of the degree of enhancement
of the current which results from constructive feedback of materials by the redox cycling mechanism between adjacent electrodes, or between an electrode and a conductive reflecting barrier.

For the smallest solution layer thickness of 51 μm, the feedback between the conductive barrier and the generator electrode was 21.4% when the stainless steel barrier was used as the auxiliary electrode. No significant difference was observed for the FB factor when an external auxiliary electrode was employed. The feedback between the generator and collector electrodes was 23.2% when an insulating Macor barrier was employed. The FB factor increased to 49.8% when both the collector and the conductive barrier acted as feedback elements to the generator. In short, both the collector and the conductive barrier act in an equivalent capacity to promote redox cycling.

In addition to feedback, the conductive reflecting barrier also provided conditions for a more rapid establishment of steady-state. Figure 17 illustrates the current transients for potential-step experiments using three different barrier conditions, where the transients approach the same value for the steady-state current at sufficiently long times.

A similar effect was observed by Engstrom in studies of scanning electrochemical microscopy (SECM) where differences in the probe current were observed when the specimen examined
Figure 17. Collector electrode current transients: different reflecting barriers. The transients represent diffusion-limited electrolysis of 0.4958 mM BHMF at a twin filar electrode ($W=100 \, \mu m$, $l_g=51 \, \mu m$). A) A stainless-steel auxiliary electrode as barrier; B) A stainless-steel barrier, and an external auxiliary electrode; C) A Macor barrier, and an external auxiliary electrode. $E_{GEN}=400 \, mV$, $E_{COL}=100 \, mV$ vs. SCE.
Figure 17

Collector Current (μA)

Time (sec)
was either a conductor or non-conductor (25). A conducting specimen acted to enhance the probe current due to a diffusional feedback mechanism under experimental conditions where direct electrolysis at the specimen was assumed to be absent (ie., the specimen was at an open-circuit potential). This feedback mechanism was only observed when the microelectrode probe of the SECM was closer to the specimen than approximately 3-5 times the probe radius, which corresponds to an $I_z/W$ value of 3-5 as well. Above these distances, the feedback element (ie, the auxiliary electrode for experiments at filar electrodes) was sufficiently removed from the surface of the electrodes to result in a minimal effect upon the concentration profiles of the working electrodes.

Semi-Empirical Treatment of Experimental Data

Clough has used semi-empirical relations derived from the one-dimensional diffusional geometry of a cofacial twin electrode to approximate the behavior observed for twin filar electrodes in open solution (20). It is useful to determine the degree of accuracy with which these expressions describe the behavior of twin filar electrodes in a thin layer of solution. Figure 18 illustrates the current transients for a chronoamperometric experiment at a twin filar electrode ($W=100 \ \mu m$) in a thin solution layer 127 $\mu m$ thick. The four
Figure 18. Semi-empirical analysis of a chronoamperometric experiment. Data points represent diffusion-limited electrolysis of BHMF at a twin filar electrode (W=100 μm, l_z=127 μm). [BHMF]=0.4958 mM. E_{GEN}=400 mV, E_{COL}=100 mV vs. SCE. Solid curves are the calculated semi-empirical transient curves which rapidly converge at long (A and D) and short (B and C) times. A) and B): collector electrode current; C) and D): generator electrode current.
Figure 18
semi-empirical expressions (62-65) were used to describe the transient curves to within 5% error.

A semi-empirical analysis of the dimensionless current data of the digital model indicates that this treatment yields the best fit for small values of the dimensionless geometric factor, \( l_z/W \). At \( l_z/W \leq 0.5 \), the four semi-empirical equations describe the behavior of the two electrodes. As the value of \( l_z/W \) is increased, a region in both transient curves develops where the difference between the semi-empirical values and the model currents differ by more than 5%. This "window" of poor agreement enlarges as the value of \( l_z/W \) is increased.

Figure 19-A is a plot of the dimensionless collector and generator current transients for a simulated potential-step experiment at a twin filar electrode where \( l_z/W = 3.75 \). The solid lines are semi-empirical fits to the simulated data at short and long times. Figure 19-B illustrates the degree of agreement for the collector current by plotting the absolute value of the percent error:

\[
|\% \text{ error}| = \frac{(i_{\text{SIMULATED}} - i_{\text{SEMIEmpirical}})}{i_{\text{SIMULATED}}} \times 100\% \quad (70)
\]

as a function of time. At long and short times, this error is less than 1%. At intermediate times, however, the error is as high as 37%, and the semi-empirical equations fail to describe the behavior of the twin filar electrodes.

As these semi-empirical expressions were derived from equations describing the behavior of cofacial twin electrodes,
Figure 19. Semi-empirical analysis of a simulated chronoamperometric experiment. A) Simulated current transients for a thin-layer experiment ($l_z/W=3.80$). Solid curves are the calculated semi-empirical transient curves which rapidly converge at long (1 and 4) and short (2 and 3) times. 1) and 2): collector electrode current; 3) and 4): generator electrode current. B) Absolute value of the percent error in the collector current as a function of time for the collector current. 1) Short time; 2) Long time.
Figure 19
it is not surprising to find that the best agreement is observed for twin filar electrodes with small $l_z/W$ values. The equivalence between a cofacial twin electrode and a coplanar twin filar electrode may be readily envisioned for the case of an infinitely thin layer of solution confined to the surface of the filar electrodes. By imagining a thin layer where a reflecting barrier is placed in close physical proximity to the filar electrode surface, the diffusional behavior can be described as occurring in one dimension between the edges of the twin electrode filaments.

In the limit of an infinitely thin layer, the electrode geometry may be described by an equivalent cofacial twin electrode with a gap width approaching $W/2$. The evolution of the thin-layer system to a nearly one-dimensional domain may be observed by digital simulation techniques as the depth of the thin layer, $l_z$, is reduced relative to the center-line distance, $W$. Figure 20 illustrates the steady-state concentration profiles of the reduced form of a hypothetical analyte redox couple for several different values of the dimensionless geometric factor, $l_z/W$. At the smallest $l_z/W$ value of 0.1, the concentration gradient appears to be almost completely one-dimensional, as would be expected for a cofacial twin electrode.
Figure 20. Equivalence between cofacial twin and coplanar twin filar electrodes: Steady-state concentration profiles. Contour plots represent the steady-state concentration distribution of a hypothetical reduced species undergoing diffusion-limited electrolysis in a unit cell simulation of the twin filar electrode for several values of $l_z/W$: A): 1.00; B): 0.50; C): 0.25; D): 0.10.
Figure 20
Summary

The behavior of filar electrodes can be characterized completely using standard digital simulation methods. As expected from these theoretical treatments, performing experiments in a thin layer of solution produces larger, true steady-state currents due to enhanced diffusional feedback of chemical information between adjacent electrode filaments. Semi-empirical expressions derived from exact solutions to the boundary value problem for diffusion at cofacial twin electrodes also can be used to describe the behavior of twin filar electrodes to within 5% when values of $I_n/W \leq 1.25$ are employed. Unfortunately, the simplicity of this data treatment is not applicable to filar electrodes with $W$ values smaller than $\approx 25 \, \mu m$ because of the restriction placed upon the thickness of the Teflon gasket used to define the thin layer.
Part II: Mass Transport Properties of Filar Electrodes

Twin Electrode Chronoamperometry

When a twin filar electrode is employed as a generator and collector electrode pair, the collector and generator currents contain different proportions of information from molecules transported by diffusion in the orthogonal x- and z-directions. The generator current, particularly at short times, is enriched in information about molecules which arrive from the bulk solution, along the z-axis. The collector current is almost entirely the result of electrolysis of molecules diffusing along the x-axis from the adjacent generator electrode filaments.

Because these currents contain different information, these currents or linear combinations of these currents might be used to separate two analytical signals from one another, or signals from background and noise currents. In particular, these currents can be separated into components which reflect predominantly x-axis (or radial) diffusion, and z-axis (or normal) diffusion, by observing the difference or summation respectively of the collector and generator electrode currents.
Difference Current. For potential-step experiments, the difference current converges to a steady-state value on a much more rapid time scale than either the collector or the generator current transients alone, as illustrated in Figure 21. Taking the algebraic difference of the two currents tends to reinforce the x-axis components of both and tends to cancel a portion of the z-axis flux, causing the difference to behave as though the mean distance between filaments had been halved. This rapid convergence of the difference current can be predicted by an examination of the current expressions for the one-dimensional cofacial approximation to the coplanar twin filament electrode geometry. Using equations for which convergence rapidly occurs at long times, an expression for the difference current can be shown to be (20):\[ i_{\text{DIF}} = i_{\text{COL}} - i_{\text{GEN}} \] (71)\[ = -2nFAD_c(x,0) \left[ 1 + 2 \sum_{k=1}^{\infty} \exp(-4k^2\pi^2Dt/l^2) \right] \] (72)This difference current has a form identical to both collector and generator current transients, yet contains an exponential term which is larger by a factor of 4. Thus, the cofacial twin electrode model predicts a four-fold increase in the rate of convergence of the difference current to a steady-state value. This rapid convergence of the difference current is also reflected in the digital simulation results illustrated in Figure 22.
Figure 21. Chronoamperometric current transients. Data represents the diffusion-limited electrolysis of 0.4958 mM BHMF at a twin filar electrode (W=100 μm, l_z=380 μm). Difference current, \( i_{\text{diff}} = \frac{1}{2}(i_{\text{COL}} - i_{\text{GEN}}) \); Summation current, \( i_{\text{sum}} = (i_{\text{COL}} + i_{\text{GEN}}) \). \( E_{\text{GEN}} = 400 \) mV, \( E_{\text{COL}} = 100 \) mV vs. SCE.
Figure 21

Current (µA)

\[ \text{idiff} \]

\[ \text{icol} \]

\[ \text{isum} \]

\[ \text{igen} \]

\[ t \text{ (sec)} \]

4  8  12  16
Figure 22. Rapid convergence of difference current. Normalized dimensionless current \( (i/i_{n}) \) versus normalized time \( (t/t_{n}) \) for simulated electrolysis at a twin filar electrode. Bottom curves are the collector electrode response, \( i_{\text{COL}} \). Top curves are the inverse of the generator electrode response, \( -i_{\text{GEN}} \). Middle curves are the difference current, \( i_{\text{DIF}} = \frac{1}{2}(i_{\text{COL}} - i_{\text{GEN}}) \).
Summation Current. In contrast to this difference current, the summation current for a chronoamperometric experiment at a twin filar electrode (see Figure 21) produces a transient with quite different behavior. As with the difference current, an examination of the cofacial twin electrode model provides insight into the behavior of the sum of the collector and generator currents. An expression for the summation current using the equations which converge rapidly at short times may be represented as (20):

\[ i_{\text{SUM}} = i_{\text{COL}} + i_{\text{GEN}} \]  

\[ = \frac{nFAD_{C}(x,0)}{(\pi Dt)^{\frac{1}{2}}} \left[ 1 + 2 \sum_{k=1}^{\infty} (-1)^{k} \exp(-k^{2}l^{2}/(4Dt)) \right] \]  

At short times, the infinite series expansion term conditionally converges to a value of one-half, and the summation current becomes:

\[ i_{\text{SUM}} \approx \frac{nFAD_{C}(x,0)}{(\pi Dt)^{\frac{1}{2}}} [ 1 + 2 (\frac{1}{2}) ] \]  

\[ = \frac{nF(2A)DC_{C}(x,0)}{(\pi Dt)^{\frac{1}{2}}} \]  

which has a \( t^{-\frac{1}{2}} \) dependence, analogous to the Cottrell equation describing one-dimensional diffusion to a planar macroscopic electrode (13). A plot of the summation current of Figure 21 as a function of \( t^{-\frac{1}{2}} \) yielded a straight line (\( r=0.996 \)) with a slope of 6.66 \( \mu \text{A/s}^{\frac{1}{2}} \). This value agrees with the computed value of 6.82 \( \mu \text{A/s}^{\frac{1}{2}} \), where the projected geometric areas of the two working electrodes was used for the area term.
The predominance of normal (z-axis) diffusion in the summation current can be explained as follows. When a potential step is applied to the generator electrode, the analyte is instantaneously electrolyzed at the surface. As the products diffuse to adjacent collector electrode filaments, they are detected and reconverted to the starting compound. Both electrodes establish well defined radial diffusion profiles. Assuming that the diffusion coefficients of the oxidized and reduced form of the analyte redox couple are nearly equal, the flux resulting from these radial profiles is similar in magnitude but opposite in sign. Upon summation, these equivalent radial components effectively cancel, leaving an essentially one-dimensional (z-axis) diffusion condition which gives rise to the Cottrellian behavior.

The rates at which each of the currents in Figure 21 approach steady-state are consistent with the rates predicted by equations 58, 59 and 72. The times required to reach steady-state to within 5% were 4, 12, and 12 seconds for the difference, collector and generator respectively.

Noise Analysis

The signal-to-noise ratios in the four current transients of Figure 21 are not identical. Expressions for the currents, including noise components, can be presented in a simple form as:
\[
i_{\text{COL}} = i_{\text{SIG,COL}} + i_{\text{R,N.,COL}} \tag{77}
\]
\[
-i_{\text{GEN}} = i_{\text{SIG,GEN}} + i_{\text{R,N.,GEN}} \tag{78}
\]

where \( i_{\text{R,N.}} \) is the random noise current, and \( i_{\text{SIG}} \) is the analytical current of interest. The relative standard deviations of the currents in Figure 21 are 1.4, 2.2, 1.8 and 4.5\% for the collector, generator, difference and summation currents respectively. Computation of the difference current effectively averages the random noise of the collector and generator electrodes. The summation current, on the other hand, has a random noise error which is larger than the sum of the two current noises. Although the collector current has the smallest random error, the difference current is a valuable alternative for the analytical signal of choice because of the more rapid attainment of steady-state with only a slightly larger random noise error.

One consequence of the difference-current analysis for potential-step data is the possibility of removing correlated noise from the current transients. Correlated noise at a twin filar electrode may be defined as a noise component of the current of one electrode which is directly related to a noise component of the current at the other electrode. Correlated noise has been observed at twin intercommunicating electrodes in at least two forms.

We have identified correlated noise at twin filar electrodes with events which occur simultaneously at the generator and collector electrodes. When these noise events
occur at or near steady-state, they may be removed readily using a simple self-correction algorithm. Figure 23-A illustrates deviations from the predicted chronoamperometric behavior for a twin filar electrode (W = 100 μm) which occurred in the same time intervals and which were of the same magnitude for both transients. A convective pulse swept products of electrolysis of the generator electrode to the adjacent collector electrode filaments, momentarily enhancing the steady-state collector current. At the same time, this convective pulse brought an equivalent amount of fresh reactant to the generator electrode from adjacent collector electrodes, which momentarily enhanced the steady-state generator current by the same magnitude.

To remove this noise, it must first be identified and quantitated. Equations 77 and 78 may be modified to reflect the presence of correlated noise:

\[
\begin{align*}
    i_{\text{COL}} &= i_{\text{SIG,\text{COL}}} \pm i_{\text{R.N.,\text{COL}}} + i_{\text{C.N.,\text{COL}}} \\
    -i_{\text{GEN}} &= i_{\text{SIG,\text{GEN}}} \pm i_{\text{R.N.,\text{GEN}}} + i_{\text{C.N.,\text{GEN}}} 
\end{align*}
\]

(79)

(80)

where \( i_{\text{C.N.}} \) is the correlated noise current. When the difference current is computed, the correlated noise is reinforced:

\[
\begin{align*}
    i_{\text{COL}} - i_{\text{GEN}} &= (i_{\text{SIG,\text{COL}}} + i_{\text{SIG,\text{GEN}}}) \pm i_{\text{R.N.,\text{COL}}} + i_{\text{R.N.,\text{GEN}}} \\
    &\quad + (i_{\text{C.N.,\text{COL}}} + i_{\text{C.N.,\text{GEN}}}) 
\end{align*}
\]

(81)

Assuming the collector and generator currents approach the same steady-state value, \( i_{ss} \), and ignoring the random noise
Figure 23. Correlated noise analysis. A) 'Raw' chronoamperometric current transients for the diffusion-limited electrolysis of 0.4958 mM BHMF at a twin filar electrode (W=100 μm, l_s=51 μm). E_{GEN}=400 mV, E_{COL}=100 mV vs. SCE. Upper curve: Inverse of the generator electrode current, -i_{GEN}; Lower curve: Collector electrode response, i_{COL}. B) The correlated noise function, (\frac{1}{2}(i_{COL} - i_{GEN}) - i_s). C) Corrected current transients. Upper curve: -(i_{GEN} + i_{NOISE}); Lower curve: i_{COL} - i_{NOISE}. 
Figure 23

A. Raw Currents (µA)

B. Noise Current (µA)

C. Corrected Currents (µA)

Time (seconds)
currents, when the correlated noise is equivalent in each transient, equation 81 becomes:

\[ i_{COL} - i_{GEN} = 2i_{ss} + 2i_{C.N.} \]  

(82)

The correlated noise function, \( i_{NOISE} \), is then defined as:

\[ i_{NOISE} = \tfrac{1}{4}(i_{COL} - i_{GEN}) - i_{ss} \]  

(83)

Figure 23-B illustrates this noise function as any deviation from the zero-current line. This correlated noise was then subtracted from the raw collector current transient, and added to the raw generator current transient, to produce the correlated-noise corrected curves in Figure 23-C. This method of correction was successful in removing correlated noise which occurred at or near steady-state, because the noise event simultaneously affected both current transients by approximately the same magnitude.

When a perturbation occurs exclusively at the generator electrode, the response is propagated through the solution by diffusion and observed at the collector electrode. Engstrom and coworkers have studied this "diffusional distortion in the monitoring of dynamic events" at macroelectrodes using a microelectrode probe (26). By monitoring the current at the collector electrode a known distance away from the perturbation source, the excitation event (an unwanted noise signal) is determined. The generator current is then corrected through convolution techniques for a given impulse response function, which is dependent upon the diffusional geometry. Engstrom et. al. have shown that the diffusional
collection process is functionally equivalent to an electronic low-pass filter, as high frequency components are attenuated. The effective time constant for this "diffusional filter" increases with the distance between the source of the perturbation and the sensing element. This distance dependence on the magnitude of the diffusively propagated signal to a collector was first observed by Sluyters for a cofacial twin electrode (55).

**Twin Electrode Cyclic Voltammetry**

Recently, several groups have used interdigitated electrodes in a cyclic voltammetric experiment where the potential of the collector electrode was held at a fixed value, while the potential of the generator electrode was scanned through the region of interest (11,12,14,19,23). For such generation/collection cyclic voltammetric (G/C-CV) experiments, steady-state voltammograms are observed by monitoring the collector current as a function of the generator electrode potential. In order for steady-state voltammograms to be observed at modest scan rates (10 mV/s), narrow electrodes which are very closely spaced ($W \approx 1-5 \mu m$) must be constructed using fabrication technologies which are inaccessible to most analytical laboratories. Electrodes of larger spacings ($W \approx 50-200 \mu m$) have been routinely constructed on the benchtop. The unique nature of the mass transport behavior of intercommunicating filar electrodes may
be used to enhance the utility of these larger electrodes for such G/C-CV experiments.

Figure 24 illustrates G/C-CV experiments for a twin filar electrode (W=100 μm) at three different scan rates. At fast scan rates, on the order of several hundred millivolts per second, little of the electrogenerated product has time to diffuse the necessary 50-100 μm to the collector electrode (Figure 24-A). Conventional peak-shaped voltammograms are observed at the generator electrode due to the fact that diffusion layers of adjacent filaments do not overlap, and mass transport is approximately cylindrical (2,10,56). At scan rates on the order of several tens of millivolts per second (Figure 24-C), species produced at the generator electrode have adequate time to diffuse to adjacent collector electrodes where they are detected and recycled. The shape of both the generator and collector electrode voltammograms is sigmoidal, indicating virtually steady-state diffusion conditions. At intermediate scan rates (Figure 24-B), voltammograms at the generator electrode show evidence of diffusional feedback from the collector electrode, but do not reach the steady-state, and both voltammograms show substantial hysteresis. When twin electrodes with spacings larger or smaller than 100 μm are used (11) the response to varying scan rates is similar, though there will be quantitative differences in the rates resulting in the three classes of response shown in Figure 24.
Figure 24. Generation/collection cyclic voltammograms. The curves represent electrolysis of BHMF (0.6746 mM) at a twin filar electrode ($W=100 \, \mu m$, $L=380 \, \mu m$). Scan rates [mV/s]: A) 348; B) 116; C) 5.8. Upper traces: Collector electrode voltammograms ($E_{COL} = 0 \, mV$ vs. SCE); Lower traces: Generator electrode voltammograms.
Figure 24

$E_{\text{GEN}}$ (mV vs. SCE)
When the G/C-CV experiment is performed in a thin-layer cell, steady-state is achieved more rapidly, and the collection efficiency (defined as $|i_{\text{COL}} / i_{\text{GEN}}| \times 100\%$) is increased. The cap of the cell (D in Figure 3-1) is a reflecting barrier which confines the product of the generator electrode reaction to the immediate vicinity of the electrodes, enhancing collection of the product. In addition, it creates a finite diffusion condition which limits the flux of reactant normal to the generator electrode surface.

If a reflecting barrier is placed a distance, $l_z=W$ from the electrode plane, collection efficiencies of 70-90% are observed, and steady-state currents are achieved in a time comparable to $W^2/D$. This is illustrated in Table 1. At slow scan rates and small values of $l_z$, collection efficiencies approach 90%; while at rapid scan rates, there is little difference among the collection efficiencies for the four geometries, all of which are below $\approx20\%$. At rapid scan rates, there is insufficient time for the diffusion layers to reach either the adjacent electrode, or the reflecting barrier before the scan is reversed.

**Difference Voltammogram.** Hysteresis-free steady-state voltammograms may be obtained for larger values of $W$, and at higher scan rates, by computing the algebraic difference between the collector and generator voltammograms in a G/C-CV experiment. Recall that taking the algebraic difference of the two currents tends to reinforce the x-axis components of
Table 1. Collection efficiencies at the switching potential for generation/collection cyclic voltammetry

<table>
<thead>
<tr>
<th>Collection efficiencies (%)</th>
<th>( {l_z} / W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan rate (mV/s)</td>
<td>0.51</td>
</tr>
<tr>
<td>5.8</td>
<td>86.2</td>
</tr>
<tr>
<td>11.6</td>
<td>86.5</td>
</tr>
<tr>
<td>23.2</td>
<td>82.0</td>
</tr>
<tr>
<td>58.0</td>
<td>66.1</td>
</tr>
<tr>
<td>116.0</td>
<td>39.9</td>
</tr>
<tr>
<td>232.0</td>
<td>22.6</td>
</tr>
<tr>
<td>348.0</td>
<td>14.7</td>
</tr>
</tbody>
</table>

^ For electrolysis of 0.675 mM BHMF in pH 7.0 phosphate buffer; \( E_{\text{COL}} = 0 \) V vs. SCE; switching potential at 510 mV vs SCE. ^b The scan rates for the open solution geometry were 12.0, 24.1, 48.2, 120.5, and 241.0 mV/s.
both, and tends to cancel a portion of the z-axis flux, causing the difference to behave as though the mean distance between filaments had been halved. Figure 25 verifies our hypothesis for twin filar electrodes, in experiments where the difference voltammograms are observed for BHMF at three different scan rates. Notice that hysteresis in the difference voltammogram is much less than in either the collector or generator voltammogram alone. Of course, this hysteresis diminishes for all three voltammograms as the scan rate is decreased. At scan rates on the order of 10 mV/s, the difference voltammograms at 100 μm electrode separations are virtually free of hysteresis (Figure 25-C). Nernst analysis of this difference voltammogram, plotting the generator electrode potential as a function of \( \ln((i_{lim} - i)/i) \), is shown in Figure 26. The log plot is linear \((r=0.998)\) with a slope of 0.0259 \((T=26.2 \degree C)\). The intercept of the line, 260 mV versus SCE, is identical with the \( E_0 \) for BHMF determined from cyclic voltammetry at a macroscopic gold disc electrode under identical conditions. To obtain comparably small hysteresis in a steady-state voltammogram at a single disc electrode of a diameter equivalent to the width of one band of the twin filar electrode \((50 \mu m)\), the required scan rate would be 25 mV/s, an experiment which would last 11 hours \((61)! \)

**Summation Voltammogram.** The algebraic sum of the collector and generator currents in Figure 24 produces an
Figure 25. Difference voltammograms for the data presented in Figure 24, \((i_{\text{COL}} - i_{\text{GEN}})\). Scan rates [mV/s]: A) 348; B) 116; C) 5.8.
Figure 25

Current

$E_{\text{GEN}}$ (mV vs. SCE)

500 300 100 0

A.

B.

C.

$5 \mu A$
Figure 26. Nernst analysis of the difference voltammogram of Figure 25C.
Figure 26

\[ E_{\text{GEN}} \text{ (mV vs. SCE)} \]

\[ \ln \left( \frac{i_{\text{lim}} - i}{i} \right) \]
analytical signal with quite different properties. Such a summation voltammogram resembles an ordinary peak-shaped cyclic voltammogram (Figure 27). This shape reflects a diffusion process dominated by one-dimensional (z-axis) diffusion. At slow scan rates, the radial diffusion component experienced by the collector electrode is similar in magnitude, yet opposite in sign to the radial diffusion at the generator electrode. Upon summation, these two components effectively cancel to provide a voltammogram due primarily to the normal diffusion occurring at the generator electrode.

The degree of cancellation of these radial components is a function of the scan rate and the cell geometry. Heinze used digital simulation methods to examine the effects of radial diffusion at microelectrodes and their influence on the peak potential separation ($\Delta E_p$) in cyclic voltammetric experiments for nernstian redox couples (36). Large deviations from the expected $\Delta E_p$ value of 59 mV/n (at 25°C) are observed for cases which experience substantial radial diffusion.

