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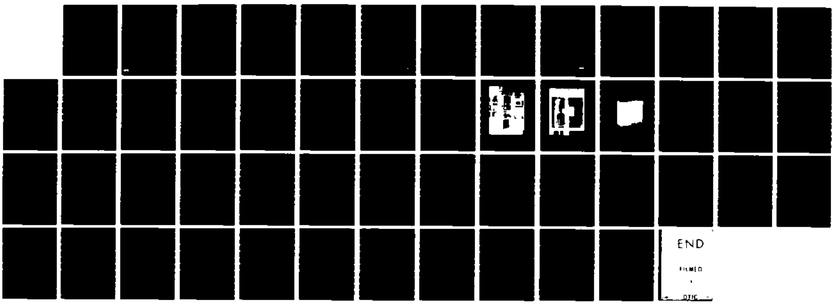

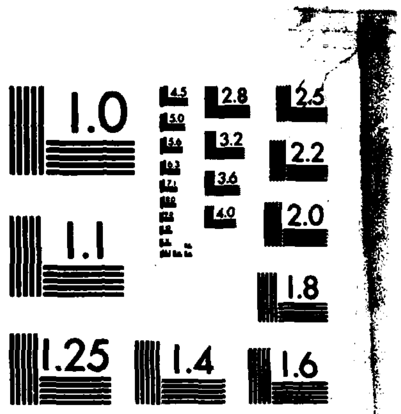

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PREDICTION OF CRACK GROWTH IN AQUEOUS ENVIRONMENTS

First Annual Report

June 1983

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This first annual progress report describes the current status of a research program to develop a predictive model for stress corrosion cracking and corrosion fatigue. Our approach is to simultaneously characterize the electrochemical and mechanical state of the crack during the failure process.

The electrochemical parameters for both bulk (uncracked) and cracked specimens are being determined using AC impedance techniques. The repassivation kinetics for the system under study are established by performing "scratching" or

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straining electrode experiments on the bulk specimens if data are not available in the literature. The environmentally assisted crack growth rates are measured as necessary on compact tension specimens using fracture mechanics procedures and analyses. These measurements are made simultaneously with the AC impedance measurements on actively growing cracks.

The results of such experiments should indicate the effects of microstructure, electrochemistry, and loading condition on the failure process and allow a computational failure model to be constructed. Initial work has concentrated on a titanium alloy in a 3.5% NaCl solution; however, the predictive model is also expected to apply to other systems of interest.

CONTENTS

FIGURES

I INTRODUCTION

The following discussion highlights the need to characterize simultaneously the electrochemical and mechanical states in a growing stress corrosion or corrosion-fatigue crack. We also point out the need for a suitable method for investigating electrochemical behavior within a crack. The research program described here addresses these needs and ultimately aims at using the resulting data to develop a predictive model for stress corrosion cracking (SCC) and corrosion fatigue (CF).

The load-bearing capacity of most alloys can be weakened by a corrosive environment. Two common forms of environment-sensitive mechanical property degradation are SCC and CF. Both forms greatly influence the safety, reliability, and economics of many components used in military and commercial power generation, transportation, and energy conversion systems. Therefore, substantial effort has been made to understand environment-assisted crack growth, to identify and develop materials that have improved environment resistance, and to formulate computational, predictive models.[1-15]

As a result, various models have been proposed over the years for SCC, CF, or other types of environment-assisted crack growth. Wei and Landes,[10] for example, considered the crack growth rate in a CF situation to consist of the sum of the crack growth rate in an inert environment and an environment-assisted growth rate. The Wei and Landes theory has been shown to explain adequately many features of the CF behavior of Ti and Ti-6Al-4V in NaCl solutions.[11] Furthermore, this work emphasized the need for a better understanding of the processes that occur at the crack tip, particularly at threshold load levels for crack growth and at low loading frequencies (< 1 Hz).

For SCC alone, Logan[7] proposed a model for cracking in aqueous environments based on a slip-dissolution mechanism at the crack tip. This mechanism, now widely accepted,[5-7] relates crack growth to the enhanced anodic dissolution current at the crack tip resulting from the intermittent mechanical rupture of an environmentally created film at the crack tip.

Logan's model has been modified to include a variety of rate-controlling processes that include repassivaton rate, microcreep, solution renewal, and critical charge concepts.[8] If the processes occurring within the crack were better understood, it would be possible to determine the appropriate slip-dissolution model for any given material, environment, and load application.

Quantitative modeling of the cracking process is complicated because it involves complex interactions between the cracking material, the environment, and the applied load. Because specimen microstructure, surface chemistry, electrochemistry, and loading conditions are expected to influence cracking behavior, they should be accounted for in attempts to model crack growth. Clearly, simultaneous characterization of the mechanical and electrochemical state at the crack tip is required for development of a reliable, predictive crack growth model.

The mechanical state at the crack tip is usually described in these models using classical fracture mechanics parameters such as the linear elastic stress intensity (K parameter)[16,17] or, more recently, the elastic-plastic stress intensity (J parameter),[18,19]. Unfortunately, the electrochemical state of the crack tip is not so easily characterized because, until recently, no reliable experimental method existed that could either provide measurements directly within the crack or could convert measurements made external to the crack into crack tip parameters. Some attempts have been made to measure the local chemistries that develop at crack tips by using microanalytical chemical techniques on specimens that are actually cracking or on artifical crevices that had been constructed to simulate stress corrosion cracks. However, most of past crack growth models have used electrochemical data obtained on bulk specimens and have assumed that such data, such as the free corrosion potential, are representative of values inside the crack, or these bulk values were extrapolated to crack tip values by means of some postulated model. As might be expected, crack growth rates predicted by such models are several orders of magnitude different from those that are actually observed.[20,21]

One possible method for evaluating the electrochemical state of material in the vicinity of a crack tip is the AC impedance technique. This technique, under development for the past several years,[22-26] has only recently been applied to the problem of environmentally assisted cracking. This approach shows promise for determining crack tip electrochemical parameters by applying the transmission line model to deconvolve the measured AC impedance spectra of growing cracks. A detailed description of this technique as applied to the problem of environmentally assisted cracking is given in the following section.

II THEORETICAL CONSIDERATIONS

The stress corrosion or corrosion-fatigue crack is modeled by a cracked electrode. The solid and electrolyte phases in the cracked electrode are represented by resistance elements parallel to the direction of the corrosion current flux, and the interfacial resistance is represented by an impedance distributed between the other two resistances. The electrode may be treated as "one-dimensional" if the potential (E), current flux (I), and reactant concentrations (c) vary only with the depth within the crack and not with the lateral position along the crack. In this case, the local values of E, I, and c may be replaced by their average values in a line perpendicular to the crack plane.

Ksenzheck and Stender[27] discussed the conditions that are applicable to transforming a three-dimensional problem into a one-dimensional one. The mathematical model for the electrical representation shown in Figure 1 requires solutions to a set of differential equations of the form

$$\frac{d^2 I_s}{dx^2} + \frac{d\ \ln(Z)}{dx}\ \frac{dI_s}{dx} - \frac{(r_s + r_e)I_s}{Z} = -\frac{r_e I}{Z} \qquad (1)$$

$$\frac{d^2 I_e}{dx^2} + \frac{d\ \ln(Z)}{dx}\ \frac{dI_e}{dx} - \frac{(r_s + r_e)I_e}{Z} = -\frac{r_s I}{Z} \qquad (2)$$

$$\frac{d^2 \Delta E}{dx^2} - \frac{(r_s + r_e)}{Z}\ \Delta E = 0 \qquad (3)$$

where r is the resistance; subscripts e and s refer to the electrolyte and solid phases, $I = I_s + I_e$, Z is the interfacial impedance, x is distance into the crack, and $\Delta E = E_s - E_e$.

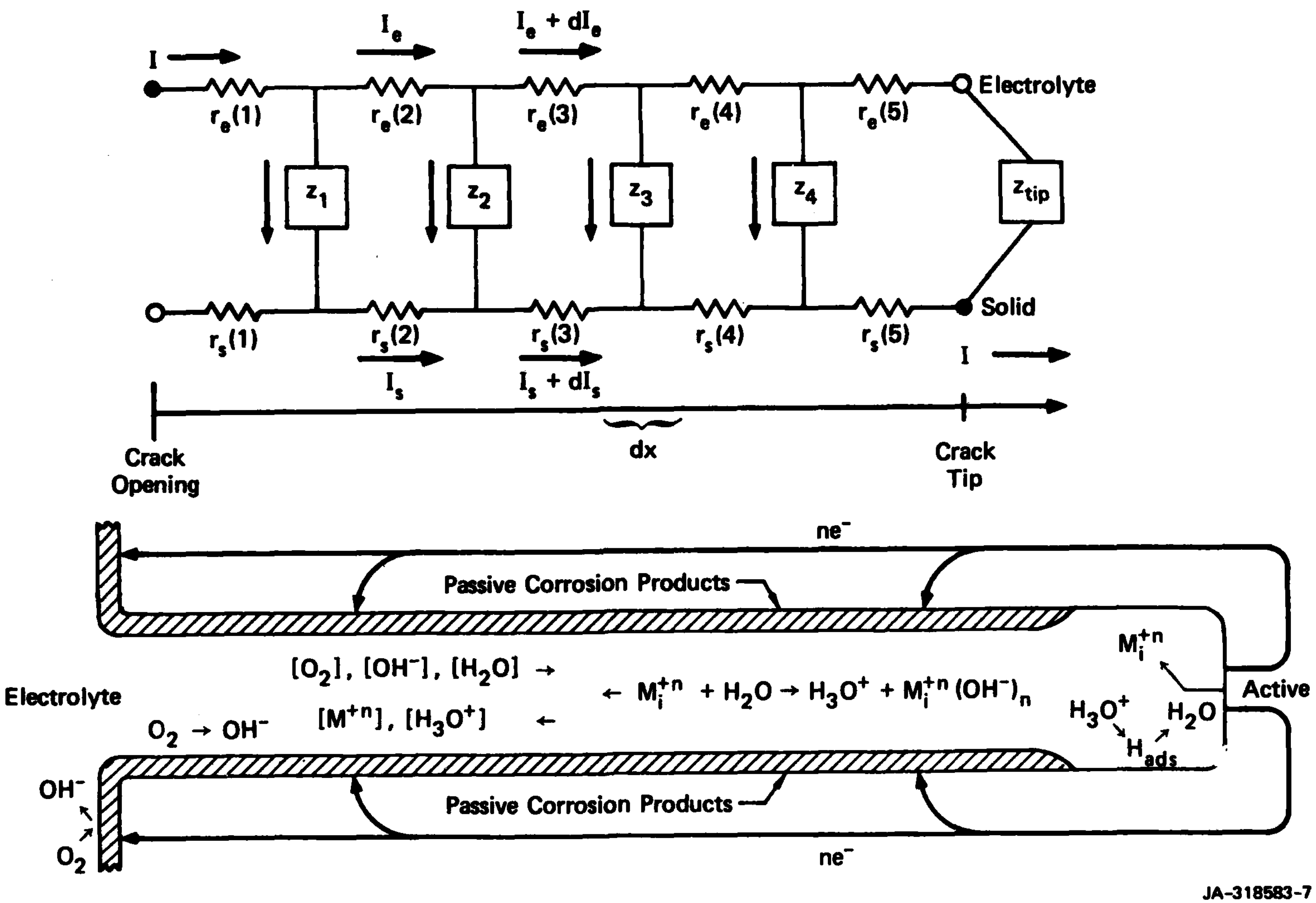


FIGURE 1 TRANSMISSION LINE MODEL FOR A CRACK IN AN AQUEOUS ENVIRONMENT

For the simplest set of boundary conditions corresponding to an electrolyte-filled right cylindrical crack in which r_s and r_e are independent of x and the solid and electrolyte phase current contacts are diametrically opposed, as shown in Figure 1, the transmission line impedance Z_{tl} is given by [28]

$$Z_{tl} = \frac{4r_s r_e + (r_s^2 + r_e^2)(e^{\gamma l} + e^{-\gamma l})}{(r_s + r_e)(e^{\gamma l} - e^{-\gamma l})} + \frac{r_s r_e l}{r_s + r_e} \tag{4}$$

where l is the current crack length, and

$$\gamma = [(r_s + r_e)/Z_i]^{1/2} \tag{5}$$

The interfacial impedance, Z_i, in equation (5) is equivalent to that at a plane-parallel electrode. That is, it contains the information that would be available if it were possible to determine the electrochemical kinetic properties of each infinitesimal element, dx, of the electrode thickness in the x direction.

The conventional[22-24] equivalent circuit for Z_i is shown in Figure 2. The components of this circuit contain the electrochemical kinetic parameters that are important in evaluating the behavior of a cracked electrode. Brief descriptions of these parameters follow.

Double Layer Capacitance, C. The double-layer capacitance, C, is directly proportional to the area of the electrolyte/solid phase interface. Thus, given a knowledge of the double-layer capacitance per unit area, C', under the prevailing conditions of reactant concentration, temperature, and potential, one can determine C by deconvolving the measured transmission line impedance. This value of C can then be used to estimate the total wetted area per unit electrode thickness,[28] which we define as A'. Values of C' may be available from the literature or can be measured directly for a plane-parallel electrode of known area.