Figure 28 is a plot of $\Delta E_p$ of the summation voltammogram as a function of scan rate for four different cell geometries at a W=100 μm twin filar electrode. At low scan rates, $\Delta E_p$ for all cases approaches the theoretical "linear diffusion only" value of 59 mV/n. Identical steady-state radial diffusion profiles are established at both electrodes, so that the radial current components cancel upon summation. The open
Figure 27. Summation voltammogram. Data points represent electrolysis of 0.6746 mM BHMF at a twin filar electrode (W=100 μm) in an open solution. The solid line is the theoretical response expected for one-dimensional diffusion to a planar macroscopic electrode. $E_{\text{Col}} = 0$ mV vs. SCE. Current is normalized to the peak current value. Scan rate: 7 mV/s.
Figure 27
Figure 28. Effect of radial mass transport on peak separation in summation voltammograms. Values of $\Delta E_p (\text{mV})$ of the summation voltammograms are plotted as a function of scan rate for electrolysis of 0.6746 mM BHMF at a twin filar electrode ($W=100 \ \mu m$).
Figure 28: Scan Rate (mV/s) vs. $\Delta E_p$ (mV), for $i_{sum}$

- $\ell_z/W = 0.51$
- $\ell_z/W = 1.27$
- $\ell_z/W = 3.80$
- Open Solution

Scan Rate (mV/s) vs. $\Delta E_p$ (mV) for different values of $\ell_z/W$.
solution geometry illustrates that the $\Delta E_p$ value is virtually scan rate independent, and nearly equal to the theoretical "linear-diffusion only" value. The semi-infinite linear diffusion condition provided by the open solution geometry also enables identical radial diffusion profiles to be established at both electrodes, which again virtually cancel upon summation.

At very rapid scan rates, the collector electrode current is negligible so that the summation voltammogram results only from current at the generator electrode, which experiences predominantly cylindrical diffusion. At slow scan rates of about 10 mV/s, the shape of the summation voltammogram can be described as due to one-dimensional (z-axis) diffusion as shown in Figure 27, where experimental data for the forward scan of the voltammogram of BHMF is compared to the theoretical current function for diffusion to a planar macroscopic electrode (48).

At sufficiently slow scan rates, the summation voltammogram yields a macroelectrode response indicative of the cell geometry. Digital simulations techniques were employed to examine the summation voltammogram behavior as a function of the dimensionless geometric factor, $l_z/W$. Figure 29 shows the dimensionless summation currents for the forward scan, normalized to the peak current for several values of $l_z/W$. For very thin solution layers, the summation current yields a response indicative of restricted one-dimensional
Figure 29. Simulated summation voltammograms. Dimensionless current is normalized to the peak current value for each scan. The solid line is the theoretical response expected for one-dimensional diffusion to a planar macroscopic electrode.
Figure 29

Normalized Current

$E_{GEN}$ (Volts)

$\frac{L_z}{W}$

- Over 2.0
- 1.25
- 0.5
- 0.25
diffusion to a planar macroscopic electrode where the half-wave potential of the redox couple occurs at the current peak. As the thickness of the solution layer becomes larger, the forward scan response approaches a limit predicted for semi-infinite linear diffusion, where the half-wave potential is now at a value where the current equals 85% of the current peak (48).

Summary

Because currents measured at independently potentiostated, intercommunicating electrodes contain different information, the separation of two analytical signals from one another, or signals from background and noise currents has been realized experimentally. In particular, by computing the difference and summation of the collector and generator currents, the measured currents have been separated into components which reflect predominantly x-axis (radial) and z-axis (normal) diffusion. The difference current converges to a steady-state value four times more rapidly than either collector or generator current alone, as predicted by theory. Appropriate manipulation of the currents enables the correction of current transients for correlated noise which occur at or near steady-state.

As a consequence of this method of data manipulation, difference voltammograms constructed from G/C-CV experiments produce hysteresis-free steady-state voltammograms for larger
values of $W$, and at higher scan rates. In contrast, the summation voltammogram reflects a process dominated by normal (z-axis) diffusion, producing a conventional macroscopic electrode cyclic voltammogram. This particular analysis method enhances the utility of filar electrodes by decreasing their steady-state response time, and is applicable to open solution, as well as thin-layer geometries.
Part III: Investigation of the Information Content of Filar Electrodes

An increase in the information content of an electrochemical technique is possible by employing a sensor constructed of multiple, intercommunicating electrodes. The properties of intercommunicating electrodes can be understood by first examining the analytical strategies of electroanalysis employing a single macroscopic working electrode. In order to determine the concentration of an analyte, for example, a potential program is applied to the working electrode and the current is measured. This current is directly related to the bulk concentration of the analyte in solution. Chronoamperometry, for example, consists of applying a potential-step excitation to the working electrode. The measured current for diffusion-limited electrolysis is represented as:

\[ i = nFAD^kC/(\pi t)^k + i_{\text{charging}} + i_{\text{background}} \]  

where \( i_{\text{charging}} = \Delta E_{\text{step}}/R_s \exp (-t/(R_sC_{dl})) \) and \( i_{\text{background}} \) is current due to the electrolysis of non-analyte species, such as solvent.

Because charging currents are present at electrodes undergoing potential change, the current must be sampled at
a time after the potential step which is sufficient to allow the charging current to decay to an acceptable minimum value. The faradaic current, however, also decays with time, and a late current sampling time can drastically reduce the sensitivity of the technique. Finally, background currents are often present in the signal, requiring a second experiment on the supporting electrolyte alone, which is used to correct the analytical signal by background subtraction.

Twin filar electrodes have inherently different response compared to single electrodes. In a twin electrode chronoamperometric experiment, for example, the potential of one electrode (the generator) is stepped to a value where the analyte is electrolyzed, while the potential of the other electrode (the collector) is maintained near minimum background. When a filar electrode is placed in a thin-layer cell, the currents measured at the electrodes approach true steady-state values in times comparable to $W^2/D$. By using the steady-state collector current as the analytical signal, signal-to-noise (S/N) behavior may be improved because the current is measured at a fixed-potential electrode where charging current is absent.

The signal-to-background (S/B) ratio also may be enhanced, because the collector current is measured at a potential of minimum background electrolysis. Thus, the current measured at the collector electrode is only due to the faradaic electrolysis of the analyte. Finally, the
steady-state nature of the current can be exploited to increase the S/N ratio by signal averaging, removing small amplitude random current noises from the signal.

Multichannel Twin Filar Electrode Chronoamperometry

Potential-dependent information can be obtained using twin filar electrodes by performing a generation/collection cyclic voltammetric (G/C-CV) experiment. As illustrated previously, steady-state voltammograms are observed for G/C-CV experiments at twin filar electrodes, however only at slow scan rates (≈5 mV/s for W=100 μm). These slow scan rates can result in a lengthy analysis time. Potential-step experiments at filar electrodes, on the other hand, achieve steady-state rapidly, so that experiments last only a few seconds. A device consisting of several twin filar electrodes could be used to determine simultaneously the potential-dependent steady-state currents which are observed for a G/C-CV experiment. Such a multichannel electrochemical experiment is analogous to the multiple wavelength detection techniques in spectroscopy using polychromators to isolate several narrow wavelength regions, which are subsequently imaged onto an array of detectors.

This multiple electrode strategy was investigated for a single analyte species to obtain a steady-state voltammogram. In this experiment, ten filar electrode pairs were chosen as a compromise between requisite potential resolution,
photolithographic complexity, and potentiostatic restrictions. The potential of the ten generator electrodes of this 10x10 electrode were set at approximately equal intervals across the region of interest. The potential of the ten collector electrodes were set at a value for minimum background electrolysis, and of a sufficient magnitude to electrolyze the products of the generator electrode at a diffusion-limited rate.

The multichannel experiment may be represented mathematically as a form analogous to equation 68. The steady-state current at collector electrode $j$ is expressed as:

$$-i_{COL} = \sum_{p=1}^{10} r_{j,p} i_{GEN}^p$$  \hfill (85)

Assuming collector $j$ only detects species produced at generator $j$, the $r$ coefficient of all other terms becomes 0. The simultaneous multichannel experiment is then portrayed mathematically as:

$$i_{GEN}^1 + 0 + 0 + \ldots + 0 + 0 = -i_{COL}^1$$
$$0 + i_{GEN}^2 + 0 + \ldots + 0 + 0 = -i_{COL}^2$$
$$0 + 0 + i_{GEN}^3 + \ldots + 0 + 0 = -i_{COL}^3$$
$$\vdots$$
$$0 + 0 + 0 + \ldots + i_{GEN}^{10} = -i_{COL}^{10}$$  \hfill (86)

In matrix notation, this system of equations is represented as:

$$\begin{bmatrix}
  i_{GEN}^1 \\ i_{GEN}^2 \\ i_{GEN}^3 \\ \vdots \\ i_{GEN}^{10}
\end{bmatrix} \begin{bmatrix}
  1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  \vdots \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
  i_{COL}^1 \\ i_{COL}^2 \\ \vdots \\ i_{COL}^{10}
\end{bmatrix} = \begin{bmatrix}
  0 \\ 0 \\ 0 \\ \vdots \\ 0
\end{bmatrix}$$  \hfill (87)
The solution to this system of equations is a trivial one:

\[ i_{\text{GEN}} I = -i_{\text{COL}} \]  

This system of equations describes just one example of many other multiple electrode experiments where the matrix of coefficients takes on different values, depending upon the type of electrodes used.

Although background subtraction was not necessary, a preliminary experiment was required to determine the relative electroactivity of each twin electrode pair, as well as to correct for the edge effect experienced at the electrodes on the extreme edges of the array. This preliminary experiment was performed using the analyte with the potential of all generator electrodes set to the same diffusion-limited value. The steady-state collector currents were then recorded and normalized to a value between 0 and 1, where 0 indicated that the electrode was inactive and 1 indicated that the electrode was the most active of all ten. These normalization constants were used to correct subsequent multipotential data by multiplying the corresponding steady-state collector current by the appropriate value.

A steady-state collector voltammogram, representative of the 10x10 multichannel experiments, is illustrated in Figure 30-C for the electrolysis of BHMF at a 10x10 electrode (W=50 \( \mu \text{m} \), \( l_z=51 \mu \text{m} \)). The solid line represents the best least-squares fit to the data, yielding a half-wave potential of 327
Figure 30. 10x10 multichannel steady-state voltammogram. Data represents electrolysis of 0.4633 mM BHMF at a 10x10 electrode (W=50 μm, lₐ=51 μm).
A) Collector electrode transient current responses;
B) Generator electrode potential excitation (potential of all collector electrodes held at 49 mV vs. SCE); C) Steady-state collector electrode voltammogram.
Figure 30
mV vs. SCE, which agrees with the value determined by cyclic voltammetry at a macroscopic gold disc electrode under identical conditions. Only seven of the ten electrodes were active for this experiment due to alignment constraints of the connection clamps with the contact pads of the electrode, and two broken filaments which occurred during electrode fabrication. The order of assignment of the potentials slightly affected the appearance of the voltammogram, shifting the half-wave potential by up to a few mV from the expected value. The best results were obtained when adjacent electrodes were poised at successively larger values of potential.

Multiplex Chronoamperometry

The primary disadvantage of this multiple electrode strategy is the necessity of using a potentiostat which is capable of controlling the potentials and measuring the currents at multiple electrodes. This drawback can be overcome by employing a multiple electrode strategy which measures the current at only one electrode, so that only a single electrode potentiostat is required. Consider a 10x1 electrode which is an array of independent generator electrodes, all interdigitated with a common collector electrode. The common collector electrode is capable of collecting nearly all species produced by the 10 generator electrodes, particularly for thin layers of solution.
However, a potential penalty for employing this common collector electrode strategy is the possibility of observing crosstalk between adjacent generator electrodes. In order to establish an expression for the steady-state collector electrode current, crosstalk between adjacent generator electrodes must be examined.

Crosstalk between adjacent generator electrodes of the 10x1 electrode array was investigated using digital simulation techniques by holding the potential of a generator electrode in the interior of the array (such as electrode 6) at a diffusion-limited value for oxidation of the analyte. The potential of the collector electrode and the other nine generator electrodes was then held at a diffusion-limited value for reduction. Table 2 illustrates this crosstalk effect at a 10x1 electrode as steady-state collection efficiencies for species produced at electrode 6.

For $l_c/W = 1.25$, for example, the adjacent generator electrodes (5 and 7 in this case) each collected about 4.4% of the total steady-state current produced at electrode 6 (see Table 2). Electrodes further removed from this generator electrode collected less than 0.1% of the steady-state generator signal. Most of the product of electrolysis at electrode 6 is collected by filaments of the common counter electrode which are immediately adjacent to each generator electrode. For thin layers of solution, $l_c/W < 2.0$, crosstalk between adjacent generator electrodes is less than 5% and can
Table 2. Simulated steady-state crosstalk collection efficiencies at a 10x1 electrode as a function of $l_z/W$ for species generated at electrode 6.

<table>
<thead>
<tr>
<th>$l_z/W$</th>
<th>Collector</th>
<th>5 or 7</th>
<th>4 or 8</th>
<th>3 or 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>99.75</td>
<td>0.14</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.50</td>
<td>97.33</td>
<td>1.34</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1.00</td>
<td>92.24</td>
<td>3.85</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>1.25</td>
<td>91.09</td>
<td>4.39</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>2.00</td>
<td>89.65</td>
<td>4.99</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td>3.00</td>
<td>88.25</td>
<td>5.32</td>
<td>0.48</td>
<td>0.06</td>
</tr>
</tbody>
</table>
be neglected under most circumstances. Crosstalk between adjacent generator electrodes may be made arbitrarily small, however, by increasing the distance of separation between adjacent generators.

Figure 31 is a steady-state concentration profile contour plot of a hypothetical oxidized species being generated at electrode 6 of a 10x1 electrode with \( \frac{l_o}{W} = 1.25 \). The z-axis has been expanded by a factor of 15 to illustrate the confinement of the redox species to an area immediately surrounding the sixth generator electrode. Assuming that only directly adjacent electrodes contribute to the steady-state current, an expression for the steady-state collector electrode current of a 10x1 electrode may be written as:

\[
i_{ss}^0 = \sum_{p=1}^{10} \tau_{op} \frac{nFADC}{(k_{op}W)} = \sum_{p=1}^{10} \tau_{op} i_{ss}^p
\]  

(90)

For thin layers of solution, model calculations predict the \( \tau_{op} \) collection efficiencies approach unity, and that the collector electrode detects virtually the entire current from each generator electrode.

From this understanding of generation/collection voltammetry, one can envision performing an electrochemical experiment which is equivalent to the Hadamard-transform multiplex method used in spectroscopic analysis, where combinations of signals at many wavelengths are measured at a single detector. The spectrum from such a "common collector" experiment is reconstructed from a system of
Figure 31. Simulated steady-state concentration profile. The contour plots represent the steady-state concentration distribution of a hypothetical reduced species produced at generator electrode 6 of a 10x1 electrode. The potential of generator electrode 6 is held at a diffusion-limited value for oxidation while the potential of all other generator electrodes and the collector electrode is held at a diffusion-limited value for reduction. $l_e/W=1.25$. The z-axis has been expanded 15 times for clarity.
Figure 31
linearly independent equations, each representing a different combination of wavelengths which were observed. By analogy, the multiplex electrochemical experiment consists of measuring the steady-state collector current for N linearly independent combinations of N active generator electrodes. The electrochemical "spectrum" is then recovered by solving the corresponding system of linearly independent equations.

Other multiplex analysis techniques are possible with this multiple electrode experiment when coupled with a spectroscopic technique such as UV-Visible absorption spectroscopy or mass spectrometry. Under these circumstances, the spectrometer acts as the single "collection" detector which perhaps operates downstream from the electrolysis events. Modulation of the potential program applied to the array of electrodes can result in an observable effect on the detection signal. In addition, the qualitative nature of the spectroscopic detector could be used to identify the products of electrolysis.

These single channel detection methods should produce a multiplex advantage, since the signal-to-noise (S/N) ratio should be higher because each generator electrode current is sampled by the collector several times. The system of equations describing the multiplex electrochemical experiment at steady-state in its simplest form at a 10x1 electrode may be represented analogous to equation 86 as:
where only one generator electrode is active for any given trial. In matrix notation, this system of equations may be represented as:

\[
\begin{bmatrix}
  i_{\text{GEN}}^1 \\
i_{\text{GEN}}^2 \\
i_{\text{GEN}}^3 \\
\vdots \\
i_{\text{GEN}}^{10}
\end{bmatrix}
= \begin{bmatrix}
  0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  \vdots \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  -i_{\text{COL}}^1 \\
i_{\text{COL}}^2 \\
i_{\text{COL}}^3 \\
\vdots \\
i_{\text{COL}}^{10}
\end{bmatrix}
= \begin{bmatrix}
  0 \\
  -i_{\text{COL}}^3 \\
  \vdots \\
  -i_{\text{COL}}^{10}
\end{bmatrix}
\]

and now describes 10 separate experiments. The solution to this system of equations is again:

\[i_{\text{GEN}} = -i_{\text{COL}} I^{-1} = -i_{\text{COL}}\] (94)

An experiment of this type offers no advantage over a simple twin electrode method of sequential potential-step trials, or the 10x10 electrode multichannel method. By performing each experiment with a linearly-independent combination of active generator electrodes, each generator current is measured more than once. This measurement frequency can be maximized to 9 (N-1 in general) times by performing each trial using all but one generator electrode as active to provide a throughput advantage. This strategy is mathematically represented as:

\[
\begin{bmatrix}
  i_{\text{GEN}}^1 \\
i_{\text{GEN}}^2 \\
i_{\text{GEN}}^3 \\
\vdots \\
i_{\text{GEN}}^{10}
\end{bmatrix}
= \begin{bmatrix}
  0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
  1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
  1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\vdots \\
  1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  -i_{\text{COL}}^1 \\
i_{\text{COL}}^2 \\
i_{\text{COL}}^3 \\
\vdots \\
i_{\text{COL}}^{10}
\end{bmatrix}
= \begin{bmatrix}
  0 \\
  -i_{\text{COL}}^3 \\
  \vdots \\
  -i_{\text{COL}}^{10}
\end{bmatrix}
\] (95)
\[ i_{\text{GEN}} M = -i_{\text{COL}} \]  

The solution to which is:

\[ i_{\text{GEN}} = -i_{\text{COL}} M^{-1} \]  

As a simple example, consider a system of three generator electrodes interdigitated with a common collector electrode. The system of equations describing this multiplex experiment would be:

\[
\begin{align*}
i_{\text{GEN}}^1 + i_{\text{GEN}}^2 + i_{\text{COL}}^1 &= -i_{\text{COL}}^1 \quad \text{experiment 1} \\
i_{\text{GEN}}^1 + i_{\text{GEN}}^3 + i_{\text{COL}}^2 &= -i_{\text{COL}}^2 \quad \text{experiment 2} \\
i_{\text{GEN}}^2 + i_{\text{GEN}}^3 + i_{\text{COL}}^3 &= -i_{\text{COL}}^3 \quad \text{experiment 3}
\end{align*}
\]  

The solution to this system of equations is:

\[
\begin{align*}
i_{\text{GEN}}^1 &= \frac{1}{2} (i_{\text{COL}}^1 + i_{\text{COL}}^2 - i_{\text{COL}}^3) \\
i_{\text{GEN}}^2 &= \frac{1}{2} (i_{\text{COL}}^1 - i_{\text{COL}}^2 + i_{\text{COL}}^3) \\
i_{\text{GEN}}^3 &= \frac{1}{2} (-i_{\text{COL}}^1 + i_{\text{COL}}^2 + i_{\text{COL}}^3)
\end{align*}
\]  

Thus, three experiments could be performed to measure three (N in general) collector currents which sampled each generator current twice (N-1 times), increasing the signal-to-noise ratio by \(\sqrt{2/(N-1)}\) for the determination of the generator electrode current.

This multiplex experiment was modelled using digital simulation techniques for a 10x1 electrode having an \(I_z/W\) value of 1.25. The electrochemical "spectrum" (the steady-state generator currents) was determined by the method of gaussian-elimination, followed by correction of the generator currents 1 and 10 for predicted edge effects. A Nernst analysis of the steady-state generator currents yielded a straight line \((r=0.981)\) having a y-intercept which agreed with the model half-wave potential of 120 mV.
The ability to construct a steady-state voltammogram using a 10x1 electrode was examined first by directly measuring the generator currents for a single experiment where each generator electrode was active, and held at a unique potential. Figure 32-C illustrates a voltammogram, representative of the 10x1 multichannel experiments, which was constructed by plotting the steady-state generator currents as a function of the applied potentials for the electrolysis of ferrocene. As for the 10x10 electrode, an additional experiment was necessary to determine the relative electroactivity of the generator electrodes for normalization purposes. A third experiment was also required, however, to correct for background electrolysis, as currents were measured at electrodes held at potentials capable of producing substantial background signals. Nernst analysis of the area-normalized background-corrected voltammogram yielded a half-wave potential of 121 mV vs. Ag/Ag⁺, compared to 118 mV as determined by cyclic voltammetry at a macroscopic gold disc electrode under identical conditions.

The multiplex electrochemical technique was performed with a 10x1 electrode where the potentials of the generator electrodes were controlled by the multiple electrode potentiostat. The potential of the collector electrode was maintained at a value of minimum background. All but one of the generator electrodes were connected for each trial of the experiment. Values for the steady-state generator currents
Figure 32. 10x1 multichannel steady-state voltammogram. Data represents electrolysis of 1.096 mM ferrocene at a 10x1 electrode ($W=40 \ \mu m$, $l_z=127 \ \mu m$). A) Generator electrode potential excitation (potential of collector electrode held at -90 mV vs. Ag/Ag'); B) Background-corrected generator electrode current response; C) Steady-state generator electrode voltammogram.
Figure 32
were computed from the system of equations describing the experiment.

While spectroscopic methods commonly exhibit excellent reproducibility (i.e., the UV spectrum of a chromophore looks the same each time an analysis is performed), electrochemical methods at solid electrodes involve inherently heterogeneous processes, and are thus limited by the nature of the history of the electrode surface. The most severe limitation of gold filar electrodes is the inability to reproducibly regenerate the activity of an electrode after each experiment. This is particularly severe for the multiplex method which involves up to 30 successive trials (3 trials for each of the 10 different generator electrode combinations). Filar electrodes are too delicate for the majority of techniques used to regenerate electrode surfaces, including in-situ electrochemical activation methods (49). The best method used to date involved sonicating the electrode in an industrial solvent stripper. This procedure was rather inconvenient for the 30 trials of the multiplex electrochemical experiment, regardless of the precision necessary in aligning the Teflon gasket with the electrode Superstrate to expose the same region of the filaments for each trial.

In addition, the measurement of a spectroscopic signal at one wavelength usually has no effect upon the signal at another wavelength. Figure 33 is a histogram of the steady-state generator currents of the 18 trials performed for the
Figure 33. Multiplex electrochemical histogram. Data points represent the absolute value of the steady-state generator electrode currents for the electrolysis of 0.5039 mM BHMF at six electrodes of a 10x1 electrode (W = 40 \mu m, \ell = 51 \mu m) used in each of 18 trials. \( E_{\text{COL}} = 0 \) mV vs. SCE. Currents for experiment M are those calculated from the system of independent equations describing the multiplex experiment. Three trials were performed for each set of active generator electrodes. Electrode and potential (mV vs. SCE) legend:

- (O): electrode 8, 410;
- (#): electrode 7, 370;
- (V): electrode 6, 310;
- (X): electrode 5, 250;
- (□): electrode 3, 200;
- (+): electrode 1, 450.
Figure 33

Steady-State Generator Current (μA)

Experiment

M 10 13 16 19 22 25 28 31 34

0.00 0.05 0.10 0.15 0.20 0.25

□ □ □ □ □ □ □ □ □ □

□ □ □ □ □ □ □ □ □ □

□ □ □ □ □ □ □ □ □ □

□ □ □ □ □ □ □ □ □ □

□ □ □ □ □ □ □ □ □ □
multiplex electrochemical experiment using the multiple electrode potentiostat for potential control and current measurement. Trials 4-6 indicate that the current at electrode 6 was enhanced when electrode 7 was open-circuited. The current at electrode 5 was also enhanced when electrode 6 was open-circuited during trials 7-9. Even electrode 3 evidenced an increase in the current for trials 10-12 when electrode 5, at least 240 \( \mu \text{m} \) distant, was open circuited.

Clearly, a substantial crosstalk effect much greater than predicted by simulation techniques was responsible for the observed enhancement of the steady-state generator currents. The effect of gradual passivation of the electrode surfaces is also evident as a slight negative slope in the histogram of Figure 33 (electrode 8, for example), which illustrates the gradual reduction of electroactivity. For the multiplex electrochemical technique to work properly, crosstalk effects should be absent and each electrode should maintain the same activity for each trial.

The last trial in Figure 33 represents the computed steady-state generator currents as determined from the matrix of steady-state collector currents used to evaluate the system of simultaneous equations describing the multiplex experiment. Several of the computed currents are in relatively large error. A significant improvement in the multiplex electrochemical experiment might be observed by diffusonally isolating each generator electrode from adjacent generators.
In this manner, disconnection of an individual electrode should not influence the currents observed at any other generator electrode. In addition, however, a convenient method of reproducibly regenerating the activity of each electrode between trials will also be crucial to the success of such multiplex methods.

Summary

The information content of an electroanalytical technique has been increased by employing an electrode consisting of many independent filaments. By using just two intercommunicating electrodes, the twin electrode advantages were realized. An array of potential-independent filaments increases the information content of an electroanalytical method much as a polychromator system does in multiwavelength spectrochemical analysis. For example, a steady-state voltammogram was obtained from a multichannel chronoamperometric experiment performed at a 10x10 electrode. Such a multichannel electroanalytical technique, although requiring a potentiostat capable of controlling many electrodes, may be useful for such methods as a multipotential sensor for high-performance liquid chromatography.

By employing a 10x1 electrode, the electrochemical analogy to a Hadamard-transform multiplex spectroscopic technique was performed. Unfortunately, the predicted multiplex advantages were not realized for this method because
of the poor between-run reproducibility in electroactivity of the electrodes. For this reason, and because crosstalk between adjacent generator filaments was severe, results of poor quality were obtained.
CONCLUSION

The analytical utility of interdigitated electrodes of 10 μm bandwidths and greater has been extended using a data analysis method which takes advantage of the unique mass transport properties of intercommunicating electrodes. This analysis scheme is particularly valuable for these "larger" microelectrodes, as electrode fabrication techniques adapted from the microelectronics industry can be performed readily on the benchtop, so that electrode fabrication remains an active part of the analytical protocol.