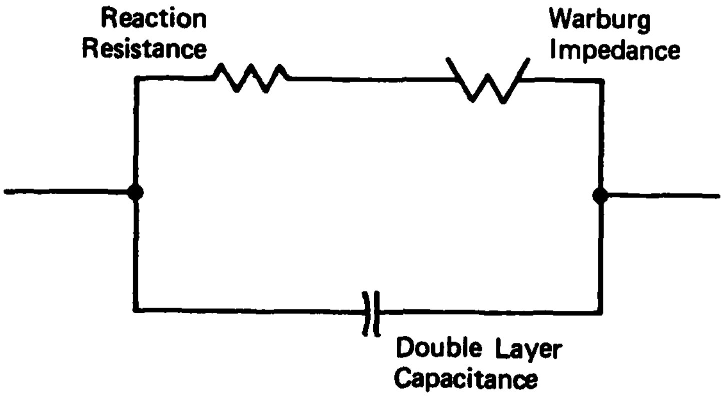


FIGURE 2 INTERFACIAL IMPEDANCE ELEMENT; RANDLES' EQUIVALENT CIRCUIT

Warburg Coefficient, σ. At moderate frequencies ($\gtrsim$ 1 Hz), the Warburg impedance, Z_w, can be expressed as [22,24,29]

$$Z_w = \sigma(1 - j)\omega^{1/2} \tag{6}$$

where

$$\sigma = \frac{RT}{n^2F^2cA''(2D)^{1/2}} \tag{7}$$

c is the reactant concentration, and A" expresses the electrode electrolyte area per unit length that is actively engaged in reaction. The other parameters in equation (7) have their usual meanings. The relationship between A' and A" can be used to define an area efficiency that accounts for the presence of passive zones, which do not contribute to the cell current during crack growth.

Diffusion Layer Thickness, δ. At the limit of low frequency, an apparent resistive shunt to the Warburg impedance is observed.[29-32] This resistance defines the steady-state DC operating behavior, and its value may be used in conjunction with σ to calculate the effective diffusion layer thickness, δ. In the derivation of equation (6), semi-infinite linear diffusion was assumed. However, in the wide regions near the crack mouth, natural convection will limit the thickness of the diffusion layer, whereas in the narrower regions near the crack tip, the dimension of the diffusion layer is proportional to the crack opening. Thus, we can account for the steady-state DC behavior[22,30-35] in the model of the cracked electrode by introducing the Nernst diffusion layer thickness as a boundary condition.

Interfacial Reaction Resistance, R_r. The reaction resistance together with A" and δ can be used to obtain information regarding the electrode kinetics[14,29,36] within the cracked electrode. The exchange current density, i_o, can be determined from the relationship

$$R_r = RT/nFA'i_o \tag{8}$$

When used in conjunction with the Stern-Geary relationship,[37] R_r provides a measure of the instantaneous corrosion rate within the crack.

Electrolyte Resistance, r_e. The electrolyte resistance per unit length in the cracked electrode, r_e, gives a measure of the amount, composition, and distribution of electrolyte in the crack. The electrolyte resistance will be controlled primarily by the crack width and to a smaller extent by the diffusion of reactant species from the bulk electrolyte and the diffusion of reaction products from the crack tip.

Solid Electrode Resistance, r_s. The solid phase resistance per unit length in the cracked electrode, r_s, provides a measure of the resistive component in the cracked electrode.

The reduction of the impedance data to obtain the parameters of interest for cracked electrodes involves applying nonlinear regression analysis to an impedance model or equivalent circuit. Broers and coworkers[38-40] have demonstrated the applicability of the transmission line model for characterizing porous electrodes in molten carbonate fuel cells, and we believe that these methods can be applied to a growing SC or CF crack.

An additional impedance element, Z_{tip}, has been included in Figure 1 to account for the special electrochemical characteristics of the crack tip. For example, if the crack grows by a mechanism of film rupture and anodic dissolution at the crack tip, then Z_{tip} can be represented as a special case of the equivalent circuit in Figure 2, with R_r determined by the exchange current density for metal dissolution (possibly involving terms for precipitation of oxide and repassivation). Under the conditions of a cyclic mechanical load, the area term A', in equation (8) must also be given as a periodic function about a mean value, A_o'. In the simplest case, A' would be linear function of the mechanical load for crack-opening displacement. Thus,

$$A_{tip} = A_{tip}^{o} \sin(\omega t + \phi) \quad (9)$$

where ω is the frequency of the load variation, and ϕ is the phase delay between load variation and film rupture.

Equation (9) suggests a second method of evaluating the electrochemistry of the crack tip environment, using the transmission line model. Under a steady electrical bias (a small DC voltage more positive than the free corrosion potential), a DC current can be made to flow from the specimen to a suitable counter electrode. This current originates with the anodic dissolution at the crack tip and is given by:

$$I\ (\omega t) = \eta / R_r \qquad (10)$$

where $\eta = V_{applied} - V_{free\ corrosion}$.

Substituting Equation (9) into Equation (8), and then substituting the resulting expression for R_r into Equation (10) yields:

$$I(\omega t) = \frac{\eta n F A^o_{tip} \sin\ (\omega t + \phi) i_o}{RT} \qquad (10')$$

This expression for $I(\omega t)$ describes the crack tip current expected for cyclic load conditions.

This can be viewed as a sinusoidal current source originating at the crack tip. The current source is situated where the interfacial reaction resistance (R_r in Figure 2) is placed in Z_{tip} in Figure 1.

Alternatively, we can define an electromechanical impedance,

$$Z_{em} = Z/I \qquad (11)$$

which may be examined as a function of the frequency (and amplitude) of the mechanical load variation.

The advantage of an electromechanical impedance study is that the perturbation is applied exactly at the point of interest (the crack tip). The alternative method, a variable frequency electrical potential variation applied to the mouth of a crack in a specimen cycled with a constant frequency mechanical load, results in a perturbation that decreases in amplitude at the crack tip, as the crack increases in length.

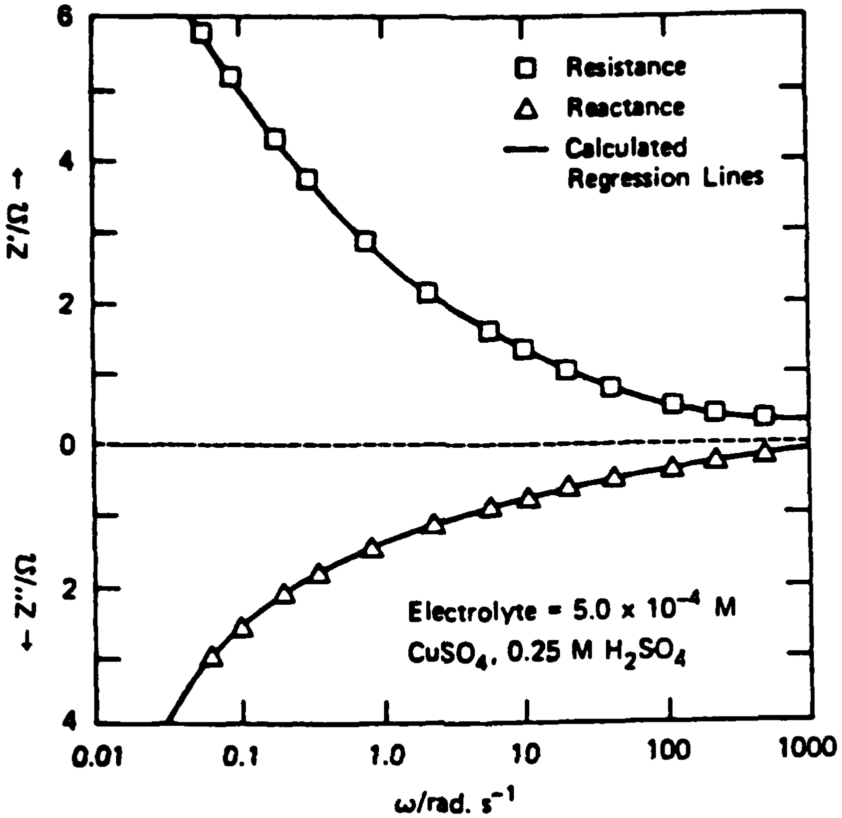
III EXPERIMENTAL METHODS

Background

To calculate accurately the many electrochemical parameters that can be obtained from AC measurements, one must make high precision impedance measurements over a wide range of frequencies, particularly at very low frequencies. The unavailability of adequate instrumentation has been the principal limitation to the characterization of cracked or porous systems by AC techniques and is largely responsible for the only modest success of Broers and coworkers.[38-40] More recently, Mund et al.[41] analyzed the performance of hydrogen electrodes in alkaline fuel cells systems from AC impedance measurements applied to a transmission line model.

The current work of Hills and coworkers[42-44] provides good verification for the application of the transmission line model and the extension of equilibrium AC measurements for predicting the steady-state electrochemical parameters. In one set of experiments, the interfacial impedance components were calculated from the measured impedance of a packed bed of graphite spheres using the transmission line model, and the results were compared with the interfacial impedance measured directly for a single sphere.

Figure 3 shows the impedance data obtained for a packed-bed electrode superimposed on the least-squares best fit of data to equation (4). The tabulated values of the double-layer capacitance, Warburg coefficient, and exchange current density for the packed bed have been calculated from this regression fit. These values may be compared with the interfacial impedance parameters measured directly for a single graphite sphere isolated from the bed. The substantial agreement between the two sets of calculated impedance parameters is strong verification for the applicability of the transmission line model to characterizing porous or cracked electrodes.



Derived Parameters	Packed Bed	Single Sphere	
C_d	154×10^{-6}	130×10^{-6}	F cm^{-2}
σ	120	120	$\Omega\ s^{-1/2}\ cm^{-2}$
i_o	6.3×10^{-3}	12.4×10^{-3}	cm^{-2}

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FIGURE 3 MEASURED AND CALCULATED IMPEDANCE SPECTRA FOR A BED OF 600-μm GRAPHITE SPHERES

It is clear from the foregoing discussion that many important operating parameters of porous and cracked electrodes are contained within the measured impedance dispersion. Two factors are fundamental in the application of this method to the in situ determination of electrode characteristics. First, impedance measurements must be of sufficient precision (better than 0.1% for each impedance component),[22] and second, the measurements must be made over a frequency range wide enough (10^{-3} to 10^{4} Hz) to adequately resolve the impedance spectrum and to allow subsequent deconvolution to obtain the electrochemical parameters.

The requirements for a high speed, high precision, impedance measurement system capable of operating at very low frequencies have been presented in detail by Macdonald and McKubre.[22] In general, these requirements are in conflict. Maximum acquisition speed is available from noise or transform methods, but these have low precision.[22] High precision is best achieved with a frequency-by-frequency measurement technique such as phase-sensitive detection, but the measurements are time consuming. Fortunately, this is not a serious hindrance when such equipment is automated and the experiments are run under computer control.

Experimental Methods for Current Program

Given the requirements discussed above, we developed an experimental facility designed to obtain data on crack electrochemistry during CF and SCC of various materials in aqueous solutions at room temperature and pressure, Figure 4 shows schematically the experiment arranged for impedance measurement of specimens under mechanical load conditions. Photographs of the setup are shown in Figure 5 (electronics), Figure 6 (test chamber), and Figure 7 (test specimen).

As detailed in Figure 4, impedance measurements were made using a Solartron Model 1250 frequency response analyzer (FRA) operated under microcomputer control. The Model 1250 is an automated, digitally demodulated, stepped frequency, impedance meter capable of 0.01%

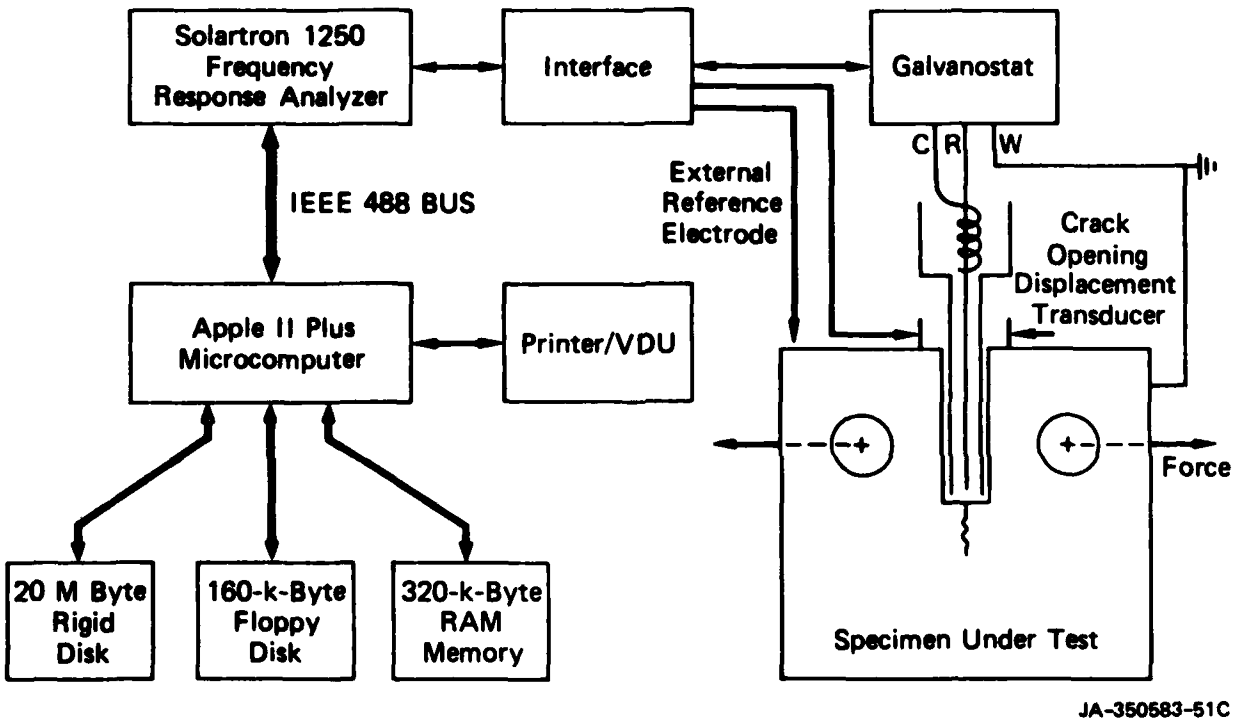

FIGURE 4 SCHEMATIC OF IMPEDANCE MEASUREMENT SYSTEM FOR STRESS CORROSION CRACK AND CORROSION FATIGUE TESTS

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FIGURE 5 FACILITY FOR MEASUREMENT OF IMPEDANCE SPECTRA OF STRESS CORROSION CRACKING OR CORROSION-FATIGUE TEST SPECIMENS