As currents at intercommunicating electrodes contain different information, these currents, or linear combinations of these currents may be used to separate analytical signals from one another, or signals from background and noise currents. In particular, these currents can be separated into components which reflect predominantly x-axis (radial) diffusion, and z-axis (normal) diffusion, by observing the difference or summation respectively of the collector and generator currents. A four-fold increase in the rate of achievement of steady-state is observed by monitoring the difference current, thus enhancing the response time of the electrode. By performing the experiment in a thin-layer cell,
the response time is further reduced, and larger, true steady-state currents are observed by enhanced diffusional feedback between the adjacent electrode filaments.

The behavior of the filar electrode in a thin-layer cell can be modelled conveniently using standard digital simulation techniques. For very thin solution layers, the behavior can be approximated by semi-empirical expressions derived from analytic equations which describe the behavior of an equivalent cofacial twin electrode.

By employing an electrode geometry consisting of many independent intercommunicating electrodes, it is possible to increase the information content of an electroanalytical technique by performing several experiments simultaneously. Steady-state voltammograms, for example, can be constructed from chronoamperometric data of a single experiment obtained by simultaneously monitoring the current at electrodes which are poised at different potentials across the region of interest. Such multichannel methods, analogous to multichannel spectroscopic techniques, are capable of obtaining the electrochemical "spectrum" in a matter of a few seconds.

In addition to the multichannel method, the electrochemical analog of the Hadamard-transform multiplex spectroscopic technique may be performed. One detector simultaneously measures the signal of several channels for this method at a device constructed of many independent
electrodes in communication with one common collector element. The poor between-run reproducibility observed at these solid electrodes, however, prevents the realization of the multiplex advantages predicted for such a technique.
APPENDIX A

Mask-Generator Program Listing
5 REM this program creates a photolithographic mask for the
6 HP 7475 plotter
7 REM written by mike harrington, 6-1989
8 KEY OFF
9 OPEN "com2:9600 S,7,1,RS,CS65535,DS,CD" AS #1
11 GOSUB 9000
12 LOCATE 16,1:PRINT " Change option P)lot electrode E)xit program"
13 PRINT
14 INPUT " Enter letter for option ",CH$15 IF CH$-"E" OR CH$-"e" THEN SYSTEM
16 IF CH$-"C" OR CH$-"c" THEN GOSUB 2000:GOTO 30
17 IF CH$-"P" OR CH$-"p" THEN GOSUB 1000:GOTO 30
18 PRINT CHR$(7);"INVALID OPTION ... Please reenter option":GOSUB 10000 . - G O T O 114
19 REM this section is used to plot the microelectrode mask
20 PRINT #1, "IN;SP",PENNO:1,";VS",VELOCITY,
21 Y-YINIT: YMIN-YINIT
22 FOR I  - 1  TO 20
23 PRINT #1, "PU;PA500,",Y,";PD;PA9000,",Y,";PU;"
24 Y - Y + DELTAY
25 PRINT #1, "PA10000,",Y ,";PD; PA1500,",Y ,";PU; 
26 Y - Y + DELTAY
27 NEXT I
28 PRINT #1, "PA500,",Y,";PD;PA9000,",Y,";PU;"
29 YMAX - Y
30 PRINT #1, "PA500,",YMIN",";PD;PA1000,";YMIN",";500",";YMAX",";500",";YMIN",";PU;PA9500"," 
31 YMIN+DELTAY",";PD"
32 PRINT #1, "PA10000,";YMIN+DELTAY",";1000",";YMAX-DELTAY",";9500",";YMIN+DELTAY",";PU;"
33 PRINT #1, "PA500,";YMIN",";RA10000,";YMAX",";PU;PA9500"," 
34 YMIN+DELTAY",";RA10000",";YMAX-DELTAY","; 
35 RETURN
36 GOSUB 9000:LOCATE 16,1 . - P R I N T  " 
37 PRINT "Initial y coordinate: ";YINIT
38 INPUT "Enter new initial y coordinate: ",YINIT
39 YINIT - ABS(INT(YINIT))
40 IF YINIT >7000 THEN YINIT-1000: PRINT CHR$(7);" Value too large, reset to default":GOSUB 10000
41 IF YINIT = 0 THEN YINIT = 1000:PRINT CHR$(7);" Value cannot be 0, reset to default":GOSUB 10000
42 RETURN
43 GOTO 2000
44 GOSUB 11000:LOCATE 16,1:PRINT " 
45 PRINT "Step size: ";DELTAY
46 INPUT "Enter new step size: ",DELTAY
47 DELTAY - ABS(INT(DELTAY))
48 IF DELTAY < 4 THEN DELTAY = 4:PRINT CHR$(7);" Value too small, reset to default":GOSUB 10000
49 IF DELTAY > 100 THEN DELTAY=100:PRINT CHR$(7);" Value too large, reset to 100":GOSUB 10000
50 RETURN
51 GOSUB 11000:LOCATE 16,1:PRINT " 
52 PRINT
5010 PRINT "Pen velocity: "; VELOCITY
5020 INPUT "Enter new pen velocity: ", VELOCITY
5030 VELOCITY = ABS(VELOCITY)
5035 IF VELOCITY = 0 THEN VELOCITY = 5: PRINT CHR$(7); "Value too small, reset to default": GOSUB 10000
5036 IF VELOCITY > 128 THEN VELOCITY = 128: PRINT CHR$(7); "Value too large, reset to 128 cm/sec": GOSUB 10000
5040 RETURN
6000 GOSUB 11000: LOCATE 16, 1: PRINT " "; PRINT
6010 PRINT "Pen number: "; PENNO
6020 INPUT "Enter new pen number <1-6>: ", PENNO
6030 PENNO = ABS(INT(PENNO))
6040 IF PENNO < 1 OR PENNO > 6 THEN PENNO = 1: PRINT CHR$(7); "Value out of range, reset to default": GOSUB 10000
6050 RETURN
7000 GOSUB 11000: LOCATE 16, 1: PRINT " "; PRINT
7010 PRINT "NUMBER OF GENERATOR FILAMENTS: "; FILAMENTS
7020 INPUT "Enter new number of generator filaments: ", FILAMENTS
7030 FILAMENTS = ABS(INT(FILAMENTS))
7040 IF FILAMENTS = 0 THEN FILAMENTS = 1: PRINT CHR$(7); "Number of filaments set to 1": GOSUB 10000
7045 IF FILAMENTS > 200 THEN FILAMENTS = 200: PRINT CHR$(7); "Too many filaments, reset to 200": GOSUB 10000
7050 RETURN
9000 CLS
9035 PRINT " SIMPLE CAD-CAM FOR FILAR MICROELECTRODES"
9036 PRINT " requires an HP 7475 plotter"
9040 PRINT: PRINT: PRINT: PRINT: PRINT
9050 PRINT " OPTIONS:  Defaults
9060 PRINT: PRINT
9070 PRINT " 1. Initial y coordinate <1000> "; YINIT
9080 PRINT " 2. Step size in 25 μm units <24> "; DELTAY
9090 PRINT " 3. Pen velocity in cm/sec <5> "; VELOCITY
9100 PRINT " 4. Pen number <1> "; PENNO
9115 PRINT " 5. Number of generator filaments <20> "; FILAMENTS
9120 RETURN
10000 FOR I = 1 TO 2000: NEXT I: RETURN
11000 LOCATE 16, 1: FOR I = 1 TO 6: PRINT " "; NEXT I: RETURN
19999 END
APPENDIX B
Multiple Electrode Potentiostat Channel Address Assignments
### Table 3. Multiple Electrode Potentiostat Channel Address Assignments

<table>
<thead>
<tr>
<th>Component Side</th>
<th>Pin</th>
<th>Signal</th>
<th>Assignment</th>
<th>Solder Side</th>
<th>Pin</th>
<th>Signal</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>+15 volts</td>
<td></td>
<td>1</td>
<td>6</td>
<td>+15 volts</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>-15 volts</td>
<td></td>
<td>2</td>
<td>7</td>
<td>-15 volts</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>+5 volts</td>
<td></td>
<td>3</td>
<td>8</td>
<td>+5 volts</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>GND</td>
<td></td>
<td>4</td>
<td>9</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>5</td>
<td>GND</td>
<td></td>
<td>5</td>
<td>10</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>Channel 15</td>
<td>Ei 1</td>
<td>6</td>
<td>11</td>
<td>Channel 14</td>
<td>Eoff 6</td>
</tr>
<tr>
<td>G</td>
<td>7</td>
<td>Ei 6</td>
<td></td>
<td>7</td>
<td>12</td>
<td>Eoff 5</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>8</td>
<td>Ei 4</td>
<td></td>
<td>8</td>
<td>13</td>
<td>Eoff 4</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>9</td>
<td>Ei 3</td>
<td></td>
<td>9</td>
<td>14</td>
<td>Eoff 3</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>10</td>
<td>Ei 2</td>
<td></td>
<td>10</td>
<td>15</td>
<td>Eoff 2</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>11</td>
<td>Ei 1</td>
<td></td>
<td>11</td>
<td>16</td>
<td>Eoff 1</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>12</td>
<td>Ei 0</td>
<td></td>
<td>12</td>
<td>17</td>
<td>Eoff 0</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>13</td>
<td>Eout</td>
<td></td>
<td>13</td>
<td>18</td>
<td>Eout</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>14</td>
<td>Ei 7</td>
<td></td>
<td>14</td>
<td>19</td>
<td>Eoff*</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>15</td>
<td>Ei 8</td>
<td></td>
<td>15</td>
<td>20</td>
<td>Eoff 7</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>16</td>
<td>Ei 9</td>
<td></td>
<td>16</td>
<td>21</td>
<td>Eoff 8</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>17</td>
<td>Ei 10</td>
<td></td>
<td>17</td>
<td>22</td>
<td>Eoff 9</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>18</td>
<td>Eoff</td>
<td></td>
<td>18</td>
<td>23</td>
<td>Eoff 10</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>19</td>
<td>Eoff</td>
<td></td>
<td>19</td>
<td>24</td>
<td>Eoff</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>20</td>
<td>Eoff</td>
<td></td>
<td>20</td>
<td>25</td>
<td>Eoff</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>21</td>
<td>Eoff</td>
<td></td>
<td>21</td>
<td>26</td>
<td>Eoff</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>22</td>
<td>Eoff</td>
<td></td>
<td>22</td>
<td>27</td>
<td>Eoff</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>23</td>
<td>GND</td>
<td></td>
<td>23</td>
<td>28</td>
<td>GND</td>
<td></td>
</tr>
</tbody>
</table>

*The channel number refers to the address to be requested on the channel selector connector to select the assigned signal at the BNC connector on the front of the Data Acquisition Unit. The Ei signals refer to the output of the respective working electrode amplifier, while Eoff refers to the offset voltage used to offset the working electrode in the respective amplifier. Eoff refers to the potential of the reference electrode. Eout* is the output signal in real time, i.e., it does not pass through a sample and hold circuit. All other signals are latched by their respective sample and holds whenever a channel other than zero is selected. Eoff 0 always reads ground.
APPENDIX C

Multiple Electrode Potentiostat Data Acquisition and Control
Source Code Listings
Figure 34. Schematic of code modules for the multiple electrode potentiostat data acquisition and control software.
(*** Main Program: MULTI. This program drives the multiple electrode potentiostat for steady-state potential step experiments measuring up to eleven independent currents. ***)

PROGRAM MULTI (input,output);
($N+$)

USES crt,
{$U c:\mike\multi\common.tpu} common,
{$U c:\mike\multi\gets.tpu} gets,
{$U c:\mike\multi\parms.tpu} parms,
{$U c:\mike\multi\filestuf.tpu} filestuf,
{$U c:\mike\multi\hpprint.tpu} hpprint,
{$U c:\mike\multi\genplot.tpu} genplot,
{$U c:\mike\multi\prntstuf.tpu} prntstuf,
{$U c:\mike\multi\dirstuf.tpu} dirstuf;
(L c:\mike\multi\getcurr.obj)

VAR done : boolean;

PROCEDURE SETATOD (channel, gain : integer);
begin
  port [atodcontrol] := 128 + gain; (disable autoincr., add 128)
  port atodchannel := channel;
end; (SETATOD)

PROCEDURE GETOFFSET (channel : integer; VAR data : integer);
VAR low, high : byte;
begin
  port [portb] := channel; (Select the Multiestat channel)
  port [atodstart] := 0; (Start conversion)
  repeat until (port [atodcontrol] and 128) = 128; (completed?)
  port [portb] := 0; (Reset Multiestat channel to zero)
  low := port [atodchannel] and 255;
  high := port [atodstart] and 15;
  data := (256 * high) + low;
  if high > 7 then data := data - 4096; (2's complement)
end; (GETOFFSET)

PROCEDURE GETCURR; external;

PROCEDURE FILEMANAGE;
VAR done : boolean;
begin
  ch := ' '; done := false;
  FILEOP;
  while NOT done do begin
    gotoxy (25,21); ch := readkey;
    repeat
      newy := 0;
      case ch of
        'C'..'c': newy := 5;
        'D'..'d': newy := 7;
        'I'..'i': newy := 9;
        'L'..'l': newy := 11;
        'S'..'s': newy := 13;
        'R'..'r': newy := 15;
        'X'..'x': newy := 17;
      end; (case)
      if newy <> 0 then gotoxy (2,newy) else BEEP (25,21,3);
      ch := readkey;
    until ((ch='/')) AND (newy <> 0));
  case newy of
    5 : FILECHNG;
    7 : begin DIRECTOR; MAINMENU; FILEOP; end;
    9 : FILEINIT;
    11 : FILELIST;
    13 : FILESPE;
15 : FILELOAD;
17 : done := true;
end; {case}
end; {while}
prenw := mainmenuwindow;
currwindow := fileopwindow;
erasewindow (currwindow);
end; {FILEMANAGE}

PROCEDURE ADJUST;
VAR electrode, data : integer;
volts : real;
finished, done : boolean;
beg
ch := ' ' ; finished := false; ADJMENU;
while (NOT finished) do begin
ch := readkey;
repeat
newy := 0;
case ch of
'D','d' : newy := 5;
'X','x' : newy := 7;
end; {case}
if newy < 0 then gotoxy (7,newy) else BEEP (25,11,3);
ch := readkey;
until ((ch = '/') AND (newy < 0));
if newy = 5 then begin
done := false;
while NOT done do begin
clrfullscr;
gotoxy (30,3); write ('Continual offset display');
for i := 0 to 10 do begin
gotoxy (40,i+5); write ('Electrode ',i:2);
end; {for}
gotoxy (30,18);
write ('Enter electrode number then "/"');
x := 62; y := 18; gotoxy (x,y);
GETNUMBER (x,y,electrode,junk,'I');
if (electrode >= 0) AND (electrode <= 10) then
done := true else BEEP (-1,-1,3);
end; {while}
clnscr; gotoxy (30,3);
write ('Continual offset display'); gotoxy (30,10);
write ('Offset for electrode :'); gotoxy (30,20);
write ('Press any key to end');
SETATOD (0,gaincode);
repeat
data := 0; GETOFFSET (ochannel[electrode],data);
volts := ((data * 20 / 4096)/gane)*2;
gotoxy (40,12); write (volts:10:6);
until keypressed;
ch := readkey; (flush the input buffer)
ch := ' ' ; offset[electrode] := volts;
MAINMENU; ADJMENU;
end (then)
else finished := true;
end; {while}
erasewindow (currwindow);
end; {ADJUST}

PROCEDURE DISPLAY;
VAR done : boolean;

PROCEDURE DISP GET DATA;
VAR electrode, data : integer;
volts : real;
beg
clrfullscr; gotoxy (17,10);
write ('Please stand by...Data acquisition in progress');
SETATOD (0, gaincode);

for electrode := 0 to 11 do begin
  data := 0; GETOFFSET (ochannel[electrode].data);
  volts := (data * 20 / 4096) / gain * 2;
  offset[electrode] := volts;
end; { for electrode }
end; { DISP_GET_DATA }

PROCEDURE DISP_SCRN;
VAR electrode : integer;
begin
  DISP_GET_DATA; clsclr;
gotoxy (T2,1); writeln ('** OFFSET TABLE **
  gotoxy (11,4); writeln ('Electrode Offset Activity');
gotoxy (11,3); writeln ('-------- ------- ------');
  for electrode := 0 to 10 do begin
    gotoxy (14,7+electrode); write (electrode: 2);
    gotoxy (22,7+electrode); write (offset[electrode]:8:4);
    gotoxy (34,7+electrode);
    if active[electrode] then write ('Active') else write
      ('Inactive');
  end; { for }
gotoxy (19,19); writeln ('zero = ',offset[ll]:8:4); PAUSE;
end; { DISP_SCRN }

begin (DISPLAY) ch := ' ' ; done := false; DISPMENU;
while (NOT done) do begin
  ch := readkey;
  repeat
    newy := 0;
    case ch of
      'D','d': newy := 5;
      'P','p': newy := 7;
      'X','x': newy := 9;
    end; { case }
    if newy < 0 then gotoxy (2,newy) else BEEP (23,13,3);
    ch := readkey;
  until ((ch='/') AND (newy < 0));
  case newy of
    5: DISP_SCRN; gotoxy (16,21);
      writeln (' ':30); PRNTSCRN; end;
    7: begin DISP_SCRN; gotoxy (25,17);
      write (' ':30); PRNTSCRN; end;
    9: done := true;
  end; { case }
  if NOT done then begin MAINMENU; DISPMENU; end;
end; { while }
  eraseswindow (currwindow);
end; { DISPLAY }

PROCEDURE PARAMENU;
VAR done : boolean;
  electrode : integer;
begin
  ch := ' ' ; done := false; PARAM;
  while (NOT done) do begin
    ch := readkey; gotoxy (25,17);
    repeat
      newy := 0;
      case ch of
        '1': newy := 5;
        '2': newy := 7;
        '3': newy := 9;
        '4': newy := 11;
        'X','x': newy := 13
      end; { case }
      if newy < 0 then gotoxy (2,newy) else BEEP (25,17,3);
      ch := readkey;
    until ((ch='/') AND (newy < 0));
  end; { while }

case newy of
  5 : PARA_ACTI;
  7 : PARA_ITER;
  9 : PARA_INTR;
 11 : PARA_SENS;
end; (case)
end; (while)
erasewindow (currwindow);
end; (PARAMENU)

PROCEDURE RUNEXPT;
VAR done : boolean;

PROCEDURE DOEXPT;
begin
  erasewindow (currwindow);
begin
  SETATOD(0, gaincode); {Channel 0, gain of xl}
  clrfullscr; writeln ('Initializing...please stand by');
  for i := 1 to 100 do for j := 0 to 10 do datu [i,j] := 0;
  sequence := sequence + 1; clrfscr;
  writeln ('Number of iterations set at: ',iterations);
  writeln ('Interval delay word set at: ',interval);
  writeln; write ('Do you wish to change these? ');
  ch := readkey; clrfscr;
  if ((ch='Y') OR (ch='y')) then PARAMENU;
  clrfullscr; BEEP (wherex,wherey,2);
  writeln ('Please turn cell on to activate the experiment');
  GETCURR; BEEP (wherex,wherey,1);
  writeln ('Please turn cell off');
  writeln ('Stand bye please, calculation in progress...');
  for i := 1 to iterations do for j := 1 to 11 do
  if datu[i,j] > 2047 then datu[i,j] := datu[i,j] - 4096;
end; (DOEXPT)

begin
  ch := '•'; done := false; EXPT;
  while (NOT done) do begin
    ch := readkey;
    repeat
      newy := 0;
      case ch of
      'E','e' : newy := 5;
      'P','p' : newy := 7;
      'R','r' : newy := 9;
      'X','x' : newy := 11;
    end; (case)
    if newy <> 0 then gotoxy (2,newy) else BEEP (12,16,3);
    ch := readkey;
    until ((ch=')') AND (newy <> 0));
  case newy of
  5 : begin DOEXPT; MAINMENU; EXPT; end;
  7 : IPLLOT;
  9 : PRINT IT;
 11 : done := true;
end; (case)
end; (while)
erasewindow (currwindow);
end; (RUNEXPT)

PROCEDURE GRAFIKS;
VAR done : boolean;
begin
  ch := '•'; done := false; GRAFMENU;
  while (NOT done) do begin
    gotoxy (25,19); ch := readkey;
    repeat
      newy := 0;
    end; (while)
  end; (case)
end; (GRAFIKS)
case ch of
    '1'  : newy := 5;
    '2'  : newy := 7;
    '3'  : newy := 9;
    '4'  : newy := 11;
    '5'  : newy := 13;
    'X','x'  : newy := 15;
end; (case)
if newy = 0 then gotoxy (2,newy) else BEEP (25,19,3); ch := readkey;
until ((ch='/') AND (newy = 0));
case newy of
    5 : IAVERAGE;
    7 : RAWDATA;
    9 : HYPERFILE;
   11 : TONEHALF;
   13 : NORMALI;
   15 : done := true;
end; (case)
end; (while)
erasewindow (currwindow);
end; (GRAFIKS)

PROCEDURE INITMAIN;
begin
    clrscr; if MONOMODE then colors := monocolours; ch := ' ';
    for i := 0 to 10 do begin
        sensitivity [i] := 3; offset [i] := 0.000;
        active [i] := true;
    end; (for)
    (Configure the 8255... D7 D6 D5 D4 D3 D2 D1 DO)
    (set bits as follows: 1 0 0 1 1 0 0 1)
    (config. mode (MODE 0), port A & C as input, port B as output)
    port [portcontrol1] := $99;
    ochannel[0] := $20; (Define the multiestat channel addresses)
    ochannel[1] := $08; (ochannel = offset channels)
    ochannel[10] := $06;
    ichannel[11] := $10; (This channel is always zero)
    ichannel[0] := $30; (ichannel = current to voltage channels)
    iterations := 10; gane := 1; gaincode := 0; interval := 2000;
    done := false; sequence := 0; INITDISK;
end; (INITMAIN)

begin (MULTI)
    INITMAIN; MAINMENU;
    while (NOT done) do begin
        gotoxy (3,22); ch := readkey;
        repeat
            newy := 0;
            case ch of
                'A','a'  : newy := 5;
                'D','d'  : newy := 7;
                'P','p'  : newy := 9;
                'G','g'  : newy := 11;
                'R','r'  : newy := 13;
                'X','x'  : newy := 15;
            end; (case)
            if newy = 0 then gotoxy (2,newy) else BEEP (23,21,3); ch := readkey;
        end; (repeat)
    end; (while)
end; (MULTI)
until ((ch='/') AND (newy <> 0));
case newy of
  5 : ADJUST;
  7 : DISPLAY;
  9 : FILEMANAGE;
 11 : GRAFIKS;
 13 : PARAMENU;
 15 : RUNEXPT;
 17 : done := true;
end; (case)
end; (while)
crlf
end. (MULTI)
(* * * Unit library member: COMMON. This segment defines all global
variables, structures and initialization data for the main program
MULTI. * * *)

UNIT COMMON;

INTERFACE

USES crt.dos;

CONST maxiter = 100; baseaddress = $710; atodcontrol = $714;
atodchannel = $715; atodstart = $716; timeacq = $717;
timerdata = $718; timercontrol = $719; porta = $71C;
portb = $71D; portc = $71E; portcontrol = $71F;
senses : array [0..7] of real = (1000, 100, 10, 1, 0.1,
10, 1000, 10000);

TYPE realll = array [0..11] of real;
senstype = packed array [0..10] of 0..7;
activetype = packed array [0..10] of boolean;
currents = array [1..maxiter, 0..10] of integer;
newttype = array [1..maxiter] of real;
datatype = string[7];
nametype = string[20];

filerec = record
    fexptname: nametype;
    fsequence: integer;
    foffset: realll;
    fsensitivity: senstype;
    fgane: integer;
    factive: activetype;
    finterval: integer;
    fiterations: integer;
    frawdata: currents;
end; (filerec)

recfile = file of filerec;

(The following windowing information was derived from source
code provided by Borland International)

CharSet = set of char;
AnyString = string[80];
ColorType = (ErrorColor, DateTimeColor, MessageColor,
MenuColor, MenuHiColor, MenuLoColor, DefaultColor);
ColorDef = record
    Fore, Back : byte;
end;
Boxes = (NoBox, ThinBox, ThickBox);
WindowRec = record
    Col, Row : byte;
    Height, Width : byte;
    Color : ColorType;
    Box : Boxes;
end;
ColorList = array[ErrorColor..DefaultColor] of ColorDef;
CONST
ON = True; OFF = False; modeid = C80;
Colors : ColorList = ((Fore : White; Back : red),
(Fore : White; Back : Black),
(Fore : LightCyan; Back : Black),
(Fore : Yellow; Back : Black),
(Fore : Yellow; Back : Black),
(Fore : LightGray; Back : Black),
(Fore : LightGray; Back : Black));
MonoColors : ColorList = ((Fore : White; Back : Black));
VAR
  ch : char;
  i, j, x, y, newx, gane, gaincode : integer;
  interval, iterations : word; datu : currents;
  ichannel, ochannel : array [0..11] of word;
  sensitivity : senstype;
  offset : real; active : activetype;
  datarec : filerec; datafile : reeflie;
  filename : nametype; date : datetype;
  sequence : integer; prevwin, CurWnd : WindowRec;

PROCEDURE DELAYIT;
PROCEDURE BEEP (x, y, tone : integer);
PROCEDURE FRNTSCRN;
PROCEDURE PAUSE;
FUNCTION MONO_MODE : boolean;
PROCEDURE FNAM (VAR filename : datetype);

FullScreenWindow : WindowRec = (Col : 1; Row : 1; Height : 25;
  Width : 80; Color : DefaultColor; Box : NoBox);
MenuWindow : WindowRec = (Col : 1; Row : 2; Height : 12;
  Width : 35; Color : MenuColor; Box : ThickBox);
MessageWindow : WindowRec = (Col : 1; Row : 24; Height : 2;
  Width : 80; Color : DefaultColor; Box : NoBox);
MainMenuWindow : WindowRec = (Col : 1; Row : 1; Height : 23;
  Width : 24; Color : MenuColor; Box : ThickBox);
FileOpWindow : WindowRec = (Col : 25; Row : 1; Height : 23;
  Width : 32; Color : MenuColor; Box : ThickBox);
GrafiksWindow : WindowRec = (Col : 25; Row : 1; Height : 21;
  Width : 40; Color : MenuColor; Box : ThickBox);
AdjustWindow : WindowRec = (Col : 32; Row : 4; Height : 16;
  Width : 24; Color : MenuColor; Box : ThickBox);
DisplayWindow : WindowRec = (Col : 32; Row : 4; Height : 16;
  Width : 24; Color : MenuColor; Box : ThickBox);
ParamWindow : WindowRec = (Col : 25; Row : 1; Height : 20;
  Width : 41; Color : MenuColor; Box : ThickBox);
ExptWindow : WindowRec = (Col : 32; Row : 3; Height : 18;
  Width : 19; Color : MenuColor; Box : ThickBox);
IOErrorWindow : WindowRec = (Col : 1; Row : 24; Height : 1;
  Width : 80; Color : ErrorColor; Box : NoBox);
GetoutWindow : WindowRec = (Col : 25; Row : 6; Height : 12;
  Width : 31; Color : ErrorColor; Box : ThinBox);
PauseWindow : WindowRec = (Col : 58; Row : 14; Height : 10;
  Width : 22; Color : MenuHiColor; Box : ThinBox);
FilenameWindow : WindowRec = (Col : 58; Row : 4; Height : 9;
  Width : 22; Color : DefaultColor; Box : ThinBox);

( Define some important keystrokes: 
  NULL = #0; Bell = #7; BS = #8; LF = #10; CR = #13; ESC = #27;
  ( cursor control keys )
HomeKey = #199; EndKey = #207; UpKey = #200;
Downkey = #208; PgUpKey = #201; PgDnKey = #209;
LeftKey = #203; InsKey = #210; RightKey = #205;
DelKey = #211;
( function keys )
F1 = #187; F6 = #192; F2 = #188; F7 = #193; F3 = #189;
F8 = #194; F4 = #190; F9 = #195; F5 = #191; F10 = #196;
}

VAR
  ch : char;
  i, j, x, y, newx, gane, gaincode : integer;
  interval, iterations : word; datu : currents;
  ichannel, ochannel : array [0..11] of word;
  sensitivity : senstype;
  offset : real; active : activetype;
  datarec : filerec; datafile : reeflie;
  filename : nametype; date : datetype;
  sequence : integer; prevwin, CurWnd : WindowRec;
PROCEDURE JUMPOUT (Retcode : byte);
PROCEDURE IOERROR (ioerr : byte; iostring : string);
PROCEDURE EXPT;
PROCEDURE PARAM;
PROCEDURE GRM SUBMENU;
PROCEDURE DISP MENU;
PROCEDURE ADJ MENU;
PROCEDURE FILEOP;
PROCEDURE MAINMENU;
PROCEDURE CLRFULLSCR;
PROCEDURE ERASE WINDOW (win : windowrec);

IMPLEMENTATION

PROCEDURE DELAY IT;
begin
  delay (interval);
end; {DELAY IT}

PROCEDURE BEEP; {Speaker control}
VAR i : integer;
begin
  sound (1); nosound;
  case tone of
    0 : begin sound (320); delay (500); nosound; end;
    1 : begin sound (440); delay (100); sound (340);
      delay (100); sound (440); delay (100);
      nosound; end;
    2 : begin
      for i := 400 to 600 do
        begin sound (i); delay (1); end;
      nosound; end
    else begin sound (60); delay (500); nosound; end;
  end; {case}
  if x <> -1 then gotoxy (x,y);
end; {BEEP}

PROCEDURE PRNT SCR N;
VAR reg : registers;
begin
  intr (5,reg); {do enough times to catch the latch}
end; {PRNTSCR N}

{The following functions were adapted from source code provided by Borland International}

function IntToString (Num, Width : integer) : AnyString;
var TempString : AnyString;
begin
  Str(Num:Width, TempString); IntToString TempString;
end; {IntToString}

function IntToPadString (Num, Width : integer) : AnyString;
begin
  if Num < 10 then
    IntToPadString := '0' + IntToString (Num, Width)
  else IntToPadString := IntToString (Num, Width);
end; {IntToPadString}

function FixString (FString : AnyString; Len : byte) : AnyString;
var StringLen : byte absolute FString;
begin
  if StringLen > Len then
    Delete(FString, Succ(Len), StringLen - Len)
  else while StringLen < Len do FString := FString + ' ';
  FixString := FString;
end; {FixString}

function CenterString (S : AnyString) : AnyString;
var Counter : byte;
begin
  for Counter := 1 to (80 - Length(S)) DIV 2 do S := ' ' + S;
  CenterString := S;
end; { CenterString }

function MonoMode : boolean;
var
  Reg : Registers; { Registers for BIOS / DOS function calls }
  Ch : char; S : String;
begin
  if ParamCount > 0 then
    S := Copy(ParamStr(1), 1, 1)
  else S := ' ';
  Ch := S[1];
  case UpCase(Ch) of
    'B', 'M': MonoMode := True;
    'C': MonoMode := False;
    else begin
      with Reg do { Call interrupt $10, get current video mode }
      begin
        AH := $0F; { Get video mode function }
        Intr($10, Reg); MonoMode := (Al $03);
      end; { with }
    end; { case }
  end; { MonoMode }
end; { MonoMode }

procedure SetColor(NewColor : ColorType);
begin
  with Colors[NewColor] do
  begin
    TextColor(Fore);
    TextBackground(Back);
  end; { with }
end; { SetColor }

procedure SetWindow(Win : WindowRec);
begin
  with Win do
  begin
    SetColor(Color);
    Window(Col, Row, Pred(Col + Width), Pred(Row + Height));
    GotoXY(1, 1);
  end; { with }
  CurrWindow := Win;
end; { SetWindow }

procedure DrawBox(Win : WindowRec);
type
  BoxRec = record
    UL, UR, LL, LR, Horiz, Vert : char;
  end;
const
  Boxes : array[ThinBox..ThickBox] of BoxRec =
    ((UL : '├'; UR : '┤'; LL : '▖'; LR : '▗' ), { ThinBox }
     (UL : '▏'; UR : '▕'; LL : '▤'; LR : '▣' ), { ThickBox }
     var Counter : byte;
begin
  with Win do
  begin
    SetWindow(FullScreenWindow); SetColor(Color);
    GotoXY(Col, Row); Write(Boxes[Box].UL);
    for Counter := 1 to (Width - 2) do Write(Boxes[Box].Horiz);
    Write(Boxes[Box].UR);
    for Counter := 1 to (Height - 2) do begin
      GotoXY(Col, Row + Counter); Write(Boxes[Box].Vert);
      GotoXY(Pred(Col + Width), WhereY); Write(Boxes[Box].Vert);
    end;
  end;
GotoXY(Col, Pred(Row + Height)); Write(Boxes[Box].LL);
    for Counter := 1 to (Width - 2) do Write(Boxes[Box].Horiz);
    Write(Boxes[Box].LR);
end; { with }
SetWindow(Win);
end; { DrawBox }

procedure ClearWindow(Win : WindowRec);
begin
    with Win do
    begin
        SetColor(DefaultColor); Window(Succ(Col), Succ(Row),
            (Col + Width - 2), (Row + Height - 2));
        GotoXY(1, 1); ClrScr;
    end;
    SetWindow(Win);
end; { ClearWindow }

procedure MakeWindow(Win : WindowRec);
begin
    with Win do
    begin
        SetWindow(Win); ClrScr;
        if Box <> NoBox then DrawBox(Win);
    end; { with }
end; { MakeWindow }

procedure EraseWindow;
begin
    with Win do
    begin
        SetWindow(Win); ClrScr;
        SetColor(DefaultColor); ClrScr; end;
    end; { EraseWindow }

procedure Print(S : AnyString; PColor : ColorType);
begin
    SetColor(PColor); Write(S);
end; { Print }

procedure PrintXY(S : AnyString; PColor : ColorType;
      Col, Row : byte);
begin
    GotoXY(Col, Row); Print(S, PColor);
end; { PrintXY }

procedure PrintMenuStringXY(Pstring : AnyString;
      Col, Row : byte);
var Counter : byte;
begin
    GotoXY(Col, Row); for Counter := 1 to Length(Pstring) do
    begin
        if PString[Counter] in ['A'..'Z'] then
            Print(PString[Counter], MenuHiColor)
        else Print(PString[Counter], MenuLoColor);
    end;
end; { PrintMenuStringXY }

procedure clrfullscr;
begin
    setwindow (fullscreenwindow); clrsce;
end; { clrfullscr }

procedure MainMenu;
begin
    clrfullscr; currwindow := mainmenuwindow;
    makewindow (MainMenuWindow);
    PrintXY ('MULTIESTAT MAIN MENU', MenuHiColor, 3, 2);
    PrintMenuStringXY ('Adjust offsets', 3, 5);
    PrintMenuStringXY ('Display offsets', 3, 7);
procedure FileOp;
begin
  prevwin := currwindow; currwindow := fileopwindow;
  makewindow (FileOpWindow);
  PrintXY ('FILE OPERATIONS MENU',MenuHiColor,6,2);
  PrintMenuStringXY ('Change active file',3,5);
  PrintMenuStringXY ('Directory',3,7);
  PrintMenuStringXY ('Initialize a new file',3,9);
  PrintMenuStringXY ('List entries of active file',3,11);
  PrintMenuStringXY ('Save workarea to active file',3,13);
  PrintMenuStringXY ('Restore entry to workarea',3,15);
  PrintXY ('--------------------'.MenuHiColor,2,19);
  gotoxy (3,23);
end;

procedure Adjmenu;
begin
  prevwin := currwindow; currwindow := adjustwindow;
  makewindow (AdjustWindow);
  PrintXY ('ADJUST OFFSETS MENU',MenuHiColor,3,2);
  PrintMenuStringXY ('Display',9,5);
  PrintMenuStringXY ('exit',9,7);
  gotoxy (3,13);
end;

procedure Dispmenu;
begin
  prevwin := currwindow; currwindow := displaywindow;
  makewindow (DisplayWindow);
  PrintXY ('DISPLAY OFFSETS MENU',MenuHiColor,3,2);
  PrintMenuStringXY ('Display to screen',3,5);
  PrintMenuStringXY ('display to Printer',3,7);
  PrintMenuStringXY ('exit',3,9);
  gotoxy (3,15);
end;

procedure Param;
begin
  prevwin := currwindow; currwindow := paramwindow;
  makewindow (ParamWindow);
  PrintXY ('PARAMETER MENU',MenuHiColor,7,2);
  PrintXY ('1'.MenuHiColor,3,5);
  PrintXY ('Display/Change Active Electrodes',DefaultColor,4,5);
  PrintXY ('2'.MenuHiColor,3,7);
  PrintXY ('Display/Change Iteration Number',DefaultColor,4,7);
  PrintXY ('3'.MenuHiColor,3,9);
  PrintXY ('Display/Change Interval Delay Word',DefaultColor,4,9);
  PrintXY ('4'.MenuHiColor,3,11);
  PrintXY ('Display/Change Sensitivities',DefaultColor,4,11);
  PrintMenuStringXY ('exit',6,13);
end;
procedure Grafmenu;
begin
  prevwin := currwindow; currwindow := grafikswindow;
  makewindow (GrafiksWindow);
  PrintXY ('GRAPHICS MENU',MenuHiColor,7,2);
  PrintXY ('1',MenuHiColor,3,5);
  PrintXY ('> Compute average currents',DefaultColor,4,5);
  PrintXY ('2',MenuHiColor,3,7);
  PrintXY ('> Display raw A/D data',DefaultColor,4,7);
  PrintXY ('3',MenuHiColor,3,9);
  PrintXY ('> Make HYPERPLOT data file',DefaultColor,4,9);
  PrintXY ('4',MenuHiColor,3,11);
  PrintXY ('> Plot current versus time^-1/2',DefaultColor,4,11);
  PrintXY ('5',MenuHiColor,3,13);
  PrintXY ('> Plot normalized currents',DefaultColor,4,13);
  PrintMenuStringXY ('eXit',6,15);
  PrintXY ('---------------',MenuHiColor,2,17);
  PrintXY ('Enter letter then "/"',DefaultColor,3,19);
end;

procedure Expt;
begin
  prevwin := currwindow; currwindow := exptwindow;
  makewindow (ExptWindow);
  PrintXY ('EXPERIMENT MENU',MenuHiColor,3,2);
  PrintMenuStringXY ('Experiment',3,5);
  PrintMenuStringXY ('Plot i vs t',3,7);
  PrintMenuStringXY ('Print data',3,9);
  PrintMenuStringXY ('eXit',3,11);
  PrintXY ('---------------',MenuHiColor,2,13);
  PrintXY ('Enter letter',DefaultColor,3,15);
  PrintXY ('then "/"',DefaultColor,3,16);
end;

procedure Pause;
VAR ch : char; prevwin : windowrec;
begin
  prevwin := currwindow; makewindow (PauseWindow);
  Printxy ('Please press any key',MenuHiColor,2,2);
  Printxy ('to continue . . .',MenuHiColor,2,3);
  BEEP (-1,-1,1); ch := readkey; erasewindow (PauseWindow);
  setwindow (prevwin);
end;

procedure IoError;
VAR prevwin : windowrec;
begin
  prevwin := currwindow; makewindow (IoErrorWindow);
  PrintXY ('I/O Error : ',ErrorColor,2,2);
  write (ioerr:2,', ',iostring); PAUSE;
  erasewindow (IoErrorWindow); setwindow (prevwin);
end;

procedure jumpout;
begin
  makewindow (GetoutWindow);
  PrintXY ('Error Recovery has been',DefaultColor,5,2);
  PrintXY ('unsuccesful',DefaultColor,11,3);
  PrintXY ('Program terminated',ErrorColor,3,5);
  PrintXY ('Contact System’s Programmer',DefaultColor,3,7);
  gotoxy (wherex.wherey); write (Retcode:2);
  Pause; HALT;
end;
procedure FName;
VAR ch : char; prevwin : windowrec;
begin
  repeat
    prevwin := currwindow; makewindow (FilenameWindow);
    PrintXY ('Enter Filename:', DefaultColor, 3, 3);
    gotoxy (3, wherey+2); readln (filename);
    PrintXY ('Filename :', DefaultColor, 3, 5);
    PrintXY (filename, MenuHiColor, 14, 5);
    PrintXY ('Is this correct?', DefaultColor, 3, 7);
    ch := readkey;
    until ((ch = 'Y') OR (ch = 'y'));
    erasewindow (filenamewindow); setwindow (prevwin);
  end;
end.
begin
end. (COMMON)
(*** Library unit GETS. Keyboard I/O facility for MULTI software to
trap keyboard errors. ***)

UNIT GETS;

INTERFACE

USES CRT;
{SU\c:\mike\multi\common.tpu} COMMON;
VAR junkr : real; junki : integer;

PROCEDURE GETNUMBER (VAR wherex, wherey, intgr : integer;
VAR r : real; kind : char);

IMPLEMENTATION

TYPE ptr = 'element;
  element = record
    number : char;
    next : ptr;
  end; (element)

VAR ten : integer; node, top : ptr;
isinteger, dot, negative : boolean;

PROCEDURE push (digit : char);
begin
  new (node); node^ .number := digit;
  node^ .next := top; top := node;
end; (PUSH)

FUNCTION POP : char;
begin
  node := top; pop := node^ .number;
  top := top^ .next; dispose (node);
end; {POP}

PROCEDURE BACKUP (VAR wherex, wherey : integer);
begin
  BEEP (wherex, wherey,0); wherex := wherex - 1;
gotoxy (wherex, wherey); ch := POP;
end; (BACKUP)

FUNCTION TENTOTHE (power : integer) : real;
VAR temp : real;
begin
  temp := 1; for i := 1 to power do temp := temp / 10;
  TENTOTHE := temp;
end; {TENTOTHE}

PROCEDURE GETNUMBER;

PROCEDURE BACKSPACE;
begin
  ch := POP; {get rid of the backspace character}
  ch := POP; {obtain last valid character entered}
  if isinteger then
    case ch of
      '1' : intgr := (intgr - 1) div 10;
      '2' : intgr := (intgr - 2) div 10;
      '3' : intgr := (intgr - 3) div 10;
      '4' : intgr := (intgr - 4) div 10;
      '5' : intgr := (intgr - 5) div 10;
      '6' : intgr := (intgr - 6) div 10;
      '7' : intgr := (intgr - 7) div 10;
      '8' : intgr := (intgr - 8) div 10;
      '9' : intgr := (intgr - 9) div 10;
      '0' : intgr := (intgr - 0) div 10;
      ',', : negative := false;
    end (case)
else (is real)
  if dot then begin
    case ch of
      '1': r := r - TENTOTHE(ten) * 1;
      '2': r := r - TENTOTHE(ten) * 2;
      '3': r := r - TENTOTHE(ten) * 3;
      '4': r := r - TENTOTHE(ten) * 4;
      '5': r := r - TENTOTHE(ten) * 5;
      '6': r := r - TENTOTHE(ten) * 6;
      '7': r := r - TENTOTHE(ten) * 7;
      '8': r := r - TENTOTHE(ten) * 8;
      '9': r := r - TENTOTHE(ten) * 9;
      '0': r := r - TENTOTHE(ten) * 0;
    end;
    ten := ten - 1;
  end (then)
else case ch of
  '1': r := (r - 1) / 10;
  '2': r := (r - 2) / 10;
  '3': r := (r - 3) / 10;
  '4': r := (r - 4) / 10;
  '5': r := (r - 5) / 10;
  '6': r := (r - 6) / 10;
  '7': r := (r - 7) / 10;
  '8': r := (r - 8) / 10;
  '9': r := (r - 9) / 10;
  '0': r := (r - 0) / 10;
end (case)
ten := ten - 1;
end (then)
end (case)
end (case)
gotoxy (wherex-2,wherey);
end (case)
end (case)
begin (GETNUMBER)
top := nil; isinteger := kind = 'I'; r := 0.000; intgr := 0;
ten := 0; wherex := wherex + 1; negative := false;
dot := false; ch := readkey; write (ch); PUSH (ch);
while (ch O '/') do begin
  if ch-chr(8) then if (top*.next O NIL) then BACKSPACE
    else BACKUP (wherex, wherey)
else if isinteger then
  if ((ch >-'0') AND (ch <= '9') OR (ch = '/') OR
      (ch = '.')) then
    case ch of
      '1': intgr := intgr * 10 + 1;
      '2': intgr := intgr * 10 + 2;
      '3': intgr := intgr * 10 + 3;
      '4': intgr := intgr * 10 + 4;
      '5': intgr := intgr * 10 + 5;
      '6': intgr := intgr * 10 + 6;
      '7': intgr := intgr * 10 + 7;
      '8': intgr := intgr * 10 + 8;
      '9': intgr := intgr * 10 + 9;
      '0': intgr := intgr * 10 + 0;
    end (case)
  else BACKUP (wherex, wherey)
else
  if ((ch >-'0') AND (ch<= '9') OR (ch=' '/) OR
      (ch='.')) then if NOT dot then
    case ch of
      '1': r := r * 10 + 1;
      '2': r := r * 10 + 2;
      '3': r := r * 10 + 3;
      '4': r := r * 10 + 4;
      '5': r := r * 10 + 5;
    end (case)
begin
  while keypressed do ch := readkey; (flush the input buffer)
end. (GETS)
UNIT FILESTUF;

INTERFACE

USES crt,
  {SU c:\mike\multi\common.tpu} common,
  {SU c:\mike\multi\gets.tpu} gets;

PROCEDURE INITDISK;
PROCEDURE FILEINIT;
PROCEDURE FILECHNG;
PROCEDURE FILELIST;
PROCEDURE FILESAVE;
PROCEDURE FILELOAD;
PROCEDURE HANDLEERROR (iocode : integer);

IMPLEMENTATION

VAR ok, bad : integer;

PROCEDURE HANDLEERROR;
VAR message : string; severe : boolean;
begin
  message := ' '; severe := true;
  if iocode in [$FF,$02,$03,$F1] then severe := false;
  case iocode of
    $02 : message := 'File not found';
    $03 : message := 'Path not found'
    $04 : message := 'File not open'
    $10 : message := 'Error in numeric format'
    $20 : message := 'Operation not allowed on logical ',
            'device'
    $21 : message := 'Not allowed in direct mode'
    $22 : message := 'Assign to standard files not allowed'
    $90 : message := 'Record length mismatch'
    $91 : message := 'Seek beyond end-of-file'
    $99 : message := 'Dirctory is full'
    $FF : message := 'File size overflow'
    $F3 : message := 'Too many open files'
  else message := 'unknown I/O error'
  end; (case)
  prevwin := fileopwindow; BEEP (10,10,1);
  ioError (iocode,message); if severe then Jumpout (iocode);
end; (HANDLEERROR)

FUNCTION OPENFILE (filename : nametype) : integer;
begin
  repeat
    assign (datafile,filename);
    {$I-} reset (datafile); {$I+}
    bad := ioresult; if bad <> 0 then HANDLEERROR (bad);
    until ((bad = $02) OR (bad = $00));
  end; OPENFILE := bad;
PROCEDURE GETOUT (bad : integer);
begin
  HANDLEERROR (bad); Jumpout (bad);
end; (GETOUT)

PROCEDURE CLOSEFILE;
begin
  repeat
    close(datafile)
  until not open (datafile)
end;
FUNCTION FINDENTRY (seqno : integer) : boolean;
begin
  seek (datafile, seqno);
  bad := iresult; if bad <> $00 then GETOUT (bad);
  if EOF (datafile) then FINDENTRY := false
  else begin FINDENTRY := true; read (datafile, datarec);
  end; (else)
end; (FINDENTRY)

PROCEDURE GETFILENAME (VAR date : datetype);
begin
  prevwin := fileopwindow; fname (date);
end; (GETFILENAME)

PROCEDURE INITDISK;
begin
  prevwin := fileopwindow; filename := 'D:'+date+'.DAT';
  ok := OPENFILE (filename);
  while ((ok<>$00) OR (ok<>$02));
  if ok<>$02 then begin
    assign (datafile, filename);
    rewrite (datafile); bad ioresult; if bad <> $00 then GETOUT (bad);
  end;
end; (INITDISK)

PROCEDURE FILEINIT;
VAR newdate : datetype; newfilename : nametype;
begin
  CLOSEFILE;
  repeat
    GETFILENAME (newdate);
    newfilename := 'D:' + newdate + '.DAT';
    ok := OPENFILE (newfilename);
  until ((ok<>$00) OR (ok<>$02));
  if ok<>$02 then begin
    assign (datafile, newfilename);
    rewrite (datafile); bad ioresult; if bad <> $00 then GETOUT (bad);
    ok := OPENFILE (filename) ;
    if ok<>$00 then GETOUT (ok);
  end; (if)
else begin
  gotoxy (3,21); write ('File '+newfilename+' exists');
  PAUSE; gotoxy (3,21); write ('Enter letter then "/"');
  end; (else)
end; (FILEINIT)

PROCEDURE FILELIST;
VAR ok, more, print : boolean;
begin
  gotoxy (3,21); write ('List to printer? ');
  ch := readkey;
  print ((ch='Y') OR (ch='y'));
  ok := FINDENTRY (i);
  writeln ('Records for file: '+filename);
  if ok = false then writeln ('File is empty.' ) ;
  else begin
    more := false; ok := FINDENTRY (i);
    while ok do begin
      with datarec do
        writeln ('Record '+int(i)+': '); readln(str, n);
      ok := FINDENTRY (i);
    end;
  end; (else)
end; (FILELIST)
writeln (i:2,' > ',fexptname, ' (',fsequence, ')
  iterations: 3, ' iterations');
more := true;
if (((i+1) mod 20) = 0) then begin
  if print then PRNTSCRN;
  PAUSE: clscr; more := false;
end; (if)
i := i + 1; ok := FINDENTRY (1);
end; (while)
writeln ('EOF reached');
if (print AND more) then PRNTSCRN;
end; (FILELIST)

PROCEDURE FILECHNG;
VAR olddate : datetype; oldfilename : nametype;
begin
  oldfilename := filename; olddate := date; CLOSEFILE;
  repeat
    GETFILENAME (date); filename := 'D:+date+.DAT';
    ok := OPENFILE (filename);
  until ((ok=$00) OR (ok=$02));
  if ok = $02 then begin
    ok := OPENFILE (oldfilename);
    if ok = $02 then GETOUT (ok)
    else begin
      filename := oldfilename;
      date := olddate;
      end; (else)
  end; (if)wei
end; (FILECHNG)

PROCEDURE FILELOAD;
VAR ok : boolean; seqno : integer;
begin
  gotoxy (3,21); write ('Which record? <-l-none> '); x := 27; y := 21;
  GETNUMBER (x,y,seqno,junkr,'I');
  if seqno > 0 then begin
    ok := FINDENTRY (seqno);
    if ok then begin
      with datarec do begin
        sequence := fsequence; offset := foffset;
        sensitivity := fsensitivity; game := fgane;
        active := factive; interval := finterval;
        iterations := fiterations; datu := frawdata;
        end; (with)
      gotoxy (3,22); write ('Record ',seqno:3,' loaded');
    end {then}
    else begin
      gotoxy (3,22); write ('Record ',seqno:3,' not found');
    end {else}
  end {then}
  end {FILELOAD}

PROCEDURE FILESAVE;
VAR ok : boolean; seqno : integer; ename : nametype;
begin
  seqno := 0; ok := FINDENTRY (seqno);
  while ok do begin
    seqno := seqno + 1; ok := FINDENTRY (seqno);
end; (while)
with datarec do begin
  gotoxy (3,21); write (' ':29);
gotoxy (3,21); write ('Enter experiment name: ');
gotoxy (3,22); readln (ename); fexptname := ename;
if sequence := sequence; foffset := offset;
sensitivity := sensitivity; fgane := gane;
  factive := active; finterval := interval;
  fiterations := iterations; frawdata := datu;
end; (with)
($1-$) seek (datafile,seqno); {+$}
bad := ioreult; if bad <> $00 then GETOUT (bad);
write (datafile,datarec);
gotoxy (3,21); write (' ':29); gotoxy (3,22);
write ('Workfile saved - position ',seqno:3);
PAUSE; gotoxy (3,22); write (' ':29);
gotoxy (3,21); write ('Enter letter then "/"');
end; {FILESAVE}

begin

end. {FILESTUF}
UNIT PARMS;
INTERFACE
USES crt,
{SU c:\mike\multi\common.tpu} common,
{SU c:\mike\multi\gets.tpu} gets;