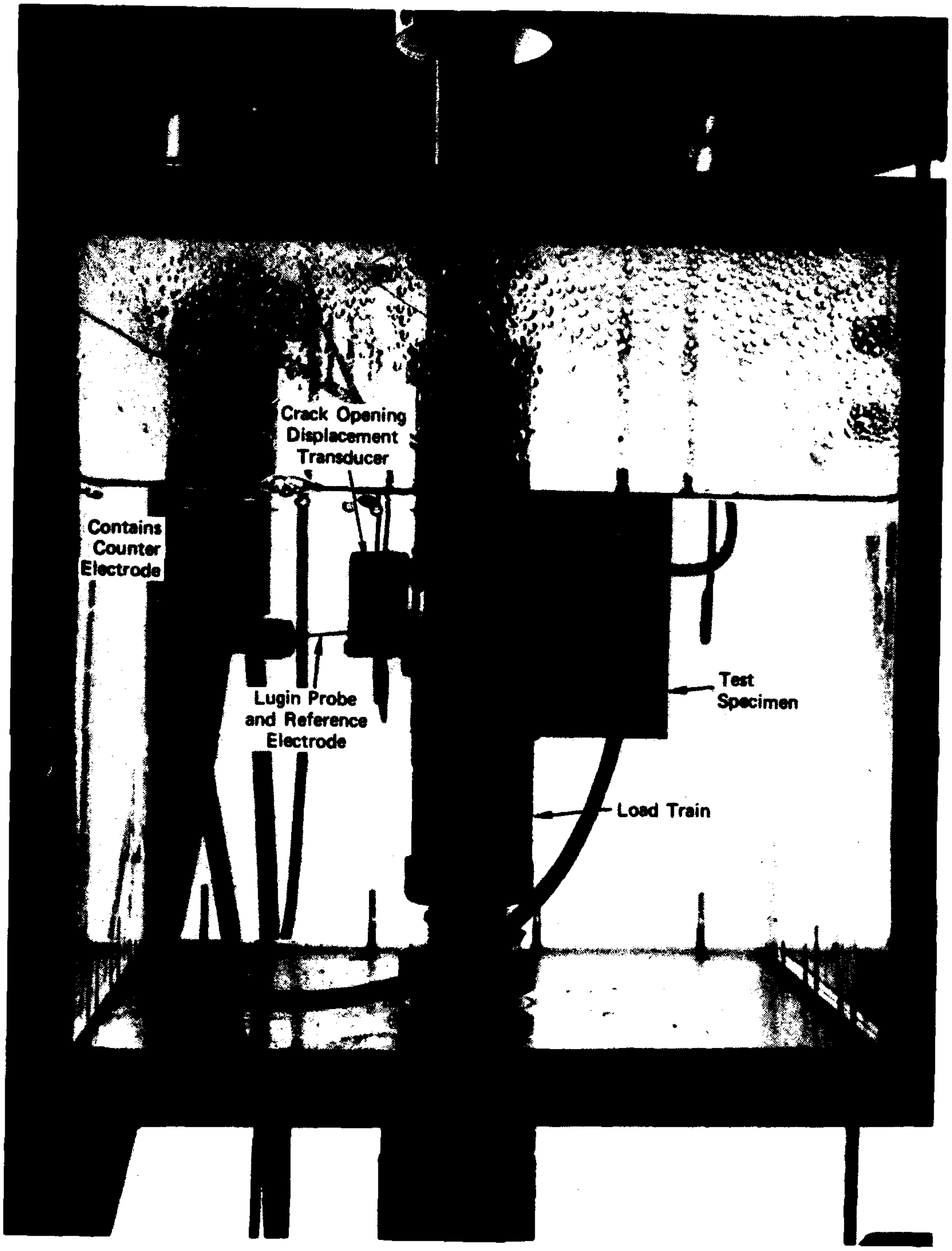

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FIGURE 6 DETAIL OF TEST CHAMBER

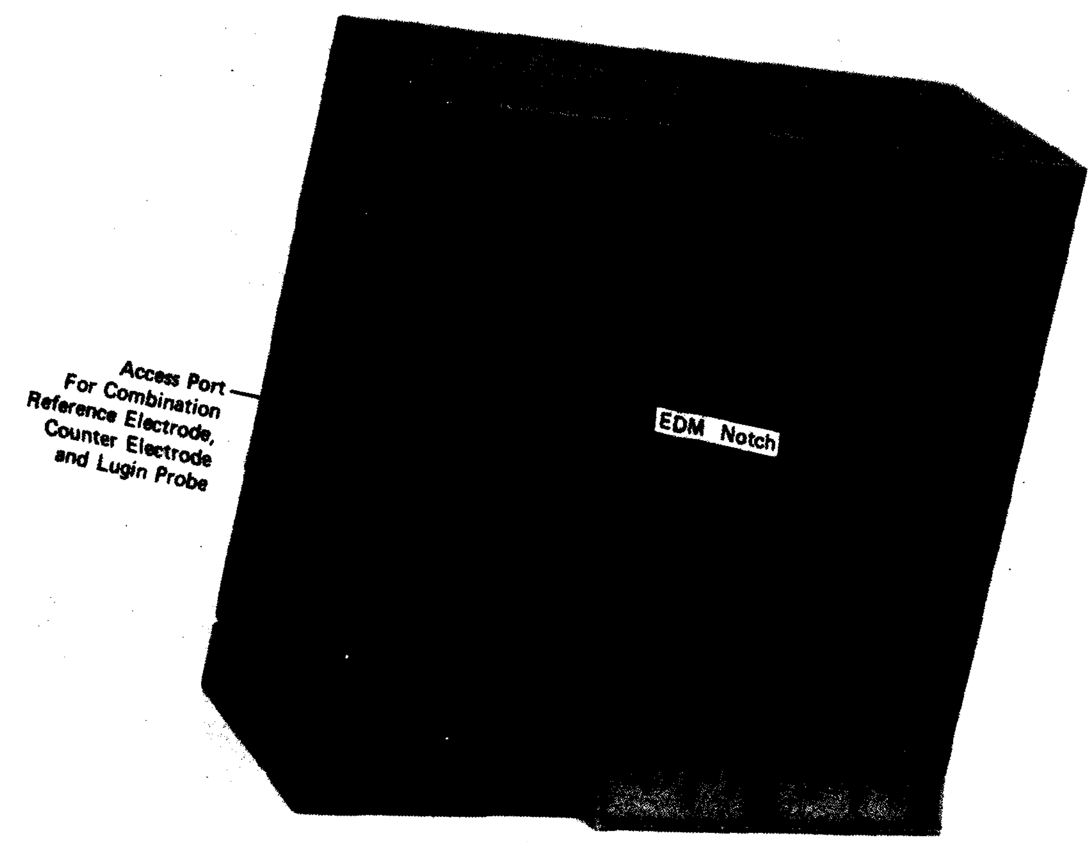

FIGURE 7 DETAIL OF TEST SPECIMEN

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precision for each impedance component in the frequency range 10^{-4} to 6×10^4 Hz. This instrument and the preceding series of frequency response analyzers (Solartron Model 1172 and 1174) have been used extensively in recent years to measure impedances in electrochemical systems.[45-49]

The FRA was operated under the control of an Apple II-Plus microcomputer with 64 K-bytes of internal random access memory (RAM) and 320 K-bytes of external RAM (Axlon "Ramdisk 320"), equipped with a 20 M-byte rigid disk (Corvus model 20 MB/M). The control program was written at SRI in Basic and 6502 Machine languages, and is included as Appendix A.

Some experiments were performed under potentiostatic control, using a Princeton Applied Research Model 173/276 potentiostat; however, most of the experiments were performed under pseudo-galvanostatic control. In the latter mode, a resistance several orders of magnitude larger than the cell impedance is placed in series with the counter electrode, and a large AC voltage is applied. To a good approximation, the current is determined by the AC voltage divided by the series resistance, independent of cell impedance.

Because of difficulties in interfacing our data acquisition system with the servohydraulic mechanical test facility, no data have yet been obtained on the electromechanical impedance (as described in Section II). The data reported in Section IV are for the results of sinusoidal current and voltage perturbations under static and cycled load conditions.

For experiments in which the load is cycled, it is necessary to synchronize the periods of the mechanical and electrical cycles. This was achieved by integrating the impedance data over one complete cycle of the mechanical load. Thus the results represent an average over a full cycle of crack-opening displacement. If these cycles are not synchronized, then the data may contain a large amount of systematic error and will inevitably show considerable scatter. For example, if the impedance measurements are integrated over a time that is short with respect to the period of the mechanical load cycle, then multiple determinations (at different electrical perturbation frequencies) may be made during a single mechanical cycle; these will cover the range from maximum to minimum crack opening. If the two periods are not synchonized, this will appear as scatter in the data set.

Because it is necessary to integrate over at least one cycle at the electrical perturbation, some error will be introduced at low frequencies when the impedance data are integrated over more than one (but not an integer number of) mechanical cycles. This is inevitable and results in some scatter in our data at very low frequencies (< 0.01 Hz).

An environmental chamber was constructed that attaches to a servo-hydraulic mechanical testing machine. This chamber and the associated attachments allow us to circulate aerated or deaerated 3.5% NaCl solution (or other electrolytes) at controlled temperatures past our fatigue precracked compact tension specimens. The crack growth can be measured by optical methods or by the compliance method, by means of a water-immersible LVDT mounted on the specimen. A special composite reference/counter electrode incorporates a silver/silver chloride electrode in a 0.25-inch-diameter Lugin probe, positioned about 0.1 inch from the start of the fatigue precrack. The fatigue precrack is at the bottom of a 2.00-inch-deep notch (1.50 inches wide by 0.010 inch thick), and the tip of the 0.25-inch-diameter Lugin probe is centered at the bottom of this notch to minimize "edge effects" on the electrochemical measurements. The counter electrode is located in a chamber to which the Lugin probe is attached. This arrangement allows us to polarize only the area at the Lugin probe tip and thus measure the response of this area.

IV PROGRESS DURING THE FIRST YEAR

Introduction

In the current program, we are applying the AC impedance technique to determine the distribution of electrochemical processes in a static and growing stress corrosion or corrosion-fatigue crack. The program consists of three research tasks:

(1) Build up the facilities necessary to measure the AC impedance spectra of growing and static stress corrosion and corrosion-fatigue cracks.

(2) Measure the AC impedance spectra of several alloys in aqueous environments as a function of loading, crack length, and potential. Measure the AC impedance spectra on strained or scratched alloys if necessary.

(3) Begin to deconvolve the AC impedance spectra to electrochemical parameters. Use the electrochemical parameters to model the environment-assisted crack growth mechanism.

During the first year of this program, we have completed the literature survey, selected the material/environment systems, designed and constructed the crack growth test facility, and performed several initial experiments. The facility development was described in Section III. This section describes the results of our preliminary experiments.

We selected HY80 steel and Ti-6Al-4V alloys in a 3.5% NaCl solution to be investigated using the AC impedance technique. These two materials were selected for the following reasons.

- Both materials have had their SCC and CF resistance documented for chloride-containing environments. Neither of these alloys will easily undergo SCC in chloride-containing environments, but both exhibit CF behavior. However, the environment can easily be manipulated to bring about SCC in both alloys.

- The HY80 and Ti-6Al-4V should have very different passivation rates, surface film properties, and active (bare metal) corrosion properties in chloride-containing environments. These differences in properties should be reflected in the AC impedance spectra and make their interpretation easier.

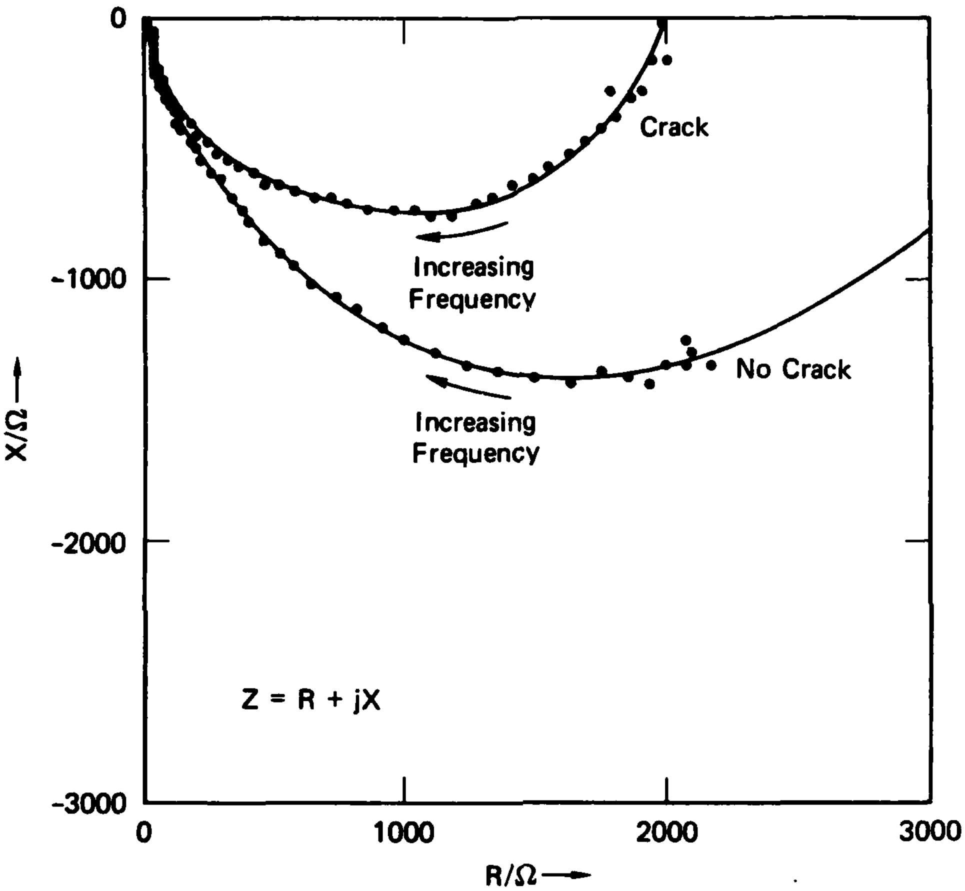
- Both materials have been used or have been considered for use in marine applications. Data are available that describe their mechanical, electrochemical, SCC and CF cracking behavior in both synthetic and natural seawater.