PROCEDURE PARA ACTI;
PROCEDURE PARA_ITER;
PROCEDURE PARA_INTR;
PROCEDURE PARA_SENS;

IMPLEMENTATION

PROCEDURE PARA ACTI;
VAR done : boolean;

PROCEDURE P_C.CGAC;
begin
gotoxy (29,21);
write ('Enter electrode number then "/'', ':20);
x := 62; y := 21; gotoxy (x,y); GETNUMBER (x,y,i,junkr,'I');
if ((i>0) AND (i<10)) then begin
gotoxy (31,i+5); write ('>'); gotoxy (29,17);
write ('A)ctivate D)eactivate', ':20); gotoxy (29,18);
write ('';:15); gotoxy (29,17); ch := readkey;
case ch of
  'A','a' : active[i] := true;
  'D','d' : active[i] := false;
  'X','x' : ; (exit only)
end; {case}
end {then}
else BEEP (-1,-1,3);
end; {P_C.CGAC}

begin {PARA ACTI}
ch := ';'; done := false;
while (NOT done) do begin
clrfullscr; gotoxy (32,1); writeln ('Activity Table');
gotoxy (29,3); writeln ('Electrode Factor');
for i := 0 to 10 do begin
  gotoxy (33,5+i); write (i:2); gotoxy (45,5+i);
  if active[i] then writeln ('Active')
  else writeln ('Inactive');
end; {for}
gotoxy (29,17); write ('C)hange', ':30); gotoxy (29,18);
write ('P)rint); gotoxy (29,19); write ('eXit');
gotoxy (29,21);
write ('Enter letter for option then "/'', ':20);
ch := readkey;
repeat
  newy := 0;
case ch of
    'C','c' : newy := 17;
    'P','p' : newy := 18;
    'X','x' : newy := 19;
end; {case}
  if newy <> 0 then gotoxy (27,newy) else BEEP (54,19,3);
  ch := readkey;
until ((ch = '/') AND (newy <> 0));
end {PARA ACTI}

begin
  gotoxy (29,17); write ('';:10); gotoxy(29,18);
  write ('';:10); gotoxy (29,19); write('';:10);
gotoxy (29,21); write (' ':40); PRNTSCRN;
end;
19 : done := true;
end; {case}
end; (while)
MAINMENU; PARAM;
end; {PARA_ACTI)

PROCEDURE PARA_ITER;
begin
repeat
  gotoxy (3,17);
  write ('Number of iterations: ',',iterations:5);
  gotoxy (3,18); write ('C)hange eX)it ?'); ch := readkey;
  if ((ch='C') OR (ch='c')) then begin
    gotoxy (3,18);
    write ('Enter new iteration number then "/" :');
    x := 3; y := 19; gotoxy (x,y);
    GETNUMBER (x, y, junki, junkkr, 'I');
    iterations := junki;
    if (iterations <0) OR (iterations > maxiter) then
      iterations := maxiter;
  end; {if}
  gotoxy (3,18); write (''
  gotoxy (3,19); write (''
  until ((ch='X') OR (ch='x'));
  currwindow := mainmenuwindow; PARAM;
end; {PARA_ITER)

PROCEDURE PARA_INTR;
begin
repeat
  gotoxy (3,17);
  writeln ('Interval number <msec>: ',interval:5);
  gotoxy (3,18); write ('C)hange eX)it ?'); ch := readkey;
  if ((ch='C') OR (ch='c')) then begin
    gotoxy (3,18);
    write ('Enter new interval number then "/" :');
    x := 3; y := 19; gotoxy (x,y);
    GETNUMBER (x, y, junki, junkkr, 'I'); interval := junki;
    if interval <0 then interval := - interval;
    if interval = 0 then interval := 1;
  end; {if}
  gotoxy (3,18); write (''
  gotoxy (3,19); write (''
  until ((ch='X') OR (ch='x'));
  currwindow := mainmenuwindow; PARAM;
end; {PARA_INTR)

PROCEDURE PARA_SENS;
VAR done : boolean;
PROCEDURE P_S_CHNG;
VAR s:integer;
begin
  gotoxy (29,21);
  write ('Enter electrode number then "/" ',':20);
  x := 60; y := 21; gotoxy (x,y);
  GETNUMBER (x,y,i,junkkr,'I');
  if ((i>0) AND (i<10)) then begin
    gotoxy (29,21);
    write ('Enter new sensitivity factor ',then "/" ',':20);
    x := 46; y := 5+1; gotoxy (x,y);
    GETNUMBER (x, y, s, junkkr, 'I');
    if ((s>0) AND (s<7)) then sensitivity[i] := s;
  end [then]
  else BEEP (-1,-1,3);
end; {P_S_CHNG)
begin {PARA_SENS)
ch := ' '; done := false;
while (NOT done) do begin
  clrfullscr; gotoxy (32,1); writeln ('Sensitivity Table');
  gotoxy (29,3); writeln ('Electrode Sensitivity');
  for i := 0 to 10 do begin
    gotoxy (32,5+i); write (i:2); (46.5+i)
    write (sensitivity[i]:1 );
    gotoxy (50,i+5); write ('<')
    case sensitivity[i] of
      0 : write ('I3');
      1 : write ('I4');
      2 : write ('I5');
      3 : write ('I6');
      4 : write ('I7');
      5 : write ('V2');
      6 : write ('V3');
      7 : write ('V4');
    end; (case)
    writeln ('>');
  end; (for)
  gotoxy (29,17); write ('(C)hange',' ':30); gotoxy (29,18);
  write ('(P)rint'); gotoxy (29,19); write ('(eX)it');
  gotoxy (29,21); write ('Enter letter for option then "/"',' ':20);
  ch := readkey;
repeat
  newy := 0;
  case ch of
    'C','c' : newy := 17;
    'P','p' : newy := 18;
    'X','x' : newy := 19;
  end; (case)
  if newy <> 0 then gotoxy (27,newy) else BEEP (62,21,3);
  ch := readkey;
until ((ch = '/') AND (newy < 0));
  case newy of
    17 : P_S_CHNG;
    18 : begin
      gotoxy (29,17); write (' ',':10); gotoxy(29,18);
      write (' ',':10); gotoxy(29,19); write (' ',':10);
      gotoxy (29,21); write (' ',':40); PRNTSCRN;
    end;
    19 : done := true;
  end; (case)
end; (while)
MAINMENU; PARAM;
end; (PARA_SENS)
begin
end. (PARMS)
(* Library unit PRNTSTUF. Data printing facility for the MULTI software system. ***)

UNIT PRNTSTUF;

INTERFACE

USES crt, printer, graph,
(SU c:\mike\multi\hpprint.tpu) hpprint,
(SU c:\mike\multi\genplot.tpu) genplot,
(SU c:\mike\multi\common.tpu) common,
(SU c:\mike\multi\gets.tpu) gets;

PROCEDURE PRINT IT;
PROCEDURE IPLLOT;

IMPLEMENTATION

VAR element : integer; factor : array [0..10] of real;
 s : string;

PROCEDURE PRINT TOP;
begin
 writeln (LST,chr(15)); {condense print}
 writeln (LST,' - * - * - *-',
 * - * - *- 
');
 writeln (LST): writeln (LST,' System: ');
 writeln (LST,'Date: ',date:7,' ':23,'Sequence #: ',
 sequence:3);
 writeln (LST); writeln (LST,iterations:4,' iterations');
 writeln (LST,interval:6,' interval delay word');
 writeln (LST);
end; {PRINT TOP}

PROCEDURE PRINT_LINE (i,j : integer);
begin
 if active[j] then
  write (LST,((datu[i,j]*20/4096)*factor[j])/gane)*2:9:4,
 else write (LST,0.00:9:4,' ');
end; {PRNT_LINE}

PROCEDURE PRINT IT;
VAR printchan : array [0..10] of boolean;
begin
 for i := 0 to 10 do
  factor[i] := senses[sensitivity[element]]; 
 for i := 0 to 10 do begin 
   gotoxy (3,15); write (' '); gotoxy (3,15); 
   ch := readkey; printchan[i] := ((ch='Y') OR (ch='y'));
end;
 gotoxy (3,15); write (' ':13); gotoxy (3,15); 
 write ('Abort print ?'); ch := readkey;
 if NOT ((ch='y') OR (ch='Y')) then begin 
   PRINT TOP: write (LST,' Time':10);
   for i := 0 to 10 do
    if printchan[i] then write (LST,' i(',i:2,')':4);
   writeln (LST);
   for i := 1 to iterations do begin 
    write (LST,(i-1)*interval/1000:9:4,' ');
    if printchan[i] then PRNT_LINE (i,j);
   writeln (LST);
   end;
   writeln (LST,chr(18)); (normal print) writeln (LST); 
 end;
 gotoxy (3,15); write (' ':15); gotoxy (3,15); 
 write (then "/"); gotoxy (3,15); write (chr(18));
begin; {PRINT_IT}

PROCEDURE IPLOT;
begin
  gotoxy (3,15); writeln ('Enter channel'); gotoxy (3,16);
  write ('<-1 to quit>'); x := 3; y := 17; gotoxy (x,y);
  GETNUMBER(x,y,element,junkr,'I*');
  if (element>=0) AND (element<ll) then begin
    number := iterations;
    heading := 'Current versus time : Electrode ';
    str (element,s); heading := heading + s; size := 'L';
    for i := 0 to 10 do
      factor[i] := senses[sensitivity[element]];
    for i := 1 to iterations do begin
      xin [i] := (i-1) * interval / 1000;
      yin [i] := (((datu[i,element] * 20/4096)*
                   factor[element])/gane)*2;
    end;
    GRAPHGEN; MAINMENU;
  end
  else if element > 0 then BEEP (-1,-1,3);
  expt;
end; {IPLOT}
begin {PRINT_STUF}
end; {PRNT_STUF}
unit GENPLOT;

INTERFACE

uses Crt, Graph, {$U c:\mike\multi\hpprint} hpprint;

VAR number : integer; heading : string;
    xin, yin, yin2, yin3 : array [1..1000] of real;

PROCEDURE graphgen;
PROCEDURE graphgen2;

IMPLEMENTATION

(The following code was adapted from source programs provided by Borland International)

CONST

DriverNames : array[0..10] of string[8] -
    ('Detect', 'CGA', 'MCGA', 'EGA', 'EGA64', 'EGAMono',
     'RESERVED', 'HercMono', 'ATT400', 'VGA', 'PC3270');

Fonts : array[0..4] of string[13] -
    ('DefaultFont', 'TriplexFont', 'SmallFont', 'SansSerifFont',
     'GothicFont');

LineStyles : array[0..4] of string[9] -
    ('SolidLn', 'DottedLn', 'CenterLn', 'DashedLn', 'UserBitLn');

FillStyles : array[0..11] of string[14] -
    ('EmptyFill', 'SolidFill', 'LineFill', 'LtSlashFill',
     'SlashFill', 'BkSlashFill', 'LbSlashFill', 'HatchFill',
     'XHatchFill', 'InterleaveFill', 'WideDotFill', 'CloseDotFill');

TextDirect : array[0..1] of string[8] - ('HorizDir', 'VertDir');

    'CenterText', 'RightText');

    'CenterText', 'TopText');

VAR

GraphDriver: integer; GraphMode: integer; MaxX, MaxY : word;
ErrorCode: integer; MaxColor: word; ch : char;
i, xmax, xmin, ymax, ymin : integer;

xinmax, xinmin, yinmax, yinmin : real;
x, y, y2, y3 : array [1..1000] of real;

procedure Initialize;
begin
    DirectVideo := False; GraphDriver := Detect;
    InitGraph(GraphDriver, GraphMode, ''); ErrorCode := GraphResult;
    if ErrorCode <> grOk then begin
        writeln('Graphics error: ', GraphErrorMsg(ErrorCode));
        Halt(1);
    end;
    Randomize; MaxColor := GetMaxColor; MaxX := GetMaxX;
    MaxY := GetMaxY;
end; { Initialize }

function Int2Str(L : LongInt) : string;
var S : string;
begin S := Int2Str : = L; end; { Int2Str }

procedure DefaultColors;
begin SetColor(MaxColor); end; { DefaultColors }

procedure DrawBorder;
var ViewPort : ViewPortType;
begin
    DefaultColors; SetLineStyle(SolidLn, 0, NormWidth);
GetViewSettings(ViewPort);
with ViewPort do Rectangle(0, 0, x2-xl, y2-yl);
end; { DrawBorder }

procedure FullPort;
begin SetViewPort(0, 0, MaxX, MaxY, ClipOn); end; { FullPort }

procedure MainWindow(Header : string);
begin
DefaultColors; ClearDevice;
SetTextStyle(DefaultFont, HorizDir, 1);
SetTextJustify(CenterText, TopText); FullPort;
OutTextXY(MaxX div 2, 2, Header);
SetViewPort(0, TextHeight('M')+4, MaxX,
MaxY-(TextHeight('M')+4), ClipOn);
DrawBorder;
SetViewPort(1, TextHeight('M')+5, MaxX-1,
MaxY-(TextHeight('M')+5), ClipOn);
xmin := 10; ymın := textheight('M')+2;
xmax := 610; ymax := MaxY-(textheight('M')+11+ymin);
end; { MainWindow }

procedure StatusLine(Msg : string);
begln
FullPort; DefaultColors; SetTextStyle(DefaultFont,HorizDir,1)
SetTextJustify(CenterText,TopText);
SetLineStyle(SolidLn,O.NormWidth); SetFillStyle(EmptyFill,0);
SetViewPort(1, TextHeight(' M ')+5, MaxX-1,
MaxY-(TextHeight('M')-2), ClipOn);
end; { StatusLine }

procedure waittogo;
begln
statusline ('Press any key to continue...');
ch := readkey; cleardevice;
end;

procedure grid;
VA R i, tpx, tpy : integer;
begin
line (xmin,ymin,xmin,ymax); line (xmin,ymax,xmax,ymax);
line (xmin,ymax+3,xmin,ymax); line (xmin-4,ymax,xmin,ymax);
for i := 1 to 10 do begin
tpx := xmin + i * ((xmax-xmin) div 10);
line (tpx,ymax+3,txp,ymax);
line (xmin-4,tpy,xmin,tpy);
end;
end;

procedure graphit;
begin
mainwindow (heading); grid;
for i := 1 to number do
putpixel (round((x[i])*(xmax-xmin)+xmin),
ymin+yman-round((y[i])*(ymax-ymin)+ymin),1);
end;

procedure annotate;
VAR xzero, yzero : integer; s, prompt : string;
begin
xzero := round((0-xinmin)/(xinmax-xinmin)*(xam-xmin))+xmin;
yzero := ymın+yman - round((0-yinmin)/(yinmax-yinmin) *
(yman-ymin))+ymin;
statusline ('Plot Y-0 ? <N>'): ch := readkey;
if (ch='Y') OR (ch='y') then line (xmin,yzero,xmax,yzero);
procedure scale0;
begin
  yinmin := +99e33; xinmin := +99e33; yinmax := -99e33;
  xinmax := -99e33;
  for i := 1 to number do begin (move data into work areas)
    x[i] := xin[i]; y[i] := yin[i];
  end;
  for i := 1 to number do begin (locate the max and min)
    if x[i] > xinmax then xinmax := x[i];
    if x[i] < xinmin then xinmin := x[i];
    if y[i] > yinmax then yinmax := y[i];
    if y[i] < yinmin then yinmin := y[i];
  end;
end; (scale0)

procedure zeroes;
begin
  write ('Include X-0? <N>'): ch := readkey;
  if (ch='Y') OR (ch='y') then if xinmax < 0 then xinmax := 0
  else if xinmin > 0 then xinmin := 0;
  write ('Include Y-0? <N>'): ch := readkey;
  if (ch='Y') OR (ch='y') then if yinmax < 0 then yinmax := 0
  else if yinmin > 0 then yinmin := 0;
end; (zeroes)

procedure scale1;
begin
  zeroes;
  for i := 1 to number do begin (scale the work area data)
    y[i] := (y[i] - yinmin)/(yinmax-yinmin);
    x[i] := (x[i] - xinmin)/(xinmax-xinmin);
  end;
end;

procedure scale2;
begin
  for i := 1 to number do begin
    y2[i] := yin2[i]; y3[i] := yin3[i];
  end;
  for i := 1 to number do begin
    if y2[i] > yinmax then yinmax := y2[i];
    if y3[i] > yinmax then yinmax := y3[i];
    if y2[i] < yinmin then yinmin := y2[i];
    if y3[i] < yinmin then yinmin := y3[i];
  end;
  zeroes;
  for i := 1 to number do begin
    y[i] := (y[i] - yinmin)/(yinmax-yinmin);
    y2[i] := (y2[i] - yinmin)/(yinmax-yinmin);
    y3[i] := (y3[i] - yinmin)/(yinmax-yinmin);
    x[i] := (x[i] - xinmin)/(xinmax-xinmin);
  end;
end; (scale2)

procedure graphit2;
begin
mainwindow (heading); grid;
for i := 1 to number do
putpixel (round((x[i])*(xmax-xmin)+xmin),
ymin+ymax-round((y[i])*(ymax-ymin)+ymin),1);
for i := 1 to number do
putpixel (round((x[i])*(xmax-xmin)+xmin),
ymin+ymax-round((y2[i])*(ymax-ymin)+ymin),1);
for i := 1 to number do
putpixel (round((x[i])*(xmax-xmin)+xmin),
ymin+ymax-round((y3[i])*(ymax-ymin)+ymin),1);
end;

procedure graphgen;
begin
initialize; scale0; scale1; graphit; annotate; waittogo;
closegraph;
end; {graphgen}

procedure graphgen2;
begin
initialize; scale0; scale2; graphit; graphit2; annotate;
waittogo; closegraph;
end; {graphgen2}
end. {genplot}
(*** Library unit HPPRINT. Graphics screen dump facility. ***)

UNIT HPPRINT;

INTERFACE

USES printer, Graph;

VAR size : char;

PROCEDURE prntdump;

IMPLEMENTATION

PROCEDURE prntdump;
VAR i, j, k : integer; byteout : word; ch : char;

begin
  setviewport (0,0,GetMaxX,GetMaxY,clipon); writeln (1st);
  writeln (lst,chr(27),'A',chr(8)); {set # dot column height}
  for i := 0 to 24 do begin
    write (lst,chr(27),size,chr(128),chr(2));
    for j := 0 to 639 do begin
      byteout := 0;
      if GETPIXEL (j,i*8+1)<>black then byteout := byteout+128;
      if GETPIXEL (j,i*8+2)<>black then byteout := byteout+64;
      if GETPIXEL (j,i*8+3)<>black then byteout := byteout+32;
      if GETPIXEL (j,i*8+4)<>black then byteout := byteout+16;
      if GETPIXEL (j,i*8+5)<>black then byteout := byteout+8;
      if GETPIXEL (j,i*8+6)<>black then byteout := byteout+4;
      if GETPIXEL (j,i*8+7)<>black then byteout := byteout+2;
      write (lst,chr(byteout));
      end; {for j}
    writeln (lst);
    end; {for i}
  writeln (lst,chr(27),'@');
end;

end. (HPPRINT)
(* Library unit GRAFSTUF. Graphics menu facility for the MULTI software system. *)

UNIT GRAFSTUF;
($N+$)

INTERFACE

USES crt, printer,
[$U c:\mike\multi\common.tpu] common,
[$U c:\mike\multi\gets.tpu] gets,
[$U c:\mike\multi\hpprint.tpu] hpprint,
[$U c:\mike\multi\genplot.tpu] genplot,
[$U c:\mike\multi\filestuf.tpu] filestuf;

PROCEDURE IAVERAGE;
PROCEDURE RAWDATA;
PROCEDURE HYPERFILE;
PROCEDURE TONEHALF;
PROCEDURE NORMALI;

IMPLEMENTATION

PROCEDURE IAVERAGE;
VAR sigma, avg, sum : array [0..10] of extended;
starting, ending, xat, yat : integer;
factor : array [0..10] of real;
begin
  clrfullscr; gotoxy (10,10);
  write ('Enter starting iteration number: ');xat WHEREX; yat WHEREY;
  GETNUMBER (xat, yat, starting, junkr,'I');
  gotoxy (10,12); write ('Enter ending iteration number: ')
  xat :- WHEREX; yat :- WHEREY;
  GETNUMBER (xat, yat, ending, junkr,'I');
  if starting > maxiter then starting := maxiter - 10;
  if starting < 0 then starting := 1;
  if ending > maxiter then ending := maxiter;
  if ending < 0 then ending := maxiter;
  gotoxy (10,16); write ('Average computation in progress.
  Range =',starting:3 ,  to 'ending:3);
  for i  :- 0 to 10 do begin
    avg [i] := 0;  sigma [i] := 0;  sum [i] := 0;
    factor [i] := sensensensitivity[i];end;
    for i  :- 0 to 10 do
      for j  :- 0 to 10 do
        sum [j] := sum [j] + (((datufi.j]*20/4096)*
      factor[j])/gane)*2;
    for i  :- 0 to 10 do
      avg [i] := sum [i] / (ending - starting + 1);
    for i  :- 0 to 10 do begin
      for j  :- 0 to 10 do
        sigma [i] := sigma [i] + sqrr((((datuf[j,i]*20/4096)*factor[i])/gane)*2 - avg[i]);
    sigma [i] := sqrt (sigma [i] / (ending - starting));
  clrfullscr; writeln;
  writeln ('File: ',filename,' ':10,'Sequence: ',sequence:3,
  'Experiment: ',datarec.fexptname);
  writeln;
  writeln (' I', ':8,'AVVERAGE I,uA', 'STD. DEV. ,uA',
  'start', 'ending:3,' end','ending:3);
  writeln (' I', ':8,--------------', '--------------');
  writeln;
  for i  := 0 to 10 do
    write (i:2, ':8,avg[i]:10:5, ':4,sigma[i]:10:5);
  writeln ('************************');
gotoxy (10,20); write ('Print this?'); ch := readkey;
if (ch='y') OR (ch='Y') then begin
  gotoxy (10,20); writeln ('  ':40); PRNTSCRN;
end;
MAINMENU; GRAFMENU;
end; (IAVERAGE)
PROCEDURE RAWDATA;
VAR starting, ending : integer; done : boolean;
begin
  ch := '+'; starting := 1; ending := 20;
repeat
  clrfullscr;
  writeln ('Iteration', ' 0':5, '1':5, '2':5, '3':5, '4':5, '5':5, '6':5, '7':5, '8':5, '9':5, '10':5);
  writeln ('--------', '-', '-', '-', '-', '-', '-', '-', '-', '-', '-':5,
            '-' :5, '-' :5, '-' :5, '-' :5, '-' :5, '-' :5, '-' :5, '-' :5,
            '-' :5);
  for i := starting to ending do begin
    write ('  , i:3,' * ) »for j := 0 to 10 do write (datu[i,j]:4, '  ' ) ;
  writeln;
  end;
  writeln; writeln ('OPTIONS: '+' - forward, '-' - ',
  'backward, 'Q' - ',';
  ch := readkey;
  while NOT (ch in ['O', 'q' ]) do begin
    BEEP (WHEREX, WHEREY, 3); ch := readkey;
  end;
  case ch of
    '+' : begin
      starting := starting + 20;
      ending := ending + 20;
    end;
    '-' : begin
      starting := starting - 20;
      ending := ending - 20;
    end; end; (CASE)
  if (starting >= maxiter) OR (ending >= maxiter) then begin
    starting := maxiter - 19; ending := maxiter;
  end;
  if (starting <= 0) OR (ending <= 0) then begin
    starting := 1; ending := 20;
  end;
  until ((ch='q') OR (ch='Q'));
MAINMENU; GRAFMENU;
end; (RAWDATA)
PROCEDURE HYPERFILE;
VAR hypername : string[8]; hname : string[14]; hfile : text;
  xat, yat, bad, choice : integer;
begin
  gotoxy (3,19); write ('  ':22); gotoxy (3,19);
  write ('Enter filename <8 chars>: ' ) ;
  readln (hypername); hname := 'D:'+hypername+'.HPT';
  assign (hfile,hname); ($1-) rewrite (hfile); ($1+)
  bad := ioresult;
  if NOT (bad in [$00,$02]) then HANDLEERROR (bad);
  repeat
    gotoxy (3,19); write ('  ':36); gotoxy (3,19);
    write ('Enter electrode number <0..10>: ' );
    xat := WHEREX; yat := WHEREY;
    GETNUMBER (xat,yat,choice,junkr,'I');
    if choice < 0 then choice := - choice;
  if choice > 10 then BEEP (WHEREX,WHEREY,3);
until choice <= 10;
for i := 1 to iterations do
  writeln (hfile, (i-1)*interval/1000:6, ',', ((datu[i,choice]*20/4096)*
  senses[sensitivity[choice]]/gane)*2:10:6);
close (hfile); gotoxy (3,19); write (' ':36); gotoxy (3,20);
write ('File ', filename, ' created.'); gotoxy (3,19);
write ('Enter letter then */');
end; (HYPERFILE)

PROCEDURE TONEHALF;
VAR s : string; choice, xat, yat : integer;
begin
  repeat
    gotoxy (3,19); write ( ' ':36); gotoxy (3,19);
    write ('Enter electrode number <0..10>: ' ) ;
    xat := WHEREX; yat := WHEREY;
    GETNUMBER (xat, yat, choice, junkr, 'I' ) ;
    if choice < 0 then choice :- choice;
    if choice > 10 then BEEP (WHEREX,WHEREY,3);
  until choice <= 10;
  for i := 2 to iterations do begin
    xin[i-1] := 1/sqrt((i-1)*interval/1000);
    yin[i-1] := (((datu[i,choice]*20/4096)*
      senses[sensitivity[choice]])/gane)*2;
  end;
number := iterations - 1;
heading := 'Current versus time'-1/2 : Electrode ';
str (choice,s); heading + s; size := 'L';
GRAPHGEN; MAINMENU; GRAFMENU;
end; (TONEHALF)