Results

Figures 8 and 9 show impedance data for the growth of a crack in Ti-6Al-4V. The data designated as "no crack" in Figure 8 show the impedance response in the range $10^{-3} < f < 10^{4}$ Hz for a specimen subjected to a 5 Hz cyclic load but showing no superficial indication of having cracked. In the Nyquist domain this data set appears as a semicircle whose center is located above the real axis. The low frequency intercept on the real axis is very close to 2000 Ω. The high frequency region is shown in a considerably amplified form in Figure 8(b). A second semicircular region is observed with a high frequency intercept on the real axis at 52.8 Ω. The high frequency intercept corresponds to the series resistance due to the electrolyte path between the tip of the reference electrode and the base of the notch in the specimen.

In the Bode plot [Figure 8(c)], these data exhibit a single minimum in the phase occurring at approximately 0.15 Hz. The magnitude information shows two limiting plateaus (corresponding to the intercepts with the real axis in the Nyquist plot) separated by linear regions of slope -1/2, -1, and -1/4 with increasing frequency.

Examining these linear regions in order of decreasing frequency, one sees that the region at slope -1/4 corresponds to the high frequency semicircle in the Nyquist plot, shown in Figure 8(b). This region is present for unstressed specimens before cyclic loading, and appears, completely unchanged, during the entire growth of the crack. We speculate that this region is associated with diffusion in the plane of



(a) Nyquist Plot

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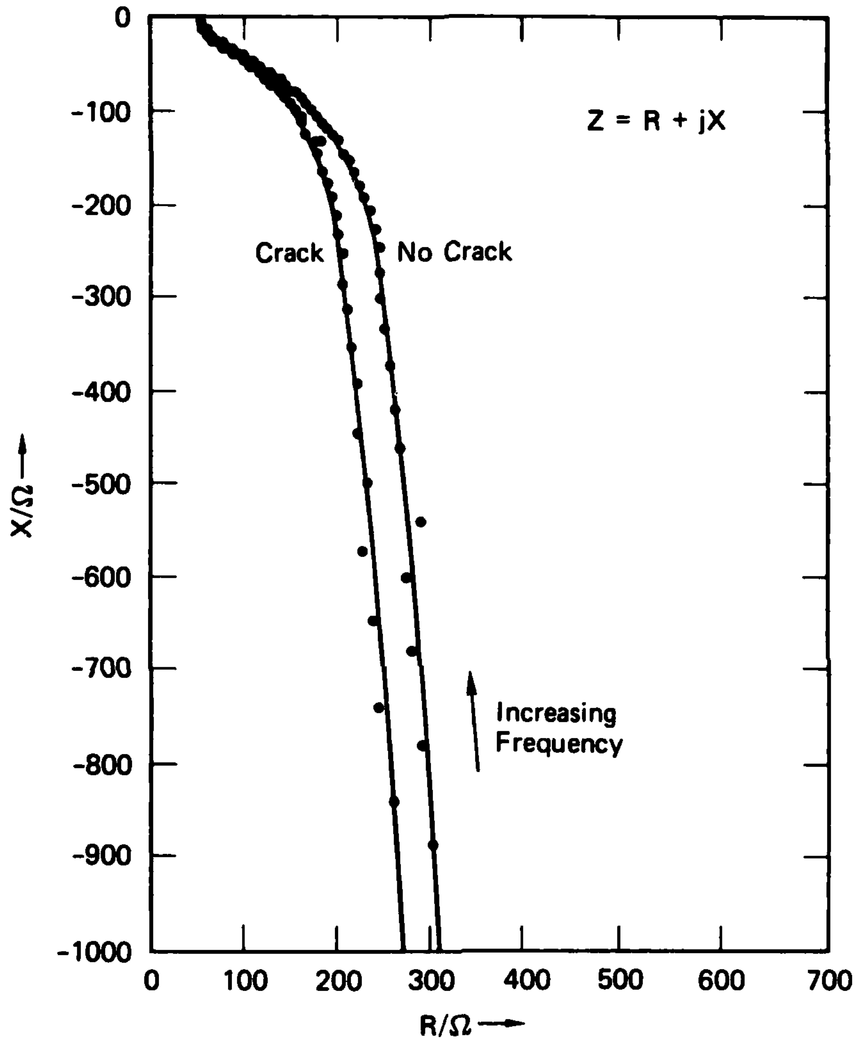
FIGURE 8 IMPEDANCE RESPONSE OF THE Ti-6Aℓ-4V SPECIMEN BEFORE AND AFTER THE APPEARANCE OF A MACROSCOPIC CRACK IN AERATED 3.5% NaCℓ SOLUTION



(b) Expanded Nyquist Plot

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FIGURE 8 IMPEDANCE RESPONSE OF THE Ti-6Aℓ-4V SPECIMEN BEFORE AND AFTER THE APPEARANCE OF A MACROSCOPIC CRACK IN AERATED 3.5% NaCℓ SOLUTION (Continued)

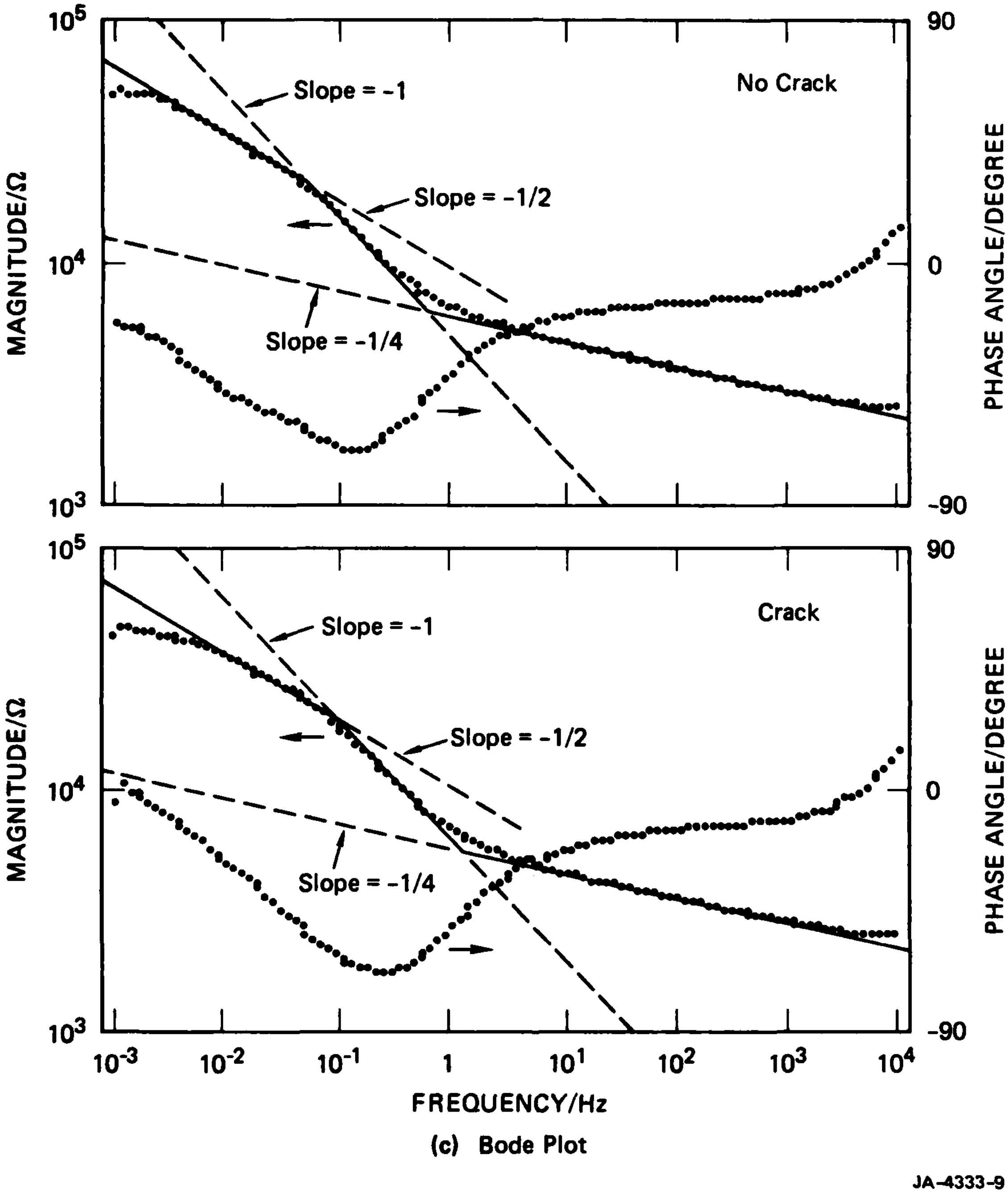

FIGURE 8 IMPEDANCE RESPONSE OF THE Ti-6Aℓ-4V SPECIMEN BEFORE AND AFTER THE APPEARANCE OF A MACROSCOPIC CRACK IN AERATED 3.5% NaCℓ SOLUTION (Concluded)

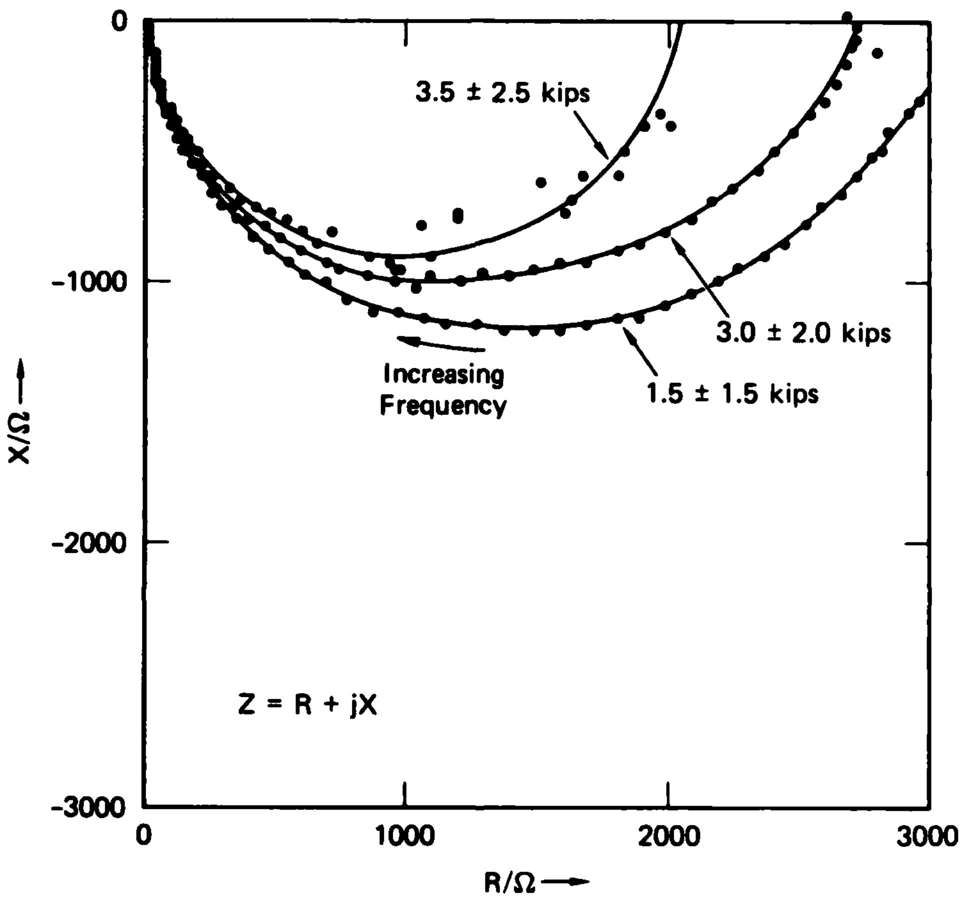

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FIGURE 9 THE EFFECT OF LOAD ON THE IMPEDANCE RESPONSE OF A MATURE CRACK IN Ti-6Aℓ-4V IN AERATED 3.5% NaCℓ SOLUTION the machined notch and perpendicular to the axis of the reference electrode. Although the region of slope -1/4 has significant extent in the Bode plot, the impedances involved are very small and have very little significance in a linear (e.g., Nyquist) plot of the data. We will not consider this zone further in this report.