PROCEDURE NORMALI;
VAR avgavg : real;
begin
  for i := 1 to iterations do begin
    yin2 [i] := 0;
    yin [i] := yin [i] + (((datu[i,0]*20/4096)*
      senses[sensitivity[0]])/gane)*2;
  for j := 1 to 10 do
    yin2 [i] := yin2 [i] + (((datu[i,j]*20/4096)*
      senses[sensitivity[j]])/gane)*2;
  end;
  for i := 1 to iterations do begin
    yin2 [i] := abs(yin2 [i]);
    yin3 [i] := (abs(yin2 [i]) + abs(yin[i]))/2
  end;
  avgavg := 0;
  for i := iterations - 4 to iterations do
    avgavg := avgavg + yin3 [i];
  avgavg := avgavg / 5;
  for i := 1 to iterations do begin
    xin[i] := (i-1)*interval/1000; yin[i] := yin[i] / avgavg;
    yin2[i] := yin2[i]/avgavg; yin3 [i] := yin3 [i] / avgavg;
  end;
  size := 'L'; number := iterations;
  heading := 'Normalized Currents vs. time'; GRAPHGEN2;
clrfullscr; gotoxy (10,10);
write ('Print normalized data <Y,N> ?  ' ) ; ch := readkey;
if (ch = 'Y') OR (ch = 'y') then begin
  writeln (LST,chr(15)); writeln (LST,chr(18)); (normal)
  writeln (LST,' * * *  NORMALIZED D A T A  *',
    ' * * * ') ;
  writeln (LST,' File: '.filename,' Sequence: ',sequence: 3,
      ',Experiment: ',datarec.fexptname);
  writeln (LST,chr(15)); (condense)
  writeln (LST,' time':10,'i(c) ':10,'abs(i(g))':10,
      'i(avg) ':10,'time':10,'i(c)':10,'abs(i(g))':10,
      'i(avg) ':10);
\begin{verbatim}
\begin{verbatim}
i := 1;
while (i <= iterations) do begin
  writeln (LST,xin[i]:9:3,' ',yin[i]:9:4,' ',
           yin2[i]:9:4,' ',yin3[i]:9:4,' ',xin[i+1]:9:3,
           yin[i+1]:9:4,' ',yin2[i+1]:9:4,' ',yin3[i+1]:9:4);
i := i + 2;
end;
wendn (LST,chr(18)); (normal)
end;
MAINMENU; GRAFMENU;
end; (NORMALI)
begin
end. (GRAFSTUF)
\end{verbatim}
\end{verbatim}
(* Library unit DIRSTUF. Disk directory facility for MULTI software system based upon source code provided by Borland International Turbo Pascal Tutor 4.0. *)

{$1-}$

UNIT DIRSTUF;

INTERFACE

USES Crt, Dos;

PROCEDURE DIRECTOR;

IMPLEMENTATION

CONST
    Version = '4.00'; SubDirectory = 16;
    DirRows = 8; DirCols = 5;

type
    CharSet = set of char; AnyString = string[80];
    ColorType = (ErrorColor, CurrDirColor, HelpKeyColor,
        HelpMessageColor, MenuColor, MenuHiColor, MenuLoColor,
        SubDirColor, FileColor, HiSubDirColor, HiFileColor, DefaultColor);
    OpType = (DirOp, LogOp, EscapeOp);
    SelectType = (All, FileOnly, DirOnly, None);
    PromptType = array[DirOp..logOp] of record
        Prompt1, Prompt2 : string[24];
        Search, Select : SelectType;
    end;
    ColorDef = record
        Fore, Back : byte;
    end;
    Boxes = (NoBox, ThinBox, ThickBox);
    WindowRec = record
        Col, Row : byte;
        Height, Width : byte;
        Color : ColorType;
        Box : Boxes;
    end;
    ColorList = array[ErrorColor..DefaultColor] of ColorDef;

CONST
    ON = True; OFF = False:

Colors : ColorList = (
    (Fore : White; Back : Red),
    (Fore : Yellow; Back : Black),
    (Fore : Black; Back : LightGray),
    (Fore : LightGray; Back : Blue),
    (Fore : LightCyan; Back : Black),
    (Fore : Black; Back : Yellow),
    (Fore : Yellow; Back : Black),
    (Fore : Black; Back : LightGray),
    (Fore : LightGray; Back : Black),
    (Fore : Black; Back : Yellow),
    (Fore : Yellow; Back : Black),
    (Fore : Black; Back : LightGray),
    (Fore : LightGray; Back : Black),
    (Fore : Black; Back : Yellow),
    (Fore : Yellow; Back : Black),
    (Fore : Black; Back : LightGray),
    (Fore : LightGray; Back : Black));
MonoColors : ColorList = ( (Fore : White; ( ErrorCode )
Back : Black), (CurrDirColor )
Back : Black), (HelpKeyColor )
Back : LightGray), (HelpMessageColor )
Back : Black),
(Fore : White; (MessageColor )
Back : Black),
(Fore : White; (MenuColor )
Back : Black),
(Fore : White; (MenuHiColor )
Back : Black),
(Fore : LightGray; (MenuLoColor )
Back : Black),
(Fore : White; (SubMenuColor )
Back : Black),
(Fore : LightGray; (HiSubMenuColor )
Back : Black),
(Fore : Black; (HiFileColor )
Back : LightGray),
(Fore : LightGray; ( DefaultColor )
Back : Black));

FullScreenWindow : WindowRec = (Col : 1; Row : 1; Height : 25; Width : 80; Color : DefaultColor; Box : NoBox);
MenuWindow : WindowRec = (Col : 1; Row : 2; Height : 5; Width : 35; Color : MenuColor; Box : ThickBox);
DirWindow : WindowRec = (Col : 1; Row : 14; Height : 10; Width : 80; Color : FileColor; Box : ThickBox);
CurrDirWindow : WindowRec = (Col : 1; Row : 1; Height : 2; Width : 80; Color : CurrDirColor; Box : NoBox);
PromptWindow : WindowRec = (Col : 1; Row : 9; Height : 5; Width : 80; Color : DefaultColor; Box : NoBox);
MessageWindow : WindowRec = (Col : 1; Row : 24; Height : 2; Width : 80; Color : DefaultColor; Box : NoBox);
Prompt : PromptType = ((Prompt1: 'Dir mask: '; Prompt2 : '';
Search : All; Select : None),
(Prompt1 : 'Change drive/directory: ';
Search : DirOnly; Select : DirOnly));
NULL = #0; Bell = #7; BS = #8; LF = #10; CR = #13; ESC = #27;
HomeKey = #199; EndKey = #207; UpKey = #200; DownKey = #208;
PgUpKey = #201; PgDnKey = #209; LeftKey = #203; InsKey = #210;
RightKey = #205; DelKey = #211; F1 = #187; F6 = #192;
F2 = #186; F7 = #193; F3 = #189; F8 = #194; F4 = #190;
F9 = #195; F5 = #191; F10 = #196;

var
CurrOp : OpType; CurrWindow : WindowRec; SR : SearchRec;

(** FILEMGR1. INC and FILEMGR2. INC are include modules for the Library
unit DIRSTUF. Source code available from Turbo Pascal Tutor 4.0,
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{$I c:\mike\multi\filemnu1.inc}
{$I c:\mike\multi\filemnu2.inc}

PROCEDURE InitScreen;
begin
  ChangeCursor(OFF); setwindow (fullscreenwindow); CClrScr;
  if MonoMode then Colors := MonoColors;
  PrintCurrentDir; PrintMenu;
end; ( InitScreen )

PROCEDURE ExecuteOp (Op : OpType);
var File1, File2 : AnyString;
begin ( ExecuteOp )
with Prompt[Op] do begin
  File1 := GetDirFileName(Prompt1, 1, Op);
  if File1 = ESC then Exit;
  if Prompt[Op].Prompt2 <> '"' then
    begin
      File2 := GetFileName(Prompt[Op], Prompt2, 3);
      if (File2 = ESC) or (File2 = ')') then Exit;
    end;
  end; { with }
  case Op of
  DirOp : ;
  LogOp : LogDir(File1);
end; { case }
end; { ExecuteOp }

PROCEDURE DIRECTOR;
begin
  InitScreen; GetMenuOption(CurrOp);
  while CurrOp <> EscapeOp do begin
    SetWindow(PromptWindow); ExecuteOp(CurrOp);
    EraseWindow(PromptWindow); GetMenuOption(CurrOp);
  end;
  changecursor (on); setwindow (fullscreenwindow); clrscr;
end; { DIRECTOR }

begin
end. { DIRSTUF }
(*** Assembly language module GETCURR. ***)

; 80286 assembly language program for data acquisition using the
; scientific solutions 12 bit a/d LABMASTER board called from
; TURBO PASCAL as GETCURR

DATA SEGMENT WORD PUBLIC
EXTRN ITERATIONS : WORD
EXTRN INTERVAL : WORD
EXTRN ICHANNEL : WORD
EXTRN DATU : WORD
EXTRN DELAYIT : FAR
BASEADDR EQU 0710h
ATODCNTL EQU 0714h
ATODCHAN EQU 0715h
ATODSTART EQU 0716h
TIMERACQ EQU 0717h
TIMERDATA EQU 0718h
TIMERCNTL EQU 0719h
PORTA EQU 071Ch
PORTB EQU 071Dh
PORTC EQU 071Eh
PORTCNTL EQU 071Fh
LPCT DW ?
DATA ENDS

CODE SEGMENT BYTE PUBLIC
ASSUME CS: CODE, DS: DATA
PUBLIC GETCURR

GETCURR PROC NEAR
CALL INITIAL ; INITIALIZE EVERYTHING
CALL WAITOGO ; WAIT FOR 'CELL' SWITCH
REP1: CALL HLDSMPL ; SET SAMPLE & HOLD AND CHECK TIME
         CALL SAMPLI ; GET THE CURRENT VALUES
         CALL CNTDWN ; GO TO INTERVAL TIME DELAY
         LOOP REP1 ; ANOTHER SET OF DATA POINTS?
         RET

GETCURR ENDP

INITIAL PROC NEAR
MOV DX, PORTCNTL ; CONFIGURE THE 8255A
MOV AL, 099h ; PORTS A & C - INPUT, PORT B - OUTPUT
OUT DX, AL
MOV CX, ITERATIONS ; LOAD NUMBER OF ITERATIONS
MOV BX, 0000h ; INITIALIZE BX FOR DATU COUNT
RET

INITIAL ENDP

WAITOGO PROC NEAR
MOV DX, PORTA
WTG1: IN AL, DX
TEST AL, 00100000b
JNZ WTG1 ; CHECK FOR BIT 5
JNZ WTG1
RET

WAITOGO ENDP

HLDSMPL PROC NEAR
MOV DX, PORTB
MOV AX, ICHANNEL[0000h]
OUT DX, AL
RET

HLDSMPL ENDP

SAMPLI PROC NEAR
PUSH CX ; SAVE THE CX REGISTER
MOV LPCT, 0000h ; RESET LOOP COUNTER
XCHG BX, LPCT ; SWAP THE BX INDEX & LPCT
S11: MOV DX, PORTB

MOV AX, IC[BX] ; SEND ADDRESS
OUT DX, AL
MOV DX, ATODSTART ; START THE A/D
MOV AL, 01h
OUT DX, AL
MOVSX BX, SI2
MOV DX, ATODCNTL ; WAIT FOR COMPLETION
IN AL, DX
TEST AL, 10000000b ; LOOK FOR HIGH BIT 7 AS COMPLETION
JZ SI2
MOV DX, ATODCHAN ; LOAD CONVERTED VALUE (LOW BYTE)
IN AL, DX
MOV CL, AL
MOV DX, ATODSTART ; BUILD THE VALUE IN THE C REGISTER
IN AL, DX
AND AL, 0Fh ; MASK OFF THE HIGH NIBBLE
MOV CH, AL
XCHG BX, LPCT
MOV DATU[BX], CX ; GIVE THE PASCAL VARIABLE THE DATA
INC BX ; MOVE INDEX TO NEXT SPOT IN ARRAY
INC BX
XCHG BX, LPCT ; SWAP CX & LPCT AGAIN
INC BX ; INCREMENT LOOP VARIABLE
INC BX
CMP BX, 16h ; DONE IF PERFORMED 11 TIMES
JNZ SI1
XCHG BX, LPCT ; I.E. (INDEX-22-16h)
POP CX ; RESTORE ORIGINAL BX & LPCT
POP BX ; RESTORE THE CX REGISTER
POP CX
POP BX
POP AX
RET
SAMPLI ENDP

CNDOWN PROC NEAR
MOV DX, PORTB ; RESET THE ADDRESS TO ZERO
MOV AL, 00h
OUT DX, AL
PUSH AX
PUSH BX
PUSH CX
PUSH DX
CALL DELAYIT
POP DX
POP CX
POP BX
POP AX
RET
CNDOWN ENDP

CODE ENDS
END
APPENDIX D

Digital Simulation Source Code Listings
(* Program FILAR. Used to digitally simulate diffusion in a unit cell of a twin filar electrode. *)

PROGRAM FILAR (INPUT, OUTPUT);
USES crt;

CONST XMAX = 8; YMAX = 4; AINIT = 0.000; BINIT = 1.000;
DMA = 0.25; DMB = 0.25; MAX_PASS = 500;

TYPE CONCENTRATION = ARRAY (.1..YMAX, 1..XMAX.) OF REAL;

VAR FAOLD, FANEW, FBOLD, FBNEW : CONCENTRATION;
CURRENT_PASS, CURRENT_YMAX : INTEGER;
IFILE : 'TEXT;
THETA : 'ARRAY [0..1] OF REAL;

PROCEDURE INITIALIZE;
VAR I, J : INTEGER;
BEGIN
  FOR I := 1 TO YMAX DO
    FOR J := 1 TO XMAX DO
      BEGIN
      FAOLD (.I,J.) := AINIT; FANEW (.I,J.) := AINIT;
      FBOLD (.I,J.) := BINIT; FBNEW (.I,J.) := BINIT;
      END;
  ASSIGN (IFILE, 'C:\MIKE\IFILE.DAT'); REWRITE (IFILE);
  WRITELN (IFILE, 'TIME':7, '=', 'I(0)':7, 'I(AVG)'); CURRENT_PASS := 1;
  CURRENT_YMAX := ROUND(3 * SQRT(CURRENT_PASS)); IF CURRENT_YMAX > YMAX THEN CURRENT_YMAX := YMAX;
  CLRSCR; GOTOXY (10,10);
  WRITELN ('SIMULATION IN PROGRESS. . .  PLEASE DO NOT DISTURB'); GOTOXY (10,12);
END; (* INITIALIZE *)

FUNCTION DONE : BOOLEAN;
BEGIN
  IF CURRENT_PASS < (MAX_PASS+1) THEN DONE := FALSE
  ELSE BEGIN
    DONE := TRUE; CURRENT_PASS := CURRENT_PASS - 1;
    WRITELN ('FILAR SIMULATION COMPLETE. . .');
    WRITE (CHR(7),CHR(7));
  END;
END; (* DONE *)

PROCEDURE DIFFUSION_WITHIN_BOUNDARIES;
VAR I, J : INTEGER;
BEGIN
  FOR I := 2 TO (CURRENT_YMAX - 1) DO
    FOR J := 2 TO XMAX-1 DO BEGIN
      FANEW (.I,J.) := FAOLD (.I,J.) + DMA * (FAOLD (.I+1,J.) + FAOLD (.I,J+1.) - 4 * FAOLD (.I,J.) + FAOLD (.I,J-1.) + FAOLD (.I-1,J.));
      FBNEW (.I,J.) := FBOLD (.I,J.) + DMB * (FBOLD (.I+1,J.) + FBOLD (.I,J+1.) - 4 * FBOLD (.I,J.) + FBOLD (.I,J-1.) + FBOLD (.I-1,J.));
    END;
END; (* DIFFUSION WITHIN_BOUNDARIES *)

PROCEDURE DIFFUSION_AT_CORNERS;
BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.2,1.) - 2 * FAOLD (.1,1.) + FAOLD (.1,2.));
  FANEW (.CURRENT_YMAX,1.) := FAOLD (.CURRENT_YMAX,1.) + DMA * (FAOLD (.CURRENT_YMAX-1,1.) - 2 * FAOLD (.CURRENT_YMAX,1.) + FAOLD (.CURRENT_YMAX,2.));
  FBNEW (.1,1.) := FBOLD (.1,1.) + DMB * (FBOLD (.2,1.) -
2 * FBOLD (.1,1.) - FBOLD (.1,2.) + DMB *
(FBOLD (.1,(CURRENT YMAX-1),1.) - 2 * FBOLD (.1,1.) + FBOLD (.1,YMAX,1.));
FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA *
(FAOLD (.2,XMAX.) - 2 * FAOLD (.1,XMAX.) + FAOLD (.1,XMAX-1.));
FANEW (.CURRENT YMAX,XMAX.) := FAOLD (.CURRENT YMAX,XMAX.) + DMA *
(FAOLD (.CURRENT YMAX-1,XMAX.) - 2 * FAOLD (.CURRENT YMAX,XMAX.) + FAOLD (.CURRENT YMAX, (XMAX-1).));
FBNEW (.1,XMAX.) := FBOLD (.1,XMAX.) + DMB *
(FBOLD (.2,XMAX.) - 2 * FBOLD (.1,XMAX.) + FBOLD (.1,XMAX-1.));
FBNEW (.CURRENT YMAX,XMAX.) := FBOLD (.CURRENT YMAX-1,XMAX.) - 2 * FBOLD (.CURRENT YMAX,XMAX.) + FBOLD (.CURRENT YMAX, (XMAX-1).));
END; (* DIFFUSION_AT_CORNERS *)

PROCEDURE DIFFUSION_AT_HORIzONTAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (XMAX-1) DO BEGIN
FANEW (.1,1.) := FAOLD (.1,1.) + DMA *
(FAOLD (.2,1.) - 3 * FAOLD (.1,1.) + FAOLD (.1,(I-1).) +
FAOLD (.1,(I+1).));
FANEW (.CURRENT YMAX,1.) := FAOLD (.CURRENT YMAX,1.) + DMA *
(FAOLD (.CURRENT YMAX-1,1.) - 3 * FAOLD (.CURRENT YMAX,1.) + FAOLD (.CURRENT YMAX, (I-1).) +
FAOLD (.CURRENT YMAX, (I+1).));
FBNEW (.1,1.) := FBOLD (.1,1.) + DMB *
(FBOLD (.2,1.) - 3 * FBOLD (.1,1.) + FBOLD (.1,(I-1).) +
FBOLD (.1,(I+1).));
FBNEW (.CURRENT YMAX,1.) := FBOLD (.CURRENT YMAX-1,1.) - 3 * FBOLD (.CURRENT YMAX,1.) + FBOLD (.CURRENT YMAX, (I-1).) +
FBOLD (.CURRENT YMAX, (I+1).));
END; (* FOR *)
END; (* DIFFUSION_AT_HORIzONTAL_EDGES *)

PROCEDURE DIFFUSION_AT_VERTICAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (CURRENT YMAX-1) DO BEGIN
FANEW (.1,1.) := FAOLD (.1,1.) + DMA *
(FAOLD (.1+1,1.) - 3 * FAOLD (.1,1.) + FAOLD (.1,2.) +
FAOLD (.1,(I-1).));
FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA *
(FAOLD (.1+1,XMAX.) - 3 * FAOLD (.1,XMAX.) +
FAOLD (.1,(XMAX-1).) + FAOLD (.1, (I-1).) +
FAOLD (.1, (I+1).) - 3 * FBOLD (.1,1.) + FBOLD (.1,2.) +
FBOLD (.1,(I-1).) + FBOLD (.1,(I+1).));
FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA *
(FBOLD (.1+1,XMAX.) - 3 * FBOLD (.1,XMAX.) +
FBOLD (.1,(XMAX-1).) + FBOLD (.1, (I-1).) +
FBOLD (.1, (I+1).));
END; (* FOR *)
END; (* DIFFUSION_AT_VERTICAL_EDGES *)

PROCEDURE FARADAIC CONVERSION;
VAR CURRENT0, CURRENT1, TIME : REAL; I, J : INTEGER;
BEGIN
CURRENT0 := 0; CURRENT1 := 0;
FOR I := 1 TO (XMAX div 4) DO BEGIN
J := XMAX-I+1; CURRENT0 := CURRENT0 + FANEW [1,I];
CURRENT1 := CURRENT1 - FBNEW [1,I] + FANEW [1,I]; (CUR1:=CUR2)
FANEW [1,1] := FANEW [1,1] + FANEW [1,1]; FANEW [1,1] := 0;
FANEW [1,J] := FANEW [1,J] + fbnew[1,J]; FBNEXT [1,J] := 0;    END; (* FOR *)
TIME := CURRENT PASS;
WRITE (FILE,TIME:7:4,' ',CURRENT0:7:4,' ',CURRENT1:7:4,' ',((ABS(CURRENT0) + ABS(CURRENT1))/2):7:4);
END; (* FARADAIC_CONVERSION *)

PROCEDURE SETUP FOR NEXT ITERATION;
VAR I, J : INTEGER;
BEGIN
  FOR J := 1 TO XMAX DO BEGIN
    FOR I := 1 TO CURRENT YMAX DO BEGIN
      FAOLD(.I,J.) := FANEW(.I,J.);
      FBOLD(.I,J.) := FBNEXT(.I,J.);
    END; (* FOR I *)
  END; (* FOR *)
  CURRENT PASS := CURRENT PASS + 1;
  CURRENT YMAX := ROUND(3*SQRT(CURRENT PASS));
  IF CURRENT YMAX > YMAX THEN CURRENT YMAX := YMAX;
END; (* SETUP FOR NEXT ITERATION *)

PROCEDURE FILE CONCENTRATION ARRAYS:
VAR AFILE, BFILE : TEXT; I,J : INTEGER;
BEGIN
  ASSIGN (AFILE,'C:\MIKE\AFILE.DAT');
  ASSIGN (BFILE,'C:\MIKE\BFILE.DAT');
  REWRITE (AFILE); REWRITE (BFILE);
  WRITE (AFILE,'SPECIES A; YMAX WAS ',CURRENT YMAX,
  ' ; XMAX WAS ',XMAX);
  WRITE (BFILE,'SPECIES B; YMAX WAS ',CURRENT YMAX,
  ' ; XMAX WAS ',XMAX);
  FOR I := 1 TO CURRENT YMAX DO BEGIN
    WRITE (AFILE,(1-17:7); WRITE (BFILE,(1-1):7);
    FOR J := 1 TO XMAX DO BEGIN
      WRITE (AFILE,FANEW (.I,J.):6:3);
      WRITE (BFILE,FBNEXT (.I,J.):6:3);
    END; (* FOR *)
    WRITE (AFILE); WRITE (BFILE);
  END; (* FOR *)
  CLOSE (AFILE); CLOSE (BFILE); CLOSE (FILE);
END; (* FILE_CONCENTRATION ARRAYS *)

BEGIN
  INITIALIZE;
  REPEAT
    DIFFUSION WITHIN BOUNDARIES; DIFFUSION AT CORNERS;
    DIFFUSION AT HORIZONTAL EDGES; DIFFUSION AT VERTICAL EDGES;
    FARADAIC CONVERSION; SETUP FOR NEXT ITERATION;
    UNTIL DONE;
  FILE_CONCENTRATION ARRAYS;
END. (*FILAR *)
(*** Program COFACIAL. Use to simulate diffusion at a cofacial twin electrode. ***)

PROGRAM COFACIAL;
USES CRT;

CONST XMAX = 20; ANINIT = 0.000; BINIT = 1.000;
DMA = 0.5; DMB = 0.5; MAX_PASS = 500;

TYPE CONCENTRATION = ARRAY (.1..XMAX.) OF REAL;

VAR FAOLD, FANEW, FBOLD, FBNEW : CONCENTRATION;
CURRENT_PASS : INTEGER; IFILE : TEXT;

PROCEDURE INITIALIZE;
VAR I, J : INTEGER;
BEGIN
  FOR I := 1 TO XMAX DO BEGIN
    FAOLD (.1.) := AINIT; FANEW (.I.) := AINIT;
    FBOLD (.1.) := BINIT; FBNEW (.I.) := BINIT;
  END; (* FOR *)
  ASSIGN (IFILE,'C:\MIKE\IFILE.DAT'); REWRITE (IFILE);
  WRITELN (IFILE,'TIME':7,',','I(0)':7,',','I(l)':7,' ','CURRENT_PASS 1 ; CLRSCR; GOTOXY (10,10);
  WRITELN (0'); WRITELN ('COFACIAL SIMULATION IN PROGRESS...PLEASE DO NOT','DISTURB');
  GOTOXY (10,12);
END; (* INITIALIZE * )

FUNCTION DONE : BOOLEAN;BEGIN
  IF CURRENT_PASS < (MAX_PASS+1) THEN DONE := FALSE
  ELSE BEGIN
    DONE := TRUE; CURRENT_PASS := CURRENT_PASS - 1;
    WRITELN ('COFACIAL SIMULATION COMPLETE...');
    WRITE (CHR(7), CHR(7));
  END; (* ELSE *)
END; (* DONE * )

PROCEDURE DIFFUSION WITHIN_BOUNDRARIES;
VAR I : INTEGER;
BEGIN
  FOR I := 2 TO (XMAX - 1) DO BEGIN
    FANEW (.1.) := FAOLD (.I.) + DMA * (FAOLD (.1+1.) +
      - 2 * FAOLD (.1.) + FAOLD (.1-1.));
    FBNEW (.1.) := FBOLD (.I.) + DMB * (FBOLD (.1+1.) +
      - 2 * FBOLD (.1.) + FBOLD (.1-1.));
  END; (* FOR *)
END; (* DIFFUSION_WITHIN_BOUNDARIES *)

PROCEDURE DIFFUSION_AT_EDGES;
VAR I : INTEGER;
BEGIN
  FOR I := 2 TO (XMAX - 1) DO BEGIN
    FANEW (.1.) := FAOLD (.1.) + DMA * (FAOLD (.2.) - FAOLD (.1.));
    FAEXP (.XMAX.) := FAOLD (.XMAX.) +
      (FAOLD (.XMAX-1.) - FAOLD (.XMAX.));
    FBNEW (.1.) := FBOLD (.1.) + DMB * (FBOLD (.2.) - FBOLD (.1.));
    FBNEW (.XMAX.) := FBOLD (.XMAX.) +
      DMB * (FBOLD (.XMAX-1.) - FBOLD (.XMAX.));
  END; (* FOR *)
END; (* DIFFUSION_AT_EDGES *)