At intermediate frequencies, all data sets obtained show a region of slope -1. This corresponds to a f^{-1} dependence and is the form expected for the equivalent circuit in Figure 2, at intermediate and high frequencies, when diffusion of metal ions from the electrode surface are not rate limiting. A region of slope -1 in a Bode plot corresponds to a semicircle with its center located on the real axis in the Nyquist representation. The beginnings of a semicircle of great magnitude (on the scale shown) can be seen in Figure 8(b); the parameters of this semicircle are determined by the interfacial reaction resistance, R_r, and the double-layer capacitance, C (see Section II).

Impedance data obtained from unstressed specimens before the application of a cyclic load display a f^{-1} dependence (Bode slope = -1) down to limitingly low frequencies. Only under cyclic loading conditions does a region of slope -1/2 appear, and this region becomes increasingly significant as a crack is observed to grow. Thus, we associate the region of slope -1/2 in a Bode plot with the presence of a crack.

Figures 8(a), (b) and (c) each show two curves: one labeled "crack" and the other labeled "no crack" on the basis of visual inspection of the sides of the compact tension specimen. Because both show a region of $f^{-1/2}$ dependence in Figure 8(c), it is apparent that the curve designated as "no crack" has at least a vestigial rupture, associated with cyclic loading of the oxide film at the crack tip. The curve labeled "crack" was obtained when a crack of about 3 mm length was observed at the side of the specimen.

A region of apparent $f^{-1/2}$ dependence (slope -1/2) for the impedance within the crack is predicted by equations (4) and (5). The transmission line impedance, Z_{tl}, contains terms in $e^{\gamma l}$, which can be expanded as a Taylor series.

$$e^{\gamma l} = 1 + \gamma l + (\gamma l)^2/2! + (\gamma l)^3/3! + \ldots \qquad (12)$$

For $\gamma l << 1$, the third and subsequent terms in this series can be neglected. Substituting equation (12) into equation (4), we obtain an expression of the form

$$Z_{tl} = a + b/\gamma + \text{additional terms} \qquad (13)$$

where a and b are undetermined constants, and the higher order terms have decreasing significance.

Because γ is a function of $Z_i^{-1/2}$ [see equation (5)], it is clear that the impedance of Z_i placed in a transmission line will have a major component that has the square root of the frequency power dependence of the interfacial impedance itself. Thus, for Z_i containing parallel resistance (R_p) and capacitive (C_p) elements only,

$$1/Z_i = 1/R_p + j2\pi fC_p \qquad (14)$$

and γ will be a function of $f^{1/2}$; from equation (13), Z_{tl} will be a function of $f^{-1/2}$, which is the form observed.

The preceeding discussion is important because a $f^{-1/2}$ dependence is often attributed to diffusional processes at a plane-parallel electrode.[22-24] By mathematically fitting the measured impedance data to the form predicted by equation (4), we can clearly see that the observed response is due to a capacitive element contained within a transmission line, rather than to diffusion; the coefficients obtained do not correspond to any known diffusional process.

The capacitance under consideration is simply that of the electrical double layer on the sides of the growing crack. A resistance appears in parallel with this, associated with Faradaic processes on the crack wall. At present, we are unable to determine whether this Faradaic process is anodic (metal dissolution) or cathodic (reprecipitation of metal or hydrogen evolution). To resolve this and other important issues, we intend to construct a discrete (finite element) transmission line model for the growing crack based on the electromechanical parameters calculated from impedance measurements.

The two data sets presented in Figure 8 are not greatly different in form; the major changes observed are in the characteristic frequency and the intercept with the real axis at limiting low frequencies. The characteristic frequency (f_o = frequency of minimum phase) moves from 0.14 to 0.32 Hz between the first and second data sets, and the limiting low frequency intercept decreases from 3915 to 1995 Ω. This is believed to be an effect of crack opening. For the data set labeled "crack", the vestigial crack, although short, is very tight and the impedance is large. Under the same load conditions, the crack opening displacement increases as the crack grows, and the impedance becomes less. In fact, a plot of limiting resistance versus crack length shows a minimum at about 1-cm crack length, the resistance then increasing as the crack lengthens, indicating that effects of crack length become more important than the average crack opening displacement.

The effects of crack opening displacement can be examined by varying the cyclic load conditions. Specimens were cycled at a mean load, plus and minus the cyclic load perturbation. Figure 9 shows the effects of varying both the mean and the perturbation stress levels for a mature crack (≈ 2 cm long) cycled at 0.02 Hz. For these data (and for all impedance data presented in this report), each impedance determination represents an average taken over one complete period of the cyclic load and thus reflects some weighted average of crack opening displacements. Figure 9 clearly shows the effect of crack opening (proportional to load) on the limiting low frequency resistance. From a superficial examination, it would appear that the effects of the load perturbation level are more significant than those of mean load. However, we have not attempted to separate the effects of mean and perturbation stress levels quantitatively.

Summary and Conclusions

The principal features of the AC impedance response of a Ti-6Al-4V specimen under cyclic load conditions in 3.5% NaCl appears to be due to faradaic processes at the crack tip and a transmission line impedance associated with the crack walls. We have observed qualitatively the effects of crack length and crack opening displacement.

V SECOND YEAR RESEARCH PLANS

Within the framework of the three research tasks listed in Section IV, we plan to perform the following specific subtasks during the second year.

(1) Under constant load conditions (the SCC situation), continue to measure AC impedance spectra inside static and growing cracks as a function of crack length, stress intensity, and specimen potential. Material/environment combinations other than Ti-6Al-4V and HY80 in 3.5% NaCl solutions will be examined to obtain AC impedance data for a range of SCC behavior.

(2) Under cyclic loading (or CF) conditions, continue to measure AC impedance spectra inside static and growing cracks in Ti-6Al-4V and HY80 specimens in 3.5% NaCl as a function of crack length, ΔK, R ratio, loading frequency, and specimen potential under cyclic loading (or CF) conditions. By varying ΔK and the R ratio, we hope to see the effect of crack closure on the AC impedance spectra. The electrochemical/mechanical impedance will be measured and evaluated to see if it can help in determining the crack growth mechanism. Additional material/environment combinations will be examined if time permits.

(3) Begin to deconvolve the AC impedance spectra into electrochemical parameters that are pertinent to environment-assisted cracking. Evaluate various cracking models based on this information.

During Year 3 we will do only a few key experiments; most of our effort will be to use the data gathered in Year 1 and Year 2 to explain and model the electrochemical and mechanical processes that occur in SCC or CF.

REFERENCES

1. A. J. Forty and D. Van Rooyen, Eds., Proceedings of Conference on Fundamental Aspects of Stress Corrosion Cracking (NACE, Houston, Texas, 1969).

2. O. F. Devery, A. J. McEvily, and R. W. Staehle, Eds., Corrosion Fatigue: Chemistry, Mechanics and Microstructure (NACE, Houston, Texas, 1979).

3. Z. A. Foroulis, Ed., Proceedings of Conference on Environment-Sensitive Fracture of Engineering Materials (The Metallurgical Society of AIME, Warrendale, Pennsylvania, 1979).

4. J. C. Scully, Ed., The Theory of Stress Corrosion Cracking in Alloys, (NATO, Brussels, 1971).

5. A. J. McEvily and A. P. Bond, J. Electrochem Soc., 112, 131 (1965).

6. F. P. Ford, Metal Science, 326 (July 1978).

7. H. L. Logan, J. Res. Nat. Bur. Stand., 48, 99 (1952).

8. P. Doig and P.E.J. Flewitt, Proc. Roy. Soc., 357, 439 (1977).

9. P. Doig and P.E.J. Flewitt, Met. Trans., 12A, 923, (1981).

10. R. P. Wei and J. D. Landes, Mater. Res. Stand., 9, 25 (1969).

11. P. B. Dawson and R. M. Pelloux, Met. Trans., 5A, 723 (1974).

12. D. Schlain, "Corrosion Properties of Titanium and its Alloys," Bureau of Mines Bulletin No. 619, U.S. Department of the Interior (1964).

13. J. D. Jackson and W. K. Boyd, "Corrosion of Titanium," DMIC Memorandum 218 (Battelle Memorial Institute, Columbus, Ohio, 1966).

14. Werkst. Korros., 30, 1979, 846 (1979).

15. J. F. Newman, Corrosion Science, 21, 487 (1981).

16. R. D. Caligiuri, L. E. Eiselstein, and M. J. Fox, "Low Temperature Sensitization of Weld Heat-Affected Zones in Type 304 Stainless Steel," lecture presented at Proceedings of International Atomic Energy Agency Specialists Meeting on Subcritical Crack Growth, held at Freiburg, Germany (May 1981).

17. F. P. Ford, "A Mechanism of Environmentally Controlled Crack Growth of Structural Steels in High Temperature in High Temperature Water," lecture presented at Proceedings of International Atomic Energy Agency Specialists Meeting on Subcritical Crack Growth," held at Freiburg, Germany (May 1981).

18. H. Riedel and J. R. Rice, Fracture Mechanics, P. C. Paris, Ed. (ASTM STP 700 1980), p. 112.

19. H. Riedel, J. Mech. Phys. Solids, 29, 35 (1981).

20. T. P. Hoar and F. P. Ford, Corrosion Science, 13, 729 (1973).

21. F. P. Ford, "Understanding Micromechanisms of Fracture," lecture presented at Gordon Conference, New Hampshire, 1981.

22. D. D. Macdonald and M.C.H. McKubre, "Impedance Measurement in Electrochemical Systems," Chapter 2 in Modern Aspects of Electrochemistry, J. O'M Bockris, Ed., Vol. 16, (Plenum, New York, 1982).

23. D. D. Macdonald and M.C.H. McKubre, "Electrochemical Impedance Techniques in Corrosion Science," in Electrochemical Corrosion Testing, ASTM STP 727, Florian Mansfeld and Ugo Bertocci, Eds., ASTM, 1981, pp 110-169.

24. M. Sluyters-Rehback and J. H. Sluyters, in Electroanalytical Chemistry, Vol. 4, A. J. Bard, Ed. (Marcel Dekker, New York, 1970), pp. 1-128.

25. L. E. Eiselstein, R. D. Caligiuri, S. S. Wing, and B. C. Syrett, "Accelerated Corrosion of Copper-Nickel Alloys in Sulfide-Polluted Seawater: Mechanism No. 2," lecture presented at Corrosion 82, Houston, Texas, 1982.

26. M.C.H. McKubre and D. D. Macdonald, "The Rotating Cylinder-Collector Electrode (RCCE)," J. Electrochem. Soc., 127, 632 (1980).

27. O. S. Ksenzheck and V. V. Stender, Dokl. Akad. Nauk SSR, 106, 487, (1956); 107, 280 (1956).

28. M.C.H. McKubre, "Equilibrium and Steady State Studies of Continuous Flow-Through Electrode Systems," report to The University, Southampton University, Southampton, England (1978).

29. J. McHardy, J. M. Baris, and P. Stonehart, J. Appl. Electrochem, 6, 371 (1976).

30. J. O'M Bockris and A.J.N. Reddy, Modern Electrochemistry (Plenum Press, New York, 1973).

31. M.C.H. McKubre, Ph.D. thesis, Victoria University, Wellington, New Zealand (1976).

32. J. H. Sluyters, thesis, Utrecht, The Netherlands (1959).

33. A. B. Yzermans, thesis, Utrecht, The Netherlands (1965).

34. P. Drossback and J. Schultz, Electrochim. Acta, 9, 1391 (1969); 11, 669 (1966).

35. J. R. Macdonald, J. Electroanal. Chem., 32, 317 (1971).

36. D. D. Macdonald, Transient Techniques in Electrochemistry (Plenum Press, New York, 1977).

37. M. Stern and A. L. Geary, J. Electrochem. Soc., 104 (1), (1957).

38. G.H.J. Broers and M. Schenke, in International Symposium Brennstoffelmente, K. Schwabe and E. Winkler, Eds. (Akademic-Verlag, Berlin, 1968), p. 299.

39. G.H.J. Broers and M. Schenke, in Hydrocarbon Fuel Cell Technology, B. S. Baker, Ed. (Academic Press, New York, 1965), p. 225.

40. G.H.J. Broers, in Fuel Cells (American Institute of Chemical Engineers, New York, 1963), p. 90.

41. K. Mund, G. Richter, and F. von Sturm, J. Electrochem. Soc., 124, 1 (1977).

42. M.C.H. McKubre and G. J. Hills, "The Use of AC Impedance Measurements to Characterize the Steady-State Properties of Continuous Flow-Through Electrodes" (to be published).

43. G. J. Hills and M.C.H. McKubre (unpublished work).

44. M.C.H. McKubre and G. J. Hills, FORTAN IV programs written at The University, Southampton University, Southampton, England.

45. G. Gabrielli and M. Keddam, Electrochim. Acta, 19, 355 (1974).

46. R. D. Armstrong, M. P. Bell, and A. A. Metcalfe, J. Electroanal. Chem.,
84, 6 (1977); K. L. Bladen, J. Appl. Electrochem., 7, 345 (1977); A. A. Metcalfe, J. Electroanal. Chem., 88, 187 (1978).