PROCEDURE FARADAIC CONVERSION;
VAR CURRENT, CURRENT1, TIME : REAL;
BEGIN
  CURRENT := FANEW [1]; CURRENT1 := -FBNEW [XMAX];
  FANEW [XMAX] := FANEW [XMAX] + FBNEW [XMAX];
  FBNEW [XMAX] := 0; TIME := CURRENT_PASS;
PROCEDURE SETUP FOR NEXT ITERATION;
VAR I, J : INTEGER;
BEGIN
  FOR I := 1 TO XMAX DO BEGIN
    FAOLD (.I.) := FANEW (.I.); FBOLD (.I.) := FBNEW (.I.);
  END; (* FOR I *)
  CURRENT PASS := CURRENT PASS + 1;
END; (* SETUP FOR NEXT ITERATION *)

PROCEDURE FILE CONCENTRATION ARRAYS;
VAR AFILE, BFILE : TEXT; I, J : INTEGER;
BEGIN
  ASSIGN (AFILE,'C:\MIKE\AFILE.DAT');
  ASSIGN (BFILE,'C:\MIKE\BFILE.DAT');
  REWRITE (AFILE); REWRITE (BFILE);
  WRITELN (AFILE,'SPECIES A; XMAX WAS ',XMAX);
  WRITELN (BFILE,'SPECIES B; XMAX WAS ',XMAX);
  FOR I := 1 to XMAX DO BEGIN
    WRITE (AFILE,FANEW (I,J.):6:3);
    WRITE (BFILE,FBNEW (I,J.):6:3);
    IF (I MOD 10) = 0 THEN BEGIN
      WRITELN (AFILE); WRITELN (BFILE);
    END;
  END;
END; (* FOR *)
CLOSE (AFILE); CLOSE (BFILE); CLOSE (IFILE);
END; (* FILE_CONCENTRATION_ARRAYS *)

BEGIN
  INITIALIZE;
  REPEAT
    DIFFUSION WITHIN BOUNDARIES; DIFFUSION AT EDGES;
    FARADAIC CONVERSION; SETUP FOR NEXT ITERATION;
    UNTIL DONE;
    FILE CONCENTRATION ARRAYS;
END. (* COFACIAL *)
PROGRAM FILARCV (INPUT,OUTPUT);
{SN+}
USES CRT, GRAPH,
{SU C:\MIKE\HPPRINT} HPPRINT,
{SU C:\mike\GENPLOT} GENPLOT;

CONST XMAX = 8; YMAX = 10; (L/W-1.25) AINIT = 0.000;
BINIT = 1.000; DMA = 0.25; DMB = 0.25; MAX PASS = 1000;
EHALF = 0.250; EINIT = 0.000; EDELTA = 0.001; N = 1;
(EDELTA * MAX_PASS = 1.0) F = 96485; T = 298; R = 8.314;

TYPE CONCENTRATION = ARRAY (.1..YMAX,1..XMAX.) OF REAL;

VAR FAOLD, FANEW, FBOLD, FBNEW : CONCENTRATION;
CURRENT PASS, CURRENT YMAX : INTEGER;
IFILE : TEXT; THETA : "ARRAY [0..1] OF REAL;
E, DELTAE : REAL;
CUR : ARRAY [0..2,1..MAX_PASS] OF REAL;

PROCEDURE INITIALIZE;
VAR I, J : INTEGER;
BEGIN
FOR I = 1 TO YMAX DO
FOR J = 1 TO XMAX DO BEGIN
FAOLD (.I,J.) := AINIT; FANEW (.I,J.) := AINIT;
FBOLD (.I,J.) := BINIT; FBNEW (.I,J.) := BINIT;
END; (* FOR *)
E := EINIT;
THETA [0] := EXP((N * F)/(R * T)) * (E - EHALF);
THETA [1] := EXP((N * F)/(R * T)) * (E - EHALF);
DELTAE := EDELTA; ASSIGN (IFILE,'C:\MIKE\CVDATA\1@25#1.DAT');
REWITE (IFILE); WRITELN (IFILE,'TIME':7,": ",CURR PASS:- 1 ;
CURRENT -YMAX := ROUND(3 * SQRT(CURRENT PASS));
IF CURRENT YMAX > YMAX THEN CURRENT YMAX := YMAX;
CLSCR; GOTOXY (10,10);
WRITELN ('SIMULATION IN PROGRESS.. PLEASE DO NOT DISTURB');
GOTOXY (10,12);
END; (* INITIALIZE *)

FUNCTION DONE : BOOLEAN;
BEGIN
IF CURRENT PASS < (MAX PASS+1) THEN DONE := FALSE
ELSE BEGIN
DONE := TRUE; CURRENT PASS := CURRENT PASS - 1;
WRITELN ('FILAR SIMULATION COMPLETE.. -');
END; (* ELSE *)
END; (* DONE *)

PROCEDURE DIFFUSION WITHIN BOUNDARIES;
VAR I, J : INTEGER;
BEGIN
FOR I = 2 TO (CURRENT YMAX - 1) DO
FOR J = 2 TO XMAX-1 DO BEGIN
FANEW (.I,J.) := FAOLD (.I,J.) + DMA *
(FAOLD (.I+1,J.) + FAOLD (.I,J+1.) - 4 *
FAOLD (.I,J+1.) + FAOLD (.I-1,J.) +
FAOLD (.I-1,J.));
FBNEW (.I,J.) := FBOLD (.I,J.) + DMB *
(FBOLD (.I+1,J.) + FBOLD (.I,J+1.) - 4 *
FBOLD (.I,J+1.) + FBOLD (.I,J-1.) +
FBOLD (.I-1,J.));
END; (* FOR *)
END; (* DIFFUSION WITHIN BOUNDARIES *)
PROCEDURE DIFFUSION_AT_CORNERS;
BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.2,1.) - 2 * FAOLD (.1,1.) + FAOLD (.1,1.));
  FANEW (.CURRENT YMAX,1.) := FAOLD (.CURRENT YMAX,1.) + DMA * (FAOLD (.CURRENT YMAX-1,1.) - 2 * FAOLD (.CURRENT YMAX,1.) + FAOLD (.CURRENT YMAX,2.));
  FBNEW (.1,1.) := FBOLD (.1,1.) + DMB * (FBOLD (.2,1.) - 2 * FBOLD (.1,1.) + FBOLD (.1,2.));
  FBNEW (.CURRENT YMAX,1.) := FBOLD (.CURRENT YMAX,1.) + DMB * (FBOLD (.CURRENT YMAX-1,1.) - 2 * FBOLD (.CURRENT YMAX,1.) + FBOLD (.CURRENT YMAX,2.));
  FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA * (FAOLD (.2,XMAX.) - 2 * FAOLD (.1,XMAX.) + FAOLD (.1,XMAX-1.));
  FANEW (.CURRENT YMAX,XMAX.) := FAOLD (.CURRENT YMAX,XMAX.) + DMA * (FAOLD (.CURRENT YMAX-1,XMAX.) - 2 * FAOLD (.CURRENT YMAX,XMAX.) + FAOLD (.CURRENT YMAX,XMAX-1.));
  FBNEW (.1,XMAX.) := FBOLD (.1,XMAX.) + DMB * (FBOLD (.2,XMAX.) - 2 * FBOLD (.1,XMAX.) + FBOLD (.1,XMAX-1.));
  FBNEW (.CURRENT YMAX,XMAX.) := FBOLD (.CURRENT YMAX,XMAX.) + DMB * (FBOLD (.CURRENT YMAX-1,XMAX.) - 2 * FBOLD (.CURRENT YMAX,XMAX.) + FBOLD (.CURRENT YMAX,XMAX-1.));
END;

PROCEDURE DIFFUSION_AT_HORIZONTAL_EDGES;
VAR I : INTEGER;
BEGIN
  FOR I := 2 TO (XMAX-1) DO BEGIN
    FANEW (.1,I.) := FAOLD (.1,I.) + DMA * (FAOLD (.2,I.) - 3 * FAOLD (.1,I.) + FAOLD (.1,I-1.) + FAOLD (.1,I+1.));
    FANEW (.CURRENT YMAX,I.) := FAOLD (.CURRENT YMAX,I.) + DMA * (FAOLD (.CURRENT YMAX-1,I.) - 3 * FAOLD (.CURRENT YMAX,I.) + FAOLD (.CURRENT YMAX,(I-1).) + FAOLD (.CURRENT YMAX,(I+1).));
    FBNEW (.1,I.) := FBOLD (.1,I.) + DMB * (FBOLD (.2,I.) - 3 * FBOLD (.1,I.) + FBOLD (.1,I-1.) + FBOLD (.1,I+1.));
    FBNEW (.CURRENT YMAX,I.) := FBOLD (.CURRENT YMAX,I.) + DMB * (FBOLD (.CURRENT YMAX-1,I.) - 3 * FBOLD (.CURRENT YMAX,I.) + FBOLD (.CURRENT YMAX,(I-1).) + FBOLD (.CURRENT YMAX,(I+1).));
  END;
END;

PROCEDURE DIFFUSION_AT_VERTICAL_EDGES;
VAR I : INTEGER;
BEGIN
  FOR I := 2 TO (CURRENT YMAX-1) DO BEGIN
    FANEW (.I,1.) := FAOLD (.I,1.) + DMA * (FAOLD (.I+1,1.) - 3 * FAOLD (.I,1.) + FAOLD (.I,2.) + FAOLD (.I,I+1.,I));
    FANEW (.I,XMAX.) := FAOLD (.I,XMAX.) + DMA * (FAOLD (.I,(I+1),XMAX.) - 3 * FAOLD (.I,XMAX.) + FAOLD (.I+1,XMAX-1.)) + FAOLD (.I,XMAX-1.));
    FBNEW (.I,1.) := FBOLD (.I,1.) + DMB * (FBOLD (.I+1,1.) - 3 * FBOLD (.I,1.) + FBOLD (.I,2.) + FBOLD (.I-1,I+1.));
    FBNEW (.I,XMAX.) := FBOLD (.I,XMAX.) + DMB * (FBOLD (.I+1,1,XMAX.) - 3 * FBOLD (.I,XMAX.) + FBOLD (.I+1,XMAX-1.)) + FBOLD (.I,XMAX-1.));
  END;
END;
PROCEDURE FARADAIC CONVERSION;
VAR CURRENT0, CURRENT1, TIME : REAL; I, J : INTEGER;
DELTAONE, DELTATWO : REAL;
BEGIN
  CURRENT0 := 0; CURRENT1 := 0;
  FOR I := 1 TO (XMAX DIV 4) DO BEGIN
    J := XMAX-1+1;
    DELTAONE := (FANEW[1,I] - THETA[0] * FBNEW[1,I]) / 
                (THETA[0] + 1);
    DELTATWO := (FANEW[1,J] - THETA[1] * FBNEW[1,J]) / 
                (THETA[1] + 1);
    FBNEW[1,I] := FBNEW[1,I] + DELTAONE;
    FANEW[1,I] := FANEW[1,I] - DELTAONE;
    PBNEW[1,J] := PBNEW[1,J] + DELTATWO;
    FANEW[1,J] := FANEW[1,J] - DELTATWO;
    CURRENT1 := CURRENT0 + DELTAONE;
    CURRENT0 := CURRENT1 + DELTATWO;
  END;
  TIME := (CURRENT PASS-0.5) / MAX_PASS;
  IF CURRENT PASS MOD 2 = 0 THEN 
    WRITELN(IFILE, TIME:7:4,' ',E:7:4,' ',CURRENT0:7:4,' 
            CURRENT1:7:4);
  CUR[0,CURRENT PASS] := -E; CUR[1,CURRENT PASS] := CURRENT0;
  CUR[2,CURRENT PASS] := CURRENT1;
  IF CURRENT PASS = MAX_PASS DIV 2 THEN DELTAE := - DELTAE;
  E := E + DELTAE; THETA[1] := EXP(((N*F)/(R*T))*(E-EHALF));
END; (* END Faradaic conversion *)

PROCEDURE SETUP FOR NEXT ITERATION;
VAR I, J : INTEGER;
BEGIN
  FOR J := 1 TO XMAX DO BEGIN
    FOR I := 1 TO CURRENT YMAX DO BEGIN
      FAOLD (.I,J.) := FANEW (.I,J.);
      FBOLD (.I,J.) := FBNEW (.I,J.);
    END; (* FOR I *)
  END; (* FOR J *)
  CURRENT PASS := CURRENT PASS + 1;
  CURRENT YMAX := ROUND(3 * SQRT(CURRENT PASS));
  IF CURRENT YMAX > YMAX THEN CURRENT YMAX := YMAX;
END; (* End setup for next iteration *)

PROCEDURE FILE CONCENTRATION ARRAYS;
VAR AFILE, BFILE : TEXT; I, J : INTEGER;
BEGIN
  ASSIGN (AFILE, 'C:\MIKE\CVAFILE.DAT');
  ASSIGN (BFILE, 'C:\MIKE\CVBFILE.DAT');
  REWRITE (AFILE); REWRITE (BFILE);
  WRITELN (AFILE, 'SPECIES A; YMAX WAS ',CURRENT YMAX,
           ' XMAX WAS ',XMAX);
  WRITELN (BFILE, 'SPECIES B; YMAX WAS ',CURRENT YMAX,
           ' XMAX WAS ',XMAX);
  FOR I := 1 TO CURRENT YMAX DO BEGIN
    WRITE (AFILE,(I-1):7); WRITE (BFILE,(I-1):7);
    FOR J := 1 TO XMAX DO BEGIN
      WRITE (AFILE,FANEW (.I,J.):6:3);
      WRITE (BFILE,FBNEW (.I,J.):6:3);
    END; (* FOR J *)
    WRITELN (AFILE); WRITELN (BFILE);
  END; (* FOR I *)
  CLOSE (AFILE); CLOSE (BFILE); CLOSE (IFILE);
END; (* End file concentration arrays *)

PROCEDURE PLOT;
VAR I : INTEGER;
BEGIN
  NUMBER := MAX PASS;
FOR I := 1 TO MAX PASS DO BEGIN (LOAD IN 1000 POINTS MAX)
  XIN [I] := CUR [0, I]; YIN [I] := CUR [1, I];
END;

HEADING := 'CURRENT 0 VERSUS POTENTIAL';
SIZE := 'L'; GRAPHGEN;
FOR I := 1 TO MAX PASS DO YIN[I] := CUR [2, I];
HEADING := 'CURRENT 1 VERSUS POTENTIAL';
SIZE := 'L'; GRAPHGEN;
FOR I := 1 TO MAX PASS DO YIN[I] := CUR [1, I] - CUR [2, I];
HEADING := 'CURRENT 0 - CURRENT 1 VERSUS POTENTIAL';
SIZE := 'L'; GRAPHGEN;
FOR I := 1 TO MAX PASS DO YIN[I] := CUR [1, I] + CUR [2, I];
HEADING := 'CURRENT 0 + CURRENT 1 VERSUS POTENTIAL';
GRAPHGEN;
END;

BEGIN
  INITIALIZE;
  REPEAT
    DIFFUSION WITHIN BOUNDARIES; DIFFUSION AT CORNERS;
    DIFFUSION AT HORIZONTAL EDGES; DIFFUSION AT VERTICAL EDGES;
    FARA DIAIC CONVERSION; SETUP FOR NEXT ITERATION;
  UNTIL DONE;
  FILE CONCENTRATION ARRAYS; PLOT;
END. (*FILARCV *)
(* Program TENBYONE. Used to simulate diffusion at a 10x1 electrode, or an entire twin electrode array. *)

PROGRAM TENBYONE (INPUT, OUTPUT);
USES CRT;

CONST XMAX = 192; (224 IN MAINFRAME SIMULATION;)
ZMAX = 12; (X=4/4; X=Z; DMA = 0.250;
R = 8.314; F = 96^85;

TYPE CONCENTRATION = ARRAY (.1..ZMAX, 1..XMAX) OF REAL;
THETA_TYPE = ARRAY (.0..10.) OF REAL;

VAR FAOLD, FANEW, FBOLD, FBNEW : CONCENTRATION;
CURRENT PASS, CURRENT ZMAX, I, MAX PASS : INTEGER;
SUM_CURRENT, COUNTER CURRENT : REAL;
DMB, AINIT, BINIT : REAL;
IFILE, CONSOLE, INPUTFILE : TEXT; (* I/O FILES *)

THETA : THETA_TYPE; (* CONCENTRATION RATIO *)
ASYM FACTOR : THETA_TYPE; (* NORMALIZED ELECTRODE ACTIVITY *)

PROCEDURE ERROR RTN (COMPLETION_CODE : INTEGER);
BEGIN
ASSIGN (CONSOLE, 'C:\MIKE\CONSOLE.DAT'); REWRITE (CONSOLE);
WRITELN (CONSOLE, '***> USER ABEND IN TENBYONE');
CASE COMPLETION_CODE OF
1  : BEGIN (* INVALID ON/OFF OPTION *)
WRITELN (CONSOLE, 'EXECUTION HALTED. IMPROPER VALUE',
'FOR ON/OFF');
WRITELN (CONSOLE, 'OPTION OF ELECTRODE. CHOOSE A',
'VALUE OR 1 FOR ON OR A VALUE OF 0 FOR OFF.');
END; (* CASE 1 *)
2  : BEGIN (* INVALID DRATIO *)
WRITELN (CONSOLE, 'EXECUTION HALTED. IMPROPER VALUE',
'OF DIFFUSION');
WRITELN (CONSOLE, 'COEFFICIENT RATIO WAS CHOSEN',
'(D(A)/D(B)).');
WRITELN (CONSOLE, 'RATIO MUST BE GREATER THAN OR',
'EQUAL TO ONE.');
END; (* CASE 2 *)
END; (* CASE *)
CLOSE (CONSOLE); CLOSE (INPUTFILE);
WRITELN ('ERROR OCCURRED: ERROR CODE: ', COMPLETION_CODE);2);
HALT;
END; (* ERROR_RTN *)

PROCEDURE INITIALIZE;
VAR I, J : INTEGER; N : INTEGER; EZERO : REAL; T : REAL;
DRATIOAB : REAL; E : ARRAY (.0..10.) OF REAL;
BEGIN
ASSIGN (INPUTFILE, 'C:\Mike\INPUT.PRM');
RESET (INPUTFILE); READLN (INPUTFILE, EZERO);
FOR I :- 0 TO 10 DO BEGIN
READLN (INPUTFILE, E(.1.), ON OFF(. I.), ASYM FACTOR(. I.));
IF NOT ((ON OFF (.1.) = 0) OR (ON OFF (.1.) = 1)) THEN
ERROR RTN (1);
END; (* FOR *)
READLN (INPUTFILE, DRATIOAB); DMB :- DMA / DRATIOAB;
IF DMB > 0.250 THEN ERROR RTN (2);
READLN (INPUTFILE, AINIT); READLN (INPUTFILE, BINIT);
READLN (INPUTFILE, MAX PASS); READLN (INPUTFILE, N);
READLN (INPUTFILE, T); CLOSE (INPUTFILE);
FOR I :- 1 TO ZMAX DO
FOR J :- 1 TO XMAX DO BEGIN
FAOLD (.I,J.) := AINIT; FANEW (.I,J.) := AINIT;
FBOLD (.I,J.) := BINIT; FNWEW (.I,J.) := BINIT;
END; (* FOR *)
COUNTER_CURRENT := 0; SUM_CURRENT := 0;
ASSIGN (CONSOLE,'C:\PASCAL\SIMULATE\CONSOLE.DAT');
REWRITE (CONSOLE);
WRITELN (CONSOLE,'CONDITIONS AT EACH ELECTRODE:');
WRITELN (CONSOLE,'REDOX POTENTIAL: ',EZERO:5:3);
FOR I := 0 TO 10 DO BEGIN
  \( \theta_i = \exp\left(\frac{(N \times F)}{(R \times T)} \times (E_i - E_{\text{ZERO}})\right) \)
  IF ON OFF (.I.) = 1 THEN WRITELN (CONSOLE, 'ON ')
ELSE WRITELN (CONSOLE, 'OFF');
END;
WRITELN (CONSOLE,'INITIAL A CONCENTRATION :  ',AINIT:6:3);
WRITELN (CONSOLE,'INITIAL B CONCENTRATION :  ',BINIT:6:3);
WRITELN (CONSOLE,'NUMBER OF ELECTRONS :  ',N:2);
WRITELN (CONSOLE,'TEMPERATURE (KELVIN) :  ',T:7:2);
WRITELN (CONSOLE,'MAX_PASS:4,' 'ITERATIONS');
WRITELN (CONSOLE);
ASSIGN(IFILE,'C:\MIKE\IMULTI.DAT'); REWRITE (IFILE);
WRITELN (IFILE,'TIME':7,'I (1)':8,'I (2)':8,'I (3)':8,'I (5)':8,'I (6)':8,'I (7)':8,'I (8)':8,'I (10)':8,'I (0)':8,'I(sum)':8,'I(avg)':8);
CURRENT PASS := 1;
(CURRENT PASS must be greater than 0)
END; (* INITIALIZE *)
FUNCTION DONE : BOOLEAN;
BEGIN
IF CURRENT_PASS < (MAX_PASS+1) THEN DONE := FALSE
ELSE BEGIN
  DONE := TRUE; CURRENT_PASS := CURRENT_PASS - 1;
  WRITELN (CONSOLE,'TEN BY ONE SIMULATION HAS REACHED A','NORMAL COMPLETION.');
END; (* ELSE *)
END; (* DONE *)

PROCEDURE DIFFUSION WITHIN_BOUNDARIES;
VAR I, J : INTEGER;
BEGIN
  FOR I := 2 TO (CURRENT ZMAX - 1) DO
  FOR J := 2 TO XMAX-1 DO BEGIN
    FANEW (.I,J.) := FAOLD (.I,J.) + DMA * 
                (FAOLD (.I+1,J.) + FAOLD (.I,J+1.) - 4 * 
                 FAOLD (.I,J.) + FAOLD (.I,J-1.) + 
                 FAOLD (.I-1,J.));
    FBNEW (.I,J.) := FBOLD (.I,J.) + DMB *
                 (FBOLD (.I+1,J.) + FBOLD (.I,J+1.) - 4 * 
                  FBOLD (.I,J.) + FBOLD (.I,J-1.) + 
                  FBOLD (.I-1,J.));
  END; (* FOR *)
END; (* DIFFUSION WITHIN_BOUNDARIES *)

PROCEDURE DIFFUSION_AT_CORNERS;
BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.2,1.) - 2 * FAOLD (.1,1.) + FAOLD (.1,2.));
  FANEW (.CURRENT ZMAX,1.) := FAOLD (.CURRENT ZMAX,1.) + DMA *
                         (FAOLD (.CURRENT ZMAX-1,1.) - 2 * 
                          FAOLD (.CURRENT ZMAX,1.) + FAOLD (.CURRENT ZMAX,2.));
  FBNEW (.1,1.) := FBOLD (.1,1.) + DMB *
                (FBOLD (.2,1.) + FBOLD (.1,1.) + 
                 FBOLD (.1,2.));
  FBNEW (.CURRENT ZMAX,1.) := FBOLD (.CURRENT ZMAX,1.) + DMB *
                           (FBOLD (.CURRENT ZMAX-1,1.) - 2 * 
                            FBOLD (.CURRENT ZMAX,1.) + 
                            FBOLD (.CURRENT ZMAX,2.));
  FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA * (FAOLD (.2,XMAX.) - 2 * FAOLD (.1,1.) + FAOLD (.1,XMAX.) - 2 * FAOLD (.1,XMAX-1.) + FAOLD (.1,XMAX-2.));
  FBNEW (.1,XMAX.) := FBOLD (.1,XMAX.) + DMB * (FBOLD (.2,XMAX.) - 2 * FBOLD (.1,1.) + FBOLD (.1,XMAX.) - 2 * FBOLD (.1,XMAX-1.) + FBOLD (.1,XMAX-2.).)
END; (* DIFFUSION_AT_CORNERS *)
- 2 * FAOLD (.1,XMAX.) + FAOLD (.1,XMAX-1.));
FANEW (.CURRENT ZMAX,XMAX.) := FAOLD (.CURRENT ZMAX,XMAX.) +
DMA * (FAOLD (.CURRENT ZMAX-1),XMAX.) - 2 *
FAOLD (.CURRENT ZMAX,XMAX.) +
FAOLD (.CURRENT ZMAX,(XMAX-1).));
FBNEW (.1,XMAX.) := FBOLD (.1,XMAX.) + DMB * (FBOLD (.2,XMAX.) -
FBOLD (.1,XMAX.) + FBOLD (.1,XMAX-1.));
FBNEW (.CURRENT ZMAX,XMAX.) := FBOLD (.CURRENT ZMAX,XMAX.) +
DMB * (FBOLD (.CURRENT ZMAX-1),XMAX.) - 2 *
FBOLD (.CURRENT ZMAX,XMAX.) +
FBOLD (.CURRENT ZMAX,(XMAX-1).));
END; (* DIFFUSION_AT_CORNERS *)

PROCEDURE DIFFUSION_AT_HORIZONTAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (XMAX-1) DO BEGIN
FANEW (.1,I.) := FAOLD (.1,1.) + DMA * (FAOLD (.1,1.) -
3 * FAOLD (.1,1.) + FAOLD (.1,1+1.)) +
FAOLD (.1,(I+1).));
FANEW (.CURRENT ZMAX,I.) := FAOLD (.CURRENT ZMAX,I.) +
DMA * (FAOLD (.CURRENT ZMAX-1),I.) - 3 *
FAOLD (.CURRENT ZMAX,I.) + FAOLD (.CURRENT ZMAX,(I-1).) +
FAOLD (.CURRENT ZMAX,(I+1).));
FBNEW (.1,I.) := FBOLD (.1,1.) + DMB * (FBOLD (.2,1.) -
3 * FBOLD (.1,1.) + FBOLD (.1,1+1.) +
FBOLD (.1,(I+1.).));
FBNEW (.CURRENT ZMAX,I.) := FBOLD (.CURRENT ZMAX,I.) +
DMB * (FBOLD (.CURRENT ZMAX-1),I.) - 3 *
FBOLD (.CURRENT ZMAX,I.) + FBOLD (.CURRENT ZMAX,(I-1).) +
FBOLD (.CURRENT ZMAX,(I+1.).));
END; (* FOR *)
END; (* DIFFUSION_AT_HORIZONTAL_EDGES *)