47. D. Lelevre and V. Plichon, Electrochim. Acta, 23, 725 (1978).

48. P. Casson, N. A. Hampson, and M. J. Willars, J. Electroanal. Chem., 97, 21 (1979).

49. R. D. Armstrong, M. F. Bell, and A. A. Metcalfe, J. Electroanal. Chem., 77, 287 (1977).

Appendix A

IMPEDANCE DATA MANAGEMENT AND CONTROL PROGRAM

```
1  REM  "DMSS.MAIN 15/JUN/1983
3  REM BY M.C.H.MCKUBRE
10  HIMEM: 36300: LOMEM: 24577
90 ZN% = 120: IF NP% <  > 0 THEN 1000
100  DIM ZM(128),ZN(5,ZN%),ZZ(9),ZT(32),ZD$(8)
110  PRINT  CHR$ (4);"BLOAD B.FRA"
140 ZM(1) = 1:ZM(2) = 1:ZM(11) = 100:ZM(12) = 1:ZM(13) = 1:ZM(21) = 1:ZM(22) = 1:ZM(23) = 1:ZM(24) = 1:
     ZM(25) = 1:ZM(34) = 65535:ZM(35) = 1:ZM(38) = ZN%:ZM(39) = 1.1:ZM(44) = 1:ZM(45) = 0201:ZM(49) = 2
     00
150 ZM(51) = 1:ZM(53) = 1:ZM(55) = 1:ZM(56) = ZN%:ZM(57) = 1:ZM(84) = 2:ZM(85) = 2:ZM(86) = 2:ZM(121) =
     2:ZM(122) = 1:ZM(123) = 1
160 X =  FRE (0):SB% = 6:DB% = 1:VB% = 23
170  IF S% < 4 OR S% > 6 THEN S% = 5:D% = 1:V% = 0
200  GOSUB 20060
300  DATA  "FR","AM","BI","WF","MO",ZSY","LE","SR","SL","AC","AS","AV","AE","AP","QA","QB","QW","SQ","S
     G","RG"
320  DATA "IS","IC","MS","MC","HA","AU","RA","DE","DC","IP","SA","SI","RE","MA","MI","GD","GO","GS","GR
     ","NH","NS","SS","HS","SC","SO","CO"
340  DATA  "VE","AA","PD","XI","XH","XL","XO","YI","YH","YL","YO","SP","PL","SM","ST","PG","VA","UP","D
     N","FD","FO","FC","LL"
360  DATA "BK","$L","$E","$C","$F","$B","$D","$I","$Q","$P","EP","JP","CP","TM","TT","OP","FN"
380  DATA "AF","BF","RF","TF","UA","UB","UR","UT","UG","LA","LB","LR","LT","LG","SV","PP","PS","OS","OT
     ","RR","RH"
400  DATA "NR","NA","PN","ER","AI","AR","TS"
1000  TEXT : POKE 34,0: HOME : PRINT
1100  PRINT : PRINT "PROGRAM OPTIONS ARE:"
1120  PRINT : PRINT "  1...SET UP SOLARTRON"
1140  PRINT : PRINT "  2...HELP"
1160  PRINT : PRINT "  3...TAKE MEASUREMENTS"
1180  PRINT : PRINT "  4...CHAIN BODE PLOT"
1200  PRINT : PRINT "  5...CHAIN NYQUIST PLOT"
1220  PRINT : PRINT "  6...SAVE DATA ON DISK"
1230  PRINT : PRINT "  7...RETRIEVE DATA FROM DISK"
1240  PRINT : PRINT "  8...SET TIME"
1245  PRINT : PRINT "  9...CHAIN ANALYSIS PROGRAM"
1250  PRINT : PRINT "  0...EXIT PROGRAM"
1260 ZZ(3) = 0: VTAB (23):ZZ(4) = 0:ZZ(5) = 9: GOSUB 10100
1280  IF ZE%(0) = 1 THEN 1000
1300  ON ZZ(3) GOTO 1500,2500,3000,4000,5000,6000,7000,8000.9700
1320  HOME : VTAB 9: PRINT "EXIT PROGRAM": PRINT : PRINT "TYPE GOTO 1000 TO RESUME": END
1500  GOSUB 15000: GOTO 1000
1900 ZM(128) = 1:M$ = "T1F2": GOSUB 29000:ZZ(4) = ZZ(3):M$ = "T1F0": GOSUB 29000: PRINT : PRINT "RS = "
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;ZZ(4): PRINT : INPUT "USE THIS VALUE (Y/N) ? ";M$: IF M$ < > "Y" THEN 15000
1920 ZM(51) = ZZ(4): GOTO 1500: REM RP
2000 HOME : PRINT "INITIALISE"
2020 GOSUB 20000:M$ = ":'TT2'": GOSUB 21000
2040 GOSUB 29000: REM KEITHLEY
2060 GOTO 15000
2500 HOME : VTAB 5: PRINT " HELP:": PRINT " ----": VTAB 10: PRINT "  THERE IS NO HELP AVAILABLE HER
   E.": PRINT "LIFE IS LIKE THAT. IT CAN SOMETIMES BE": PRINT "HARD AND CRUEL.": PRINT "  IF YOU DON
   'T KNOW WHAT YOU ARE DOING"
2510 PRINT "IT IS POSSIBLE THAT YOU SHOULD NOT": PRINT "BE DOING IT.": PRINT "  PLEASE DO NOT HESITAT
   E TO NOT": PRINT "CALL ME,": VTAB 19: HTAB 9: PRINT "MIKE"
2520 VTAB 23: GET ZD$(0): PRINT ZD$(0): GOTO 1000
3000 HOME : VTAB 3: PRINT "NAME AND LOCATION OF SAVE DATA FILE"
3010 GOSUB 11500: PRINT : PRINT "FILE NAME WILL BE PRECEDED BY DMSS(D)-": PRINT : INPUT "ENTER FILE NA
   ME = DMSS(D)-";ZD$(0)
3015 X = FRE (0):ZF$ = ZD$(0):ZZ(8) = 77:ZD$(0) = "DMSS(P)-" + ZF$: GOSUB 11400:ZF$ = "DMSS(D)-" + ZF$
    + "#":ZZ(8) = 78
3020 PRINT : PRINT "STARTING FILE # ";:ZZ(3) = ZF%:ZZ(4) = 0:ZZ(5) = 100:ZZ(6) = 1: GOSUB 10100: IF ZE
   %(0) = 1 THEN 3020
3030 ZF% = ZZ(3):ZM(3) = ZM(118)
3040 X = FRE (0): POKE 34,0: HOME : POKE 34,3: VTAB 1: PRINT "MEASUREMENT MODE # ";ZM(127): VTAB 2: PRINT
   ZF$;ZF%: VTAB 3: PRINT "SCALE FACTOR ";ZM(53)
3050 ZM(47) = 0: HOME : VTAB 5: PRINT "STATUS PAGE": PRINT "------ ----": VTAB 8: PRINT "TOTAL # OF POI
   NTS ";ZN%: VTAB 10: PRINT "TIMED SWEEP";: HTAB 19: PRINT "ON": IF ZM(125) = 0 THEN VTAB 10: HTAB
   19: PRINT "OFF"
3060 VTAB 12: PRINT "DC VOLTAGE SWEEP";: HTAB 19: PRINT "ON": IF ZM(120) = 0 THEN VTAB 12: HTAB 19: PRINT
   "OFF"
3070 VTAB 14: PRINT "FREQUENCY SWEEP";: HTAB 19: PRINT "ON": IF ZM(34) = ZM(35) THEN VTAB 14: HTAB 19
   : PRINT "OFF"
3080 VTAB 16: PRINT "HARMONIC SWEEP";: HTAB 19: PRINT "ON": IF ZM(122) = ZM(123) THEN VTAB 16: HTAB 1
   9: PRINT "OFF"
3090 VTAB 18: PRINT "INPUT FRONT/REAR";: HTAB 19: PRINT "FRONT": IF ZM(50) > 0 THEN VTAB 18: HTAB 19:
    PRINT "REAR ": IF ZM(50) > 1 THEN VTAB 18: HTAB 19: PRINT "BOTH"
3100 VTAB 2: HTAB 28: PRINT "START @ ";ZM(124): VTAB 3: HTAB 29: PRINT "STOP @ ";ZM(125)
3110 IF ZM(126) > 0 THEN GOSUB 18200: IF ZZ(3) + ZZ(4) / 60 < ZM(124) THEN FOR II = 1 TO 4444: NEXT
   II: GOSUB 18000: GOTO 3110
3120 FR% = 1: IF ZM(50) = 2 THEN FR% = 2
3130 ZM(56) = INT (ZN% / (FR% * ZM(55) * ZM(57)))
3140 ZM(39) = (ZM(34) / ZM(35)) ^ (1 / ZM(56))
3145 ZN(0,0) = ZN%: GOSUB 18200:ZN(1,0) = ZZ(3) + ZZ(4) / 60:ZN(2,0) = ZM(127):ZN(3,0) = ZM(53):ZN(4,0)
    = 1250
3150 VTAB 23: PRINT ZM(39),ZM(57),ZM(56)
3160 VTAB 5: CALL - 958: PRINT
3170 J = 0: IF ZM(121) = 1 THEN ZM(3) = ZM(118): REM INITIAL DC
3175 GOSUB 3900: REM SET DISPLAY
3180 II = 3: GOSUB 17000
3190 FOR JZN = 1 TO 441 * ZM(117): NEXT JZN
3200 ZM(1) = ZM(35): REM F MIN.
3210 II = 1: GOSUB 17000
3220 ZM(29) = 0: IF ZM(1) > = ZM(49) THEN ZM(29) = 1: REM COUPLING
3230 II = 29: GOSUB 17100
3240 ZM(25) = ZM(122): REM INITIAL HARMONIC
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3250 II = 25: GOSUB 17000
3260 FR% = 0:ZM(30) = 0: IF ZM(50) = 1 THEN ZM(30) = 1:FR% = 1: REM REAR
3270 II = 30: GOSUB 17100:ZM(45) = 0100: IF ZM(127) = 2 THEN ZM(45) = 0200
3280  IF ZM(127) = 0 THEN ZM(45) = 0201
3290 J = J + 1: IF J = ZN% AND ZM(128) = 1 THEN 3620
3295  IF J > ZN% THEN 3580: REM   FULL
3300 II = 45: GOSUB 17000: GOSUB 18000:II = 32: GOSUB 16900: REM   MEASURE
3310 M$ = ":'OP2,1'":II = 4: GOSUB 24000: IF ZZ(4) <  > 0 THEN 3300
3320  FOR ZS = 1 TO 3:ZN(ZS - 1,J) = ZZ(ZS): NEXT ZS
3330  IF ZM(127) > 3 THEN II = 45:ZM(45) = 0200: GOSUB 17000: GOSUB 18000:M$ = ":'OP2,1'":II = 4: GOSUB
     24000: REM  CH#2
3340  IF ZM(127) < 3 THEN ZN(3,J) = 1:ZN(4,J) = 0
3350  IF ZM(127) = 3 THEN ZN(3,J) = ZN(1,J):ZN(4,J) = ZN(2,J):ZN(1,J) = ZZ(2):ZN(2,J) = ZZ(3)
3360  IF ZM(127) = 4 THEN ZN(3,J) = ZZ(2) - ZN(1,J):ZN(4,J) = ZZ(3) - ZN(2,J)
3370  IF ZM(127) = 3 THEN ZN(3,J) = ZN(1,J):ZN(4,J) = ZN(2,J):ZN(1,J) = ZZ(2):ZN(2,J) = ZZ(3)
3380  IF ZM(127) = 5 THEN  GOSUB 3800: GOTO 3420
3390  GOSUB 9500:ZN(3,J) = 1 / ZM(51):ZN(4,J) = 6.28232 * ZN(0,J) * ZM(52): GOSUB 9500:ZN(1,J) = ZN(1,J
     ) / ZM(53):ZN(2,J) = ZN(2,J) / ZM(53): REM SCALE
3400  GOSUB 9980:ZN(3,J) = ZM(3): REM MAG.&PHASE
3420 II = 1:M$ = ":'?ER'": GOSUB 24000: VTAB 21: HTAB 12: PRINT ZZ(II)
3430 ZZ(3) = 7:ZZ(4) = ZM(122):ZZ(5) = ZM(118):ZZ(6) = ZM(35): GOSUB 3990
3432 ZZ(3) = 8:ZZ(4) = ZM(123):ZZ(5) = ZM(119):ZZ(6) = ZM(34): GOSUB 3990
3434 ZZ(3) = 9:ZZ(4) = 1:ZZ(5) = ZM(120):ZZ(6) = ZM(39): GOSUB 3990
3436 ZZ(3) = 10:ZZ(4) = ZM(25):ZZ(5) = ZM(3):ZZ(6) = ZM(1): GOSUB 3990
3440  VTAB 12: HTAB 9: PRINT J - 1;"/";ZN%; TAB( 25);J;"/";ZN%
3450  FOR II = 0 TO 5: VTAB (13 + II): HTAB 6: CALL  - 868: PRINT ZN(II,J - 1); TAB( 24);ZN(II,J): NEXT
     II
3460  INVERSE : VTAB 20: HTAB 12:ZD$(0) = "FRONT": IF ZM(30) = 1 THEN ZD$(0) = " REAR"
3462  PRINT ZD$(0);: HTAB 28:ZD$(0) = "DC": IF ZM(29) = 1 THEN ZD$(0) = "AC"
3464  PRINT ZD$(0);: HTAB 36:ZD$(0) = "OFF": IF ZM(14) = 1 THEN ZD$(0) = "ON "
3466  PRINT ZD$(0): NORMAL
3480  VTAB 4: CALL  - 868: IF ZM(47) = 999 THEN  PRINT "TERMINATE"