PROCEDURE DIFFUSION_AT_VERTICAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (CURRENT ZMAX-1) DO BEGIN
FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.I+1,1.) -
3 * FAOLD (.I+1,1.) + FAOLD (.I,1.)) +
FAOLD (.I,(1+1).));
FANEW (.I,XMAX.) := FAOLD (.I,XMAX.) + DMA * (FAOLD (.I,1.) -
3 * FAOLD (.I,1.) + FAOLD (.I,1+1.) +
FAOLD (.I,XMAX-1.) + FAOLD (.I,XMAX.));
FBNEW (.1,1.) := FBOLD (.1,1.) + DMB * (FBOLD (.I+1,1.) -
3 * FBOLD (.I,1.) + FBOLD (.I,1+1.) +
FBOLD (.I,XMAX-1.) + FBOLD (.I,XMAX.));
FBNEW (.I,XMAX.) := FBOLD (.I,XMAX.) + DMB * (FBOLD (.I+1,XMAX.) - 3 * FBOLD (.I,XMAX.) +
FBOLD (.I,1+1.) + FBOLD (.I,XMAX-1.) + FBOLD (.I,XMAX.));
END; (* FOR *)
END; (* DIFFUSION_AT_VERTICAL_EDGES *)

PROCEDURE FARADAIC CONVERSION (SEGMENT : INTEGER);
VAR CURRENT1, CURRENT2, DELTA : REAL; INDEX, X : INTEGER;
FUNCTION DELTATHETA (XPOS, ELECTRODE : INTEGER) : REAL;
BEGIN
DELTATHETA := ON OFF (.ELECTRODE.) *
ASYM FACTOR (.ELECTRODE.) * (FANEW (.1,XPOS.) -
THETA (.ELECTRODE.) * FBNEW (.1,XPOS.)) /
(THETA (.ELECTRODE.) + 1);
END; (* DELTATHETA *)
BEGIN
INDEX := 16 * (SEGMENT + 1); (* X POSITION AT CORRECT LOCATION *)
(* FIRST TAKE CARE OF STEPPED ELECTRODE PAIR *)
X := 4 + INDEX; DELTA := DELTATHETA (X,SEGMENT);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := DELTA; X := 5 + INDEX;
DELTA := DELTATHETA (X,SEGMENT);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA; X := 12 + INDEX;
DELTA := DELTATHETA (X,SEGMENT);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA; X := - 13 + INDEX;
DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA; X := 9 + INDEX;
DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA; X := 9 + INDEX;
DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA; X := 16 + INDEX;
DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT1 := CURRENT1 + DELTA;
SUM CURRENT := SUM CURRENT + CURRENT1;
(* NOW TAKE CARE OF COUNTER ELECTRODE FILAMENTS *)
X := 1 + INDEX; DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT2 := DELTA; X := 8 + INDEX; DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT2 := CURRENT2 + DELTA; X := 16 + INDEX;
DELTA := DELTATHETA (X,0);
FANEW (.1,X.) := FANEW (.1,X.) - DELTA;
FBNEW (.1,X.) := FBNEW (.1,X.) + DELTA;
CURRENT2 := CURRENT2 + DELTA; WRITE (IFILE,CURRENT1:7:4,' '); COUNTER CURRENT := COUNTER CURRENT + CURRENT2;
END; (* FARAADIC_CONVERSION *)

PROCEDURE SETUP FOR NEXT ITERATION;
VAR I, J : INTEGER;
BEGIN
  FOR J := 1 TO XMAX DO BEGIN
    FOR I := 1 TO CURRENT ZMAX DO BEGIN
      FAOLD (.I,J.) := FANEW (.I,J.);
      FBOLD (.I,J.) := FBNEW (.I,J.);
    END; (* FOR I *)
  END; (* FOR *)
  COUNTER CURRENT := 0; SUM CURRENT := 0;
  CURRENT PASS := CURRENT PASS + 1;
  IF CURRENT ZMAX > ZMAX THEN CURRENT ZMAX := ZMAX;
END; (* SETUP FOR NEXT_ITERATION *)

PROCEDURE FILE CONCENTRATION ARRAYS;
VAR AFILE, BFILE : TEXT; I, J : INTEGER;
BEGIN
  ASSIGN (AFILE,'C:\PASCAL\SIMULATE\AFILE.DAT');
  ASSIGN (BFILE,'C:\PASCAL\SIMULATE\BFILE.DAT');
  REWRITE (AFILE); REWRITE (BFILE);
  Writeln (AFILE,'SPECIES A; ZMAX WAS ',CURRENT ZMAX,'; XMAX WAS ',XMAX);
  Writeln (BFILE,'SPECIES B; ZMAX WAS ',CURRENT ZMAX,'; XMAX WAS ',XMAX);
  FOR I := 1 TO CURRENT ZMAX DO BEGIN
    WRITE (AFILE,(I-1)*6,' '); WRITE (BFILE,(I-1)*6,' ');
  END; (* FOR *)
  Writeln (AFILE); Writeln (BFILE);
END; (* FOR *)
CLOSE (AFILE); CLOSE (BFILE); CLOSE (IFILE);
CLOSE (CONSOLE);
END; (* FILE_CONCENTRATION_ARRAYS *)

PROCEDURE EDGE_EFFECT_CURRENT;
VAR DELTA1, DELTA2 : REAL;
BEGIN
  DELTA1 := ON OFF (.0.) * ASYM_FACTOR (.0.) *
  (FANEW (.1,16.) - THETA (.0.) * FBNEW (.1,16.)) /
  (THETA (.0.) + 1);
  FANEW (.1,16.) := FANEW (.1,16.) - DELTA1;
  FBNEW (.1,16.) := FBNEW (.1,16.) + DELTA1;
  DELTA2 := ON OFF (.0.) * ASYM_FACTOR (.0.) *
  (FANEW (.1,177.) - THETA (.0.) * FBNEW (.1,177.)) /
  (THETA (.0.) + 1);
  FANEW (.1,177.) := FANEW (.1,177.) - DELTA2;
  FBNEW (.1,177.) := FBNEW (.1,177.) + DELTA2;
  COUNTER_CURRENT := COUNTER_CURRENT + DELTA1 + DELTA2;
END; (* EDGE_EFFECT_CURRENT *)

BEGIN
  INITIALIZE; CLRSCR; GOTOXY (10,10);
  WRITE (CHR(7),CHR(7),'SIMULATION COMPLETE.');
END. (* TENBYONE *)
(*** Data file INPUT.PRM. This file is used as the input file for the program 10x1. ***)

0.121
-0.090 1 1.000
+0.280 1 1.000
+0.240 1 1.000
+0.200 1 1.000
+0.160 1 1.000
+0.120 1 1.000
+0.080 1 1.000
+0.040 1 1.000
+0.000 1 1.000
-0.040 0 1.000
-0.080 1 1.000
1.000
1.000
500
1
298

(* REDOX POTENTIAL OF COUPLE : EZERO *)
(POTENTIAL AT COUNTER EO ON/OFF ASYM FACTOR)
(* POTENTIAL AT ELECTRODE 1 *)
(* POTENTIAL AT ELECTRODE 2 *)
(* POTENTIAL AT ELECTRODE 3 *)
(* POTENTIAL AT ELECTRODE 4 *)
(* POTENTIAL AT ELECTRODE 5 *)
(* POTENTIAL AT ELECTRODE 6 *)
(* POTENTIAL AT ELECTRODE 7 *)
(* POTENTIAL AT ELECTRODE 8 *)
(* POTENTIAL AT ELECTRODE 9 *)
(* POTENTIAL AT ELECTRODE 10 *)
(* DIFFUSION COEFFICIENT RATIO : A/B (>1) *)
(* INITIAL FRACTIONAL CONCENTRATION OF A *)
(* INITIAL FRACTIONAL CONCENTRATION OF B *)
(* MAX_PASS : MAXIMUM NUMBER OF ITERATIONS *)
(* N : NUMBER OF ELECTRONS *)
(* TEMPERATURE : KELVIN *)
(* Program TENBYTEN. Used to simulate diffusion at a 10x10 electrode. *)

PROGRAM TENBYTEN (INPUT, OUTPUT);
USES CRT;

CONST XMAX = 240; ZMAX = 8; (X=W/4; X-Z;)
DMA = 0.250; R = 8.314; F = 96485;
TYPE CONCENTRATION = ARRAY (.1..ZMAX,1..XMAX.) OF REAL;
THETA TYPE = ARRAY (.1..10,0..1.) OF REAL;
VAR FAOLD, FANEW, FBOLD, FBNEW: CONCENTRATION;
CURRENT_PASS, CURRENT_ZMAX, I, MAX_PASS: INTEGER;
DMB, AINIT, BINIT: REAL;
ICFILE, IGFILE, CONSOLE, INPUTFILE: TEXT; (* I/O FILES *)
THETA: THETA TYPE;
ASYM_FACTOR: THETA TYPE;
ON_OFF: ARRAY (.0..10,07.1.) OF INTEGER; (* ON OR OFF *)

PROCEDURE ERROR_RTN (COMPLETION_CODE: INTEGER);
BEGIN
ASSIGN (CONSOLE,'TRM:') ;
REWRITE (CONSOLE);
WRITELN (CONSOLE,'***> USER ABEND IN TENBYONE');
CASE COMPLETION_CODE OF
1 : BEGIN (* INVALID ON/OFF OPTION *)
WRITELN (CONSOLE,'EXECUTION HALTED. IMPROPER VALUE',
'FOR ON/OFF OPTION OF ELECTRODE. CHOOSE A VALUE',
'OF 1 FOR ON OR A VALUE OF 0 FOR OFF.');END; (* CASE 1 *)
2 : BEGIN (* INVALID DRATIO *)
WRITELN (CONSOLE,'EXECUTION HALTED. IMPROPER VALUE',
'(D(A)/D(B)) RATIO MUST BE GREATER THAN OR','EQUAL TO ONE.');?>
END; (* CASE 2 *)
END; (* CASE *)
CLOSE (CONSOLE); CLOSE (INPUTFILE); HALT;
END; (* ERROR_RTN *)

PROCEDURE INITIALIZE;
VAR I, J: INTEGER; N: INTEGER; EZERO: REAL; T: REAL;
DRATIOAB: REAL; E: ARRAY (.1..10,0..1.) OF REAL;
BEGIN
ASSIGN (INPUTFILE,'C:\MIKE\INPUT10.PRM');
RESET (INPUTFILE);
READLN (INPUTFILE,EZERO);
FOR I :- 1 TO 10 DO BEGIN
READLN (INPUTFILE,E(.1,0.),ON_OFF(.I,0.),
ASYM_FACTOR(.I,0.));
IF NOT (ON_OFF (.I,0.) - 0) OR (ON_OFF (.I,0.) - 1) THEN
ERROR_RTN (1);
READLN (INPUTFILE,E(.1,1.),ON_OFF(.I,1.),
ASYM_FACTOR(.I,1.));
IF NOT (ON_OFF (.I,1.) - 0) OR (ON_OFF (.I,1.) - 1) THEN
ERROR_RTN (1);
END; (* FOR *)
READLN (INPUTFILE,DRATIOAB); DMB := DMA / DRATIOAB;
IF DMB > 0.250 THEN ERROR_RTN(2);
READLN (INPUTFILE,AINIT); READLN (INPUTFILE,BINIT);
READLN (INPUTFILE,MAX_PASS); READLN (INPUTFILE,N);
READLN (INPUTFILE,T);_CLOSE (INPUTFILE);
FOR I :- 1 TO ZMAX DO
FOR J : - 1 TO XMAX DO BEGIN
FAOLD (.I,J.) := AINIT; FANEW (.I,J.) := AINIT;
FBOLD (.I,J.) := BINIT; FBNEW (.I,J.) := BINIT;
END; (* FOR *)
ASSIGN (CONSOLE,'C:\MIKE\CONSOLE.DAT');
REWRITE (CONSOLE);
WRITELN (CONSOLE, 'TENBYTEN SIMULATION — ->');
WRITELN (CONSOLE, ' CONDITIONS AT EACH ELECTRODE:');
WRITELN (CONSOLE, ' REDOX POTENTIAL: ',EZERO:5:3);
FOR I :- 1 TO 10 DO BEGIN
THETA (.I,0.) := EXP(((N*F)/(R*T))*(E(.I,0.)-EZERO));
END;
WRITE (CONSOLE, ' COL POTENTIAL ', 'I:2', ': ', E(.1,0.):5:3, ' ; THETA = ', THETA (.1,0.):10:5, ' ; ASYM', ' ; \text{FACTOR} = ', ASYM FACTOR (.1,0.):6:3, ' ; \text{THETA} = ', THETA (.1,1.):10:5, ' ; ASYM', ' ; \text{FACTOR} = ', ASYM FACTOR (.1,1.):6:3, ' ; \text{ON} ');

IF ON OFF (.1,0.) = 1 THEN WRITELN (CONSOLE, 'ON ')
ELSE WRITELN (CONSOLE, 'OFF ');

THETA (.1,1.) = \text{EXP}\left((N*F)/(R*T)\right)\times(E(.1,1.)-EZERO); WRITE (CONSOLE, ' GEN POTENTIAL ', 'I:2', ': ', E(.1,1.):5:3, ' ; THETA = ', THETA (.1,1.):10:5, ' ; ASYM', ' ; \text{FACTOR} = ', ASYM FACTOR (.1,1.):6:3, ' ; \text{OFF} ');

IF ON OFF (.1,1.) = 1 THEN WRITELN (CONSOLE, 'ON ')
ELSE WRITELN (CONSOLE, 'OFF ');

END; (* FOR *)

WRITELN (CONSOLE, ' DMA: ', DMA:5:3);
WRITELN (CONSOLE, ' DMB: ', DMB:5:3);
WRITELN (CONSOLE, ' L/W: ', ZMAX/4:5:2);
WRITELN (CONSOLE, ' INITIAL A CONCENTRATION ', 'AINIT:6:3');
WRITELN (CONSOLE, ' INITIAL B CONCENTRATION ', 'BINIT:6:3');
WRITELN (CONSOLE, ' NUMBER OF ELECTRONS ', 'N:2');
WRITELN (CONSOLE, ' TEMPERATURE (KELVIN) ', 'T:7:2');
WRITELN (CONSOLE, ' MAX PASS:4 ', 'ITERATIONS');
WRITELN (CONSOLE); ASSIGN (ICFILE, 'C:\MIKE\ICFILE.DAT'); REWRITE (ICFILE);
WRITELN (ICFILE, ' TIME':7, 'I (1)':8, 'I (2)':8, 'I (3)':8, 'I (4)':8, 'I (5)':8, 'I (6)':8, 'I (7)':8, 'I (8)':8, 'I (9)':8, 'I (10)':8);
ASSIGN (ICFILE, 'C:\MIKE\ICFILE.DAT'); REWRITE (ICFILE);
WRITELN (ICFILE, ' TIME':7, 'I (1)':8, 'I (2)':8, 'I (3)':8, 'I (4)':8, 'I (5)':8, 'I (6)':8, 'I (7)':8, 'I (8)':8, 'I (9)':8, 'I (10)':8);
CURRENT PASS := 1;

FUNCTION DONE: BOOLEAN;
BEGIN
IF CURRENT PASS < (MAX_PASS+1) THEN DONE := \text{FALSE}
ELSE BEGIN
DONE := \text{TRUE}; CURRENT PASS := CURRENT PASS - 1;
WRITELN (CONSOLE, ' TEN BY TEN SIMULATION HAS REACHED A', ' NORMAL COMPLETION.');
END; (* ELSE *)
END; (* DONE *)

PROCEDURE DIFFUSION_WITHIN_BOUNDARIES;
VAR I, J : INTEGER;
BEGIN
FOR I := 2 TO (CURRENT_ZMAX - 1) DO
FOR J := 2 TO XMAX-1 DO BEGIN
FANEW (.I,J) := FAOLD (.I+1,J) + DMA \times (2 \times FAOLD (.I-1,J));
FANEW (.I,J) := FBOLD (.I,J) + DBM \times (2 \times FBOLD (.I,J));
END; (* FOR *)
END; (* DIFFUSION_WITHIN_BOUNDARIES *)

PROCEDURE DIFFUSION_AT_CORNERS;
BEGIN
FANEW (.1,1.1) := FAOLD (.1,1.1) + DMA \times (2 \times FAOLD (.1,1.1));
FANEW (.CURRENT_ZMAX,1.) := FAOLD (.CURRENT_ZMAX,1.) + DMA \times (2 \times FAOLD (.CURRENT_ZMAX,1.));
PROCEDURE DIFFUSION_AT_CORNERS;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (XMAX-1) DO BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.2,1.) -
  3 * FAOLD (.1,1.) + FAOLD (.1,(I-1).) +
  FAOLD (.1,(I+1).));
  FANEW (.CURRENT ZMAX,1.) := FAOLD (.CURRENT ZMAX,1.) +
  DMA * (FAOLD (.CURRENT ZMAX-1,1.) -
  3 * FAOLD (.CURRENT ZMAX,1.) +
  FAOLD (.CURRENT ZMAX,(I-1).) +
  FAOLD (.CURRENT ZMAX,(I+1).));
  FBNEW (.1,1.) := FBOLD (.1,1.) + DMB * (FBOLD (.2,1.) -
  3 * FBOLD (.1,1.) + FBOLD (.1,(I-1).) +
  FBOLD (.1,(I+1).)));
  FBNEW (.CURRENT ZMAX,1.) := FBOLD (.CURRENT ZMAX,1.) +
  DMB * (FBOLD (.CURRENT ZMAX-1,1.) -
  3 * FBOLD (.CURRENT ZMAX,1.) +
  FBOLD (.CURRENT ZMAX,(I-1).) +
  FBOLD (.CURRENT ZMAX,(I+1).));
END; (* FOR *)
END; (* PROCEDURE DIFFUSION_AT_CORNERS *)

PROCEDURE DIFFUSION_AT_HORIZONTAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (XMAX-1) DO BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.1,1.) -
  3 * FAOLD (.1,2.) +
  FAOLD (.1,(I-1).) +
  FAOLD (.1,(I+1).));
  FANEW (.CURRENT ZMAX,1.) := FAOLD (.CURRENT ZMAX,1.) +
  DMA * (FAOLD (.CURRENT ZMAX-1,1.) -
  3 * FAOLD (.CURRENT ZMAX,1.) +
  FAOLD (.CURRENT ZMAX,(I-1).) +
  FAOLD (.CURRENT ZMAX,(I+1).)));
  FBNEW (.1,1.) := FBOLD (.1,1.) + DMB * (FBOLD (.1,1.) -
  3 * FBOLD (.1,2.) +
  FBOLD (.1,(I-1).) +
  FBOLD (.1,(I+1).));
  FBNEW (.CURRENT ZMAX,1.) := FBOLD (.CURRENT ZMAX,1.) +
  DMB * (FBOLD (.CURRENT ZMAX-1,1.) -
  3 * FBOLD (.CURRENT ZMAX,1.) +
  FBOLD (.CURRENT ZMAX,(I-1).) +
  FBOLD (.CURRENT ZMAX,(I+1).));
END; (* FOR *)
END; (* PROCEDURE DIFFUSION_AT_HORIZONTAL_EDGES *)

PROCEDURE DIFFUSION_AT_VERTICAL_EDGES;
VAR I : INTEGER;
BEGIN
FOR I := 2 TO (CURRENT ZMAX-1) DO BEGIN
  FANEW (.1,1.) := FAOLD (.1,1.) + DMA * (FAOLD (.I+1,1.) -
  3 * FAOLD (.I,1.) +
  FAOLD (.I,1.) +
  FAOLD (.I,1.)));
  FANEW (.1,XMAX.) := FAOLD (.1,XMAX.) + DMA * (FAOLD (.I+1,XMAX.) -
  3 * FAOLD (.I,XMAX.) +
  FAOLD (.I,XMAX.) +
  FAOLD (.I,XMAX.)));
  FANEW (.I,1.) := FAOLD (.I,1.) + DMA * (FAOLD (.I+1,1.) -
  3 * FAOLD (.I,1.) +
  FAOLD (.I,1.) +
  FAOLD (.I,1.)));
  FANEW (.I,XMAX.) := FAOLD (.I,XMAX.) + DMA * (FAOLD (.I+1,XMAX.) -
  3 * FAOLD (.I,XMAX.) +
  FAOLD (.I,XMAX.) +
  FAOLD (.I,XMAX.)));
END; (* FOR *)
END; (* PROCEDURE DIFFUSION_AT_VERTICAL_EDGES *)

PROCEDURE FARADALIC CONVERSION (SEGMENT : INTEGER);
VAR CURRENT0, CURRENT1 : REAL;
FUNCTION CONCDIFF (XPOS, COLLGEN : INTEGER) : REAL;
VAR DELTA : REAL;
BEGIN
  XPOS := XPOS + 20 * SEGMENT;
  DELTA := ON_OFF (.SEGMENT,COLLGEN.) *
ASYM FACTOR (*SEGMENT,COLGEN.) * (FANEW (.I,XPOS.) -
THETA (*SEGMENT,COLGEN.) * FBNEW (.I,XPOS.)) /
(THETA (*SEGMENT,COLGEN.) + 1);
FANEW (.I,XPOS.) := FANEW (.I,XPOS.) - DELTA;
FBNEW (.I,XPOS.) := FBNEW (.I,XPOS.) + DELTA;
CONCDIFF := DELTA;
END; (* CONCDIFF *)

BEGIN
(* FIRST TAKE CARE OF STEPPED ELECTRODE PAIR *)
CURRENT := CONCDIFF (2,0) + CONCDIFF (3,0) + CONCDIFF (10,0)
+ CONCDIFF (11,0) + CONCDIFF (18,0) + CONCDIFF (19,0);
(* NOW TAKE CARE OF GENERATOR ELECTRODE FILAMENTS *)
CURRENT1 := CONCDIFF (6,1) + CONCDIFF (7,1) + CONCDIFF (14,1)
+ CONCDIFF (15,1);
WRITE (ICFILE,CURRENT:7:4,'  ');
WRITE (IGFILE,CURRENT1:7:4,'  ');
END; (* FARADAIC_CONVERSION *)

PROCEDURE SETUP FOR NEXT ITERATION;
VAR I, J : INTEGER;
BEGIN
FOR J := 1 TO XMAX DO BEGIN
FOR I := 1 TO CURRENT ZMAX DO BEGIN
FAOLD (.I,J.) := FANEW (.I,J.);
FBOLD (.I,J.) := FBNEW (.I,J.);
END; (* FOR I *)
END; (* FOR *)
CURRENT PASS := CURRENT PASS + 1;
CURRENT ZMAX := ROUND(3 * SQRT(CURRENT PASS));
IF CURRENT ZMAX > ZMAX THEN CURRENT ZMAX := ZMAX;
END; (* SETUP FOR NEXT ITERATION *)

PROCEDURE FILE CONCENTRATION ARRAYS;
VAR AFILE, BFILE : TEXT; I, J : INTEGER;
BEGIN
REWRITE (AFILE); REWRITE (BFILE);
WRITELN (AFILE,'SPECIES A; ZMAX WAS ',CURRENT ZMAX,
'; XMAX WAS ',XMAX);
WRITELN (BFILE,'SPECIES B; ZMAX WAS ',CURRENT ZMAX,
'; XMAX WAS ',XMAX);
FOR I := 1 TO CURRENT ZMAX DO BEGIN
WRITE (AFILE,(I-1):6,'  ');
WRITE (BFILE,(I-1):6,'  ');
FOR J := 2 TO 11 DO BEGIN
WRITE (AFILE,FANEW (.I,J*20+7.):6:3,
FANEW (.I,J*20+11.):6:3);
WRITE (BFILE,FBNEW (.I,J*20+7.):6:3,
FBNEW (.I,J*20+11.):6:3);
END; (* FOR *)
WRITELN (AFILE); WRITELN (BFILE);
END; (* FOR *)
CLOSE (AFILE); CLOSE (BFILE); CLOSE (ICFILE);
CLOSE (IGFILE); CLOSE (CONSOLE);
END; (* FILE CONCENTRATION ARRAYS *)

BEGIN
INITIALIZE;
REPEAT
DIFFUSION WITHIN BOUNDARIES; DIFFUSION AT CORNERS;
DIFFUSION AT HORIZONTAL EDGES; DIFFUSION AT VERTICAL EDGES;
WRITE (ICFILE,((CURRENT PASS-0.5) / MAX PASS):7:4,'  ');
WRITE (IGFILE,((CURRENT PASS-0.5) / MAX PASS):7:4,'  ');
FOR I := 1 TO 10 DO FARADAIC CONVERSION (I);
SETUP FOR NEXT ITERATION;
WRITELN (ICFILE); WRITELN (IGFILE);
UNTIL DONE;
FILE CONCENTRATION ARRAYS;
END. (* TENBYTEN *)
(*** Data file INPUT10.PRM. This file is used as the input file for the program TENBYTEN. ***)

+0.121  (* REDOX POTENTIAL OF COUPLE : EZERO *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 1 *)
+0.280 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 1 *)
+0.240 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 2 *)
-0.090 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 2 *)
+0.150 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 3 *)
+0.200 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 3 *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 4 *)
+0.160 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 4 *)
+0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 5 *)
-0.090 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 5 *)
+0.120 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 6 *)
+0.090 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 6 *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 7 *)
+0.080 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 7 *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 8 *)
+0.000 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 8 *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 9 *)
-0.040 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 9 *)
-0.090 1 1.000  (* POTENTIAL AT COLLECTOR ELECTRODE 10 *)
-0.080 1 1.000  (* POTENTIAL AT GENERATOR ELECTRODE 10 *)
1.000  (* DIFFUSION COEFFICIENT RATIO : A/B (>-1) *)
0.000  (* INITIAL FRACTIONAL CONCENTRATION OF A *)
1.000  (* INITIAL FRACTIONAL CONCENTRATION OF B *)
1000  (* MAX PASS : MAXIMUM NUMBER OF ITERATIONS *)
1  (* N : NUMBER OF ELECTRONS *)
298  (* TEMPERATURE : KELVIN *)
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