3490  IF ZM(50) = 2 AND FR% = 0 THEN ZM(30) = 1:FR% = 1: GOTO 3270: REM  REAR
3500  IF ZM(25) < ZM(123) THEN ZM(25) = ZM(25) + 1: GOTO 3250: REM LOOP H
3510  IF ZM(1) >  = ZM(34) THEN 3540
3520 ZM(1) = ZM(1) * ZM(39): IF ZM(1) > ZM(34) THEN ZM(1) = ZM(34)
3530  GOTO 3210
3540  IF  SGN (ZM(120)) =  SGN (ZM(119) - ZM(3)) THEN ZM(3) = ZM(3) + ZM(120): GOTO 3180
3550  REM DC LIMIT REACHED
3560  IF ZM(121) = 1 THEN 3180
3570  GOTO 3210
3580  REM FULL
3590  GOSUB 18000
3600 ZM(124) = ZM(124) + ZM(126): REM INC.TIME
3610 X =  FRE (0):ZF% = ZF% + 1:ZD$(0) = ZF$ +  STR$ (ZF%):ZZ(8) = 78: GOSUB 11400: REM   SAVE DATA
3612  IF (ZZ(3) + ZZ(4) / 100) > ZM(125) OR ZM(47) = 999 THEN 1000: REM  TERMINATE
3616  IF ZM(121) = 2 THEN ZM(3) = ZM(3) + ZM(120): IF  SGN (ZM(12)) =  SGN (ZM(119) - ZM(3)) THEN 1000:
     REM DC LIMIT
3618  GOTO 3040: REM CLOSE LOOP
3620 ZM(1) = 60:II = 1: GOSUB 17000:ZN(0,ZN%) = 60: FOR A = 1 TO 441: NEXT A:M$ = "T1F1": GOSUB 29200:Z
     N(2,ZN%) = ZZ(3):M$ = "T1F0": GOSUB 29200:ZN(3,ZN%) = ZZ(3)
```

```
3630 ZN(18) = 0:II = 18: GOSUB 17000: FOR II = 1 TO 441: NEXT II:M$ = "T1F1": GOSUB 29200:ZN(4,ZN%) = Z
     Z(3):M$ = "T1F0": GOSUB 29200:ZN(5,ZN%) = ZZ(3)
3640 II = 20: GOSUB 16900: GOTO 3420
3800  REM CH1=I,CH2=V
3820 ZN(3,J) = ZM(25):ZN(4,J) = ZZ(2):ZN(5,J) = ZZ(3)
3840 ZZ(2) = 1 / ZM(51):ZZ(3) = 6.28232 * ZN(0,J) * ZM(52):ZZ(4) = ZN(1,J) * ZZ(2) - ZN(2,J) * ZZ(3):ZN
     (2,J) = ZN(1,J) * ZZ(3) + ZN(2,J) * ZZ(2):ZN(1,J) = ZZ(4): REM  I=E/R
3860 ZN(1,J) = ZN(1,J) * ZM(53):ZN(2,J) = ZN(2,J) * ZM(53):ZN(4,J) = ZN(4,J) * ZM(53):ZN(5,J) = ZN(5,J)
     * ZM(53): REM SCALE MULTIPLIER
3880  RETURN
3900  REM  DISPLAY
3920  REM
3930  VTAB 6: CALL  - 958: HTAB 8: PRINT "H     DCV     FREQUENCY": PRINT "INIT.": PRINT "FINAL": PRINT "
     STEP": PRINT "CURR.": FOR II = 0 TO 5: VTAB (13 + II): PRINT "#";II: NEXT II
3940  VTAB 20: PRINT "INPUT FROM      : COUPLING   :COMP "
3960  VTAB 21: PRINT "LAST ERROR: ": RETURN
3990  VTAB ZZ(3): HTAB 7: CALL  - 868: PRINT ZZ(4); TAB( 11);ZZ(5); TAB( 18);ZZ(6): RETURN
4000 ZD$(0) = "BODE": GOSUB 19900
4020 NP% = 1: CALL 520"DMSS.BODE"
5000 ZD$(0) = "NYQUIST": GOSUB 19900
5020 NP% = 1: CALL 520"DMSS.NYQUIST"
6000  REM SAVE DATA TO DISK
6010  GOSUB 11500: PRINT : PRINT "FILE NAME WILL BE PRECEDED BY DMSS(D)-": PRINT : INPUT "ENTER FILE NA
     ME = DMSS(D)-";ZD$(0):ZD$(0) = "DMSS(D)-" + ZD$(0)
6020 ZZ(8) = 78: GOSUB 11420: GOTO 1000
6500 ZD$(0) = ZD$(0) +  STR$ ( INT (ZZ(3) + 0.5)): RETURN
7000  REM  RETRIEVE DATA FROM DISK
7040 X =  FRE (0): GOSUB 11500: PRINT : PRINT "CURRENT FILE NAME = ";ZF$;"#";ZF%: PRINT : INPUT "   NEW
     FILE NAME = DMSS(D)-";ZD$(0):ZD$(0) = "DMSS(D)-" + ZD$(0): IF ZD$(0) <  > "DMSS(D)-" THEN ZF$ = Z
     D$(0)
7060 X =  FRE (0): INPUT "   NEW FILE  #    = ";ZF%:ZD$(0) = ZF$ + "#" +  STR$ (ZF%)
7080 ZZ(8) = 78: GOSUB 11300: GOTO 1000
8000  HOME : REM SET TIME
8020  GOSUB 18200: VTAB 8: PRINT "NEW TIME:": HTAB 9: INPUT "HOURS ";JZN: IF JZN > 99 OR JZN < 0 THEN 8
     020
8040  VTAB 11: HTAB 7: INPUT "MINUTES ";ZM(83): IF ZM(83) > 59 OR ZM(83) < 0 THEN 8040
8060 II = 83: GOSUB 17200: GOTO 1000
9000  REM DISPLAY COUNTER ROUTINE
9010  HTAB 30: PRINT "# ";JZN;"   ": RETURN
9240  PR# 3: PRINT "@(:": PRINT "'";ZD$(0);"X'": PRINT "@?;@H:": PR# 0: INPUT ZD$(0): IN# 0: RETURN
9500  REM COMPLEXDIVISION
9520 ZZ(5) = ZN(3,J) * ZN(3,J) + ZN(4,J) * ZN(4,J)
9540 ZZ(6) = (ZN(1,J) * ZN(3,J) + ZN(2,J) * ZN(4,J)) / ZZ(5)
9560 ZZ(4) = (ZN(2,J) * ZN(3,J) - ZN(1,J) * ZN(4,J)) / ZZ(5)
9580 ZN(1,J) = ZZ(6):ZN(2,J) = ZZ(4): RETURN
9700 ZD$(0) = "ANALYSIS": GOSUB 19900
9720  CALL 520"DMSS.ANALYSIS"
9970  REM MAG. & PHASE
9980 ZN(3,J) =  SQR (ZN(1,J) * ZN(1,J) + ZN(2,J) * ZN(2,J))
9985 ZN(4,J) =  ATN (ZN(2,J) / ZN(1,J)) * (180 / 3.141592654)
9990 ZN(5,J) =  LOG (ZN(3,J)) /  LOG (10): RETURN
9999  PRINT  CHR$ (13); CHR$ (4);"SAVEDMSS.MAIN": END
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10000  REM   Y/N SUBR
10010 ZE%(0) = 0: PRINT "YES ";: GET ZD$(0):ZZ(3) =  PEEK (36) - 4: IF ZD$(0) = "Y" OR ZD$(0) =  CHR$ (
    13) THEN ZZ(3) = 2: PRINT "": RETURN
10020  IF ZD$(0) = "N" THEN  POKE 36,ZZ(3): PRINT "NO ":ZZ(3) = 1: RETURN
10030 ZE%(0) = 1: GOSUB 10050: RETURN
10050  REM  ERROR SUBR
10060  PRINT  CHR$ (7):ZE%(0) = 1: RETURN
10100  REM    I/P SUBR
10110  CALL  - 868
10120 ZE%(0) = 0: PRINT ZZ(3): INPUT "  ";ZD$(0): IF ZD$(0) = "" THEN ZZ(7) = ZZ(3): GOTO 10170
10130  FOR I = 1 TO  LEN (ZD$(0)):ZQ$ =  MID$ (ZD$(0),I,1)
10140  IF ZQ$ = "+" OR ZQ$ = "-" OR ZQ$ = " " OR ZQ$ = "." OR ZQ$ = "E" THEN 10160
10150  IF ZQ$ < "0" OR ZQ$ > "9" THEN 10050
10160  NEXT I:ZZ(7) =  VAL (ZD$(0))
10170  IF ZZ(7) < ZZ(4) OR ZZ(7) > ZZ(5) THEN 10050
10180 ZZ(3) = ZZ(7): IF ZZ(6) = 1 THEN ZZ(3) =  INT (ZZ(7))
10190  FOR I = 0 TO 200: NEXT I: RETURN
11300  REM  : LOAD ARRAY
11320  POKE 98,90: POKE 99,ZZ(8): CALL 38152
11330  PRINT  CHR$ (4);"BLOAD"ZD$(0);",A"; PEEK (38394) +  PEEK (38395) * 256
11340  RETURN
11400  REM : SAVE ARRAY
11420  POKE 98,90: POKE 99,ZZ(8): CALL 38104
11430  PRINT  CHR$ (4);"BSAVE"ZD$(0)",A" PEEK (38394) +  PEEK (38395) * 256",L" PEEK (38396) +  PEEK (3
    8397) * 256"
11440  RETURN
11500  REM ASK SLOT,DRIVE AND VOLUME
11510  VTAB 6: CALL  - 958: PRINT "POINTERS CURRENTLY SET AT :": VTAB 8: PRINT "    SLOT #";S%: PRINT "
     DRIVE #";D%: PRINT "  VOLUME #";V%
11520  VTAB 12: PRINT "CHANGE POINTERS (Y/N) ? ";: GET ZD$(0): IF ZD$(0) = "N" THEN 11550
11530  PRINT : PRINT :ZZ(3) = S%:ZZ(4) = 4:ZZ(5) = 6:ZZ(6) = 0: PRINT "    SLOT ";: GOSUB 10120: IF ZE%
    (0) = 1 THEN 11530
11532 S% =  INT (ZZ(3) + 0.5)
11535  PRINT :ZZ(3) = D%:ZZ(4) = 1:ZZ(5) = 2:ZZ(6) = 0: PRINT "   DRIVE ";: GOSUB 10120: IF ZE%(0) = 1 THEN
    11535
11537 D% =  INT (ZZ(3) + 0.5): IF S% <  > 6 THEN V% = 0: GOTO 11550: REM FLOPPY
11540  PRINT :ZZ(3) = V%:ZZ(4) = 1:ZZ(5) = 67:ZZ(6) = 0: PRINT "  VOLUME ";: GOSUB 10120: IF ZE%(0) = 1
     THEN 11540
11542 V% =  INT (ZZ(3) + 0.5)
11550  PRINT : PRINT "PRESS ANY KEY TO CATALOG ": GET ZD$(0): PRINT : PRINT  CHR$ (4);"CATALOG,S"S%",D"
    D%",V"V%
11560  PRINT : PRINT "ANOTHER CATALOG  Y/N ?  ";: GOSUB 10000: IF ZE%(0) = 1 THEN 11560
11570  IF ZZ(3) = 2 THEN 11500
11580  RETURN
15000  TEXT : POKE 34,0: HOME : VTAB 5: PRINT "SET-UP OPTIONS ARE:"
15020  PRINT : PRINT "  1...RETURN TO MAIN MENU"
15040  PRINT : PRINT "  2...CREATE/MODIFY SET-UP FILE"
15060  PRINT : PRINT "  3...RETRIEVE SET-UP FILE FROM DISK"
15080  PRINT : PRINT "  4...SAVE SET-UP FILE TO DISK"
15100  PRINT : PRINT "  5...EXECUTE SET-UP FILE"
15120  PRINT : PRINT "  6...RESET (INITIALIZE) SOLARTRON"
15140  PRINT : PRINT "  7...RESET (INITIALIZE) KEITHLEY"
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15200 ZZ(3) = 1: VTAB (23):ZZ(4) = 1:ZZ(5) = 7: GOSUB 10100: IF ZE%(0) = 1 THEN 15000
15220  ON ZZ(3) GOTO 1000,15300,16600,16640,16700,2000,1900
15300  HOME : VTAB 5: PRINT "SET-UP WHICH SUBSYSTEM:"
15320  PRINT : PRINT "  1...GENERATOR"
15340  PRINT : PRINT "  2...ANALYSER"
15360  PRINT : PRINT "  3...SWEEP(S)"
15380  PRINT : PRINT "  4...IMPEDANCE STANDARD"
15400  PRINT : PRINT "  5...MEASUREMENT CONFIGURATION"
15460  PRINT : PRINT "  0...RETURN TO SET-UP OPTIONS"
15480 ZZ(3) = 0: VTAB (23):ZZ(4) = 0:ZZ(5) = 5: GOSUB 10100: IF ZE%(0) = 1 THEN 15300
15500  ON ZZ(3) GOTO 15600,15800,16000,16300,16500
15520  GOTO 15000
15600  HOME : VTAB 3: PRINT "GENERATOR"
15610  VTAB 6: PRINT "FREQUENCY ";:ZZ(3) = ZM(1):ZZ(4) = 1E - 5:ZZ(5) = 65535:ZZ(6) = 0: GOSUB 10100: IF
    ZE%(0) = 1 THEN 15610
15620 ZM(1) = ZZ(3)
15630  VTAB 9: PRINT "AMPLITUDE ";:ZZ(3) = ZM(2):ZZ(4) = 0:ZZ(5) = 10.23:ZZ(6) = 0: GOSUB 10100: IF ZE%
    (0) = 1 THEN 15630
15640 ZM(2) = ZZ(3)
15650  VTAB 12: PRINT "D.C. BIAS ";:ZZ(3) = ZM(3):ZZ(4) =  - 10.23:ZZ(5) = 10.23:ZZ(6) = 0: GOSUB 10100
    : IF ZE%(0) = 1 THEN 15650
15660 ZM(3) = ZZ(3)
15666  IF ZM(2) +  ABS (ZM(3)) > 14 THEN  VTAB 8: PRINT "COMBINED VOLTAGE TOO LARGE": GOTO 15630
15670  VTAB 15: PRINT "WAVEFORM (SIN=0,SQR=1) ";:ZZ(3) = ZM(4):ZZ(4) = 0:ZZ(5) = 1:ZZ(6) = 1: GOSUB 101
    00: IF ZE%(0) = 1 THEN 15670
15680 ZM(5) = ZZ(3)
15690  VTAB 18: PRINT "AMPLITUDE COMP. (OFF=0,ON=1) ";:ZZ(3) = ZM(14):ZZ(4) = 0:ZZ(5) = 1:ZZ(6) = 1: GOSUB
    10100: IF ZE%(0) = 1 THEN 15690
15700 ZM(14) = ZZ(3)
15710  IF ZM(14) = 0 THEN 15300
15720  HOME : VTAB 5: PRINT "AMPLITUDE OMPRESSION ON"
15730  VTAB 8: PRINT "SOURCE CHANNEL ";:ZZ(3) = ZM(11):ZZ(4) = 1:ZZ(5) = 2:ZZ(6) = 1: GOSUB 10100: IF Z
    E%(0) = 1 THEN 15730
15740 ZM(11) =  INT (100 * ZZ(3) + 0.5)
15750  VTAB 12: PRINT "VOLTAGE LEVEL ";:ZZ(3) = ZM(12):ZZ(4) = 1E - 4:ZZ(5) = 300:ZZ(6) = 0: GOSUB 1010
    0: IF ZE%(0) = 1 THEN 15750
15760 ZM(12) = ZZ(3)
15770  VTAB 16: PRINT "ERROR PERCENT ";:ZZ(3) = ZM(13):ZZ(4) = 1:ZZ(5) = 50:ZZ(6) = 0: GOSUB 10100: IF
    ZE%(0) = 1 THEN 15770
15780 ZM(13) = ZZ(3)
15790  GOTO 15300
15800  HOME : VTAB 3: PRINT "ANALYSER"
15810  VTAB 6: PRINT "INTEGRATION TIME (SECONDS) ";:ZZ(3) = ZM(21):ZZ(4) = .01:ZZ(5) = 1E4:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 15810
15820 ZM(21) = ZZ(3)
15830  VTAB 9: PRINT "MEASUREMENT DELAY ": GOSUB 15995:ZZ(3) = ZM(11):ZZ(4) = 0:ZZ(5) = 1E5:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 15830
15840 ZM(11) = ZZ(3)
15850  VTAB 14: PRINT "INITIAL HARMONIC ";:ZZ(3) = ZM(25):ZZ(4) = 1:ZZ(5) = 16:ZZ(6) = 1: GOSUB 10100: IF
    ZE%(0) = 1 THEN 15850
15860 ZM(25) = ZZ(3)
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15870  VTAB 18: PRINT "AUTO INTEGRATE  OFF=0": PRINT "CH1(L)=1,CH2(L)=2,CH1(S)=3,CH2(S)=4":ZZ(3) = ZM(2
    6):ZZ(4) = 0:ZZ(5) = 4:ZZ(6) = 1: GOSUB 10100: IF ZE%(0) = 1 THEN 15870
15880 ZM(26) = ZZ(3)
15900  VTAB 6: CALL  - 958: VTAB 8: PRINT "INPUT VOLTAGE RANGE  AUTO=0": PRINT "30MV=1,300MV=2,3V=3,30V
    =4,300V=5":ZZ(3) = ZM(27):ZZ(4) = 0:ZZ(5) = 5:ZZ(6) = 1: GOSUB 10100: IF ZE%(0) = 1 THEN 15900
15910 ZM(27) = ZZ(3)
15920  VTAB 13: PRINT "INPUT COUPLING ": PRINT "DC=0,AC=1,FREQUENCY TO CHANGE=XXX":ZZ(3) = ZX%(1):ZZ(4)
     = 0:ZZ(5) = 999:ZZ(6) = 0: GOSUB 10100: IF ZE%(0) = 1 THEN 15920
15930 ZM(49) = ZZ(3):ZM(29) = ZM(49): IF ZM(49) > 1 THEN ZM(29) = 0
15950  VTAB 18: PRINT "INPUT (FRONT=0,REAR=1,BOTH=2) ";:ZZ(3) = ZM(50):ZZ(4) = 0:ZZ(5) = 2:ZZ(6) = 1: GOSUB
    10100: IF ZE%(0) = 1 THEN 15950
15960 ZM(50) = ZZ(3):ZM(30) = ZM(50): IF ZM(50) > 1 THEN ZM(30) = 0
15990  GOTO 15300
15995  PRINT "(S=SECONDS,C=CYCLES) ";:II = 24: PRINT "CYCLES ";: GET ZD$(0): IF ZD$(0) = "S" THEN  HTAB
    22: VTAB 10: PRINT "SECONDS";:II = 23
15996  RETURN
16000  HOME : VTAB 3: PRINT "SWEEP(S)...# OF MEASUREMENTS = ";ZN%
16010  VTAB 6: CALL  - 958: PRINT "DC VOLTAGE SWEEP (Y/N) ? ";: GOSUB 10000:ZM(57) = 1: IF ZE%(0) = 1 THEN
    16010
16020  IF ZZ(3) = 1 THEN ZM(118) = ZM(3):ZM(119) = ZM(3):ZM(120) = 0: GOTO 16100
16030  VTAB 9: PRINT "INITIAL DC VOLTAGE ";:ZZ(3) = ZM(3):ZZ(4) =  - 10.23:ZZ(5) = 10.23:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16030
16040 ZM(118) = ZZ(3)
16050  VTAB 12: PRINT "FINAL DC VOLTAGE ";:ZZ(3) = ZM(119):ZZ(4) =  - 10.23:ZZ(5) = 10.23:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16050
16060 ZM(119) = ZZ(3)
16070  VTAB 15: PRINT "DC VOLTAGE STEP ";:ZZ(3) = ZM(120):ZZ(4) =  - 10.23:ZZ(5) = 10.23:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16070
16080 ZM(120) = ZZ(3)
16085  IF  SGN (ZM(119) - ZM(118)) < >  SGN (ZM(120)) THEN  VTAB 8: PRINT "ARE YOU GOING TO CIRCLE INF
    INITY ?": GOTO 16030
16088  IF ZM(120) = 0 THEN ZM(121) = 2:ZM(57) = 1:ZM(117) = 0: GOTO 16100
16090  VTAB 18: PRINT "FILL ARRAY BETWEEN DC STEPS (Y/N)";: GOSUB 10000:ZM(121) = ZZ(3): IF ZM(121) = 2
     THEN 16100
16093 ZM(57) =  INT (1.5 + (ZM(119) - ZM(118)) / ZM(120))
16095  VTAB 20: PRINT "DELAY BETWEEN DCV (/S) ";:ZZ(3) = ZM(117):ZZ(4) = 0:ZZ(5) = 1000:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16095
16097 ZM(117) = ZZ(3)
16100  VTAB 6: CALL  - 958: PRINT "FREQUENCY SWEEP (Y/N) ? ";: GOSUB 10000:ZM(56) = 1: IF ZE%(0) = 1 THEN
    16100
16105  IF ZZ(3) = 1 THEN ZM(34) = ZM(1):II = 34: GOSUB 21000:ZM(35) = ZM(1):II = 35: GOSUB 21000: GOTO
    16150
16110  VTAB 9: PRINT "FREQUENCY MINUMUM ";:ZZ(3) = ZM(35):ZZ(4) = 1E - 5:ZZ(5) = 65535:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16110
16120 ZM(35) = ZZ(3):II = 35: GOSUB 17000
16130  VTAB 12: PRINT "FREQUENCY MAXIMUM ";:ZZ(3) = ZM(34):ZZ(4) = ZM(35):ZZ(5) = 65535:ZZ(6) = 0: GOSUB
    10100: IF ZE%(0) = 1 THEN 16130
16140 ZM(34) = ZZ(3):II = 34: GOSUB 17000
16150 ZM(55) = 1: IF ZM(34) > 32767 THEN ZM(25) = 1: GOTO 16200: REM NO HARMONIC POSSIBLE
16155  VTAB 6: CALL  - 958: PRINT "HARMONIC SWEEP (Y/N) ? ";: GOSUB 10000: IF ZE%(0) = 1 THEN 16150
16160  IF ZZ(3) = 1 THEN ZM(122) = ZM(25):ZM(123) = ZM(25): GOTO 16200
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16170  VTAB 9: PRINT "INITIAL HARMONIC # ";:ZZ(3) = ZM(122):ZZ(4) = 1:ZZ(5) =  INT (65535 / ZM(34)):ZZ(
     6) = 1: GOSUB 10100: IF ZE%(0) = 1 THEN 16170
16180 ZM(122) = ZZ(3)
16190  VTAB 12: PRINT "FINAL HARMONIC # ";:ZZ(3) = ZM(123):ZZ(4) = ZM(122):ZZ(5) =  INT (65535 / ZM(34)
     ):ZZ(6) = 1: GOSUB 10100: IF ZE%(0) = 1 THEN 16190
16195 ZM(123) = ZZ(3):ZM(55) = ZM(123) - ZM(122) + 1
16200  VTAB 6: CALL  - 958: PRINT "TIMED SWEEP (Y/N) ? ";: GOSUB 10000: IF ZE%(0) = 1 THEN 16200
16210  IF ZZ(3) = 1 THEN ZM(124) = 0:ZM(125) = ZM(124):ZM(126) = ZM(125): GOTO 16290
16220  GOSUB 18000: VTAB 9: PRINT ZD$(0): REM   CLOCK
16230  VTAB 12: PRINT "START MEASUREMENTS @ HH.MM ";:ZZ(3) = ZM(124):ZZ(4) = 0:ZZ(5) = 24:ZZ(6) = 0: GOSUB
     10100: IF ZE%(0) = 1 THEN 16230
16240 ZM(124) = ZZ(3)
16250  VTAB 15: PRINT "STOP MEASUREMENTS @ HH.MM ";:ZZ(3) = ZM(125):ZZ(4) = ZM(124):ZZ(5) = 99.59:ZZ(6)
      = 0: GOSUB 10100: IF ZE%(0) = 1 THEN 16250
16260 ZM(125) = ZZ(3)
16270  VTAB 18: PRINT "MEASUREMENT INTERVAL HH.MM ";:ZZ(3) = ZM(126):ZZ(4) = 0:ZZ(5) = 24:ZZ(6) = 0: GOSUB
     10100: IF ZE%(0) = 1 THEN 16270
16280 ZM(126) = ZZ(3)
16290 ZM(56) =  INT (ZM% / (ZM(55) * ZM(57))): GOTO 15300
16300  HOME : VTAB 3: PRINT "SCALE FACTORS:"
16310  VTAB 6: PRINT "// RESISTANCE STANDARD ";:ZZ(3) = ZM(51):ZZ(4) = .1:ZZ(5) = 1E9:ZZ(6) = 0: GOSUB
     10100: IF ZE%(0) = 1 THEN 16310
16320 ZM(51) = ZZ(3)
16330  VTAB 10: PRINT "// CAPACITANCE STANDARD ";:ZZ(3) = ZM(52):ZZ(4) = 0:ZZ(5) = 1E3:ZZ(6) = 0: GOSUB
     10100: IF ZE%(0) = 1 THEN 16330
16340 ZM(52) = ZZ(3)
16350  VTAB 14: PRINT "IMPEDANCE SCALE FACTOR ";:ZZ(3) = ZM(53):ZZ(4) = 1:ZZ(5) = 1E9:ZZ(6) = 0: GOSUB
     10100: IF ZE%(0) = 1 THEN 16350
16360 ZM(53) = ZZ(3)
16490  GOTO 15300
16500  HOME : VTAB 3: PRINT "MEASUREMENT MODE:"
16510  VTAB 5: CALL  - 958: PRINT "INPUT(S):     0=2/1": HTAB 14: PRINT "1=1": HTAB 14: PRINT "2=2": HTAB
     14: PRINT "3=(2-1)/1": HTAB 14: PRINT "4=1/(2-1)": HTAB 14: PRINT "5=1&2"
16520  VTAB 11:ZZ(3) = ZM(127):ZZ(4) = 0:ZZ(5) = 5:ZZ(6) = 1: GOSUB 10100: IF ZE%(0) = 1 THEN 16520
16525 ZM(127) = ZZ(3)
16530  VTAB 13: PRINT "OPERATOR:    0=UNITY": HTAB 14: PRINT "1=JW": HTAB 14: PRINT "2=1/JW": HTAB 14: PRINT
     "3=JW^2": HTAB 14: PRINT "4=1/JW^2"
16540  VTAB 18:ZZ(3) = ZM(116):ZZ(4) = 0:ZZ(5) = 4:ZZ(6) = 0: GOSUB 10100: IF ZE%(0) = 1 THEN 16540
16545 ZM(116) = ZZ(3)
16550  VTAB 20: PRINT "COORDINATES  0=A/B": HTAB 14: PRINT "1=R/THETA": HTAB 14: PRINT "2=LOG.R/THETA"
16560  VTAB 23:ZZ(3) = ZM(46):ZZ(4) = 0:ZZ(5) = 2:ZZ(6) = 0: GOSUB 10100: IF ZE%(0) = 1 THEN 16560
16565 ZM(46) = ZZ(3)
16570  GOTO 15300
16600  HOME : VTAB 3: PRINT "RETRIEVE SET-UP FILE"
16620  GOSUB 16680:ZZ(8) = 77: GOSUB 11300: GOTO 15000
16640  HOME : VTAB 3: PRINT "SAVE SET-UP FILE TO DISK"
16660  GOSUB 16680:ZZ(8) = 77: GOSUB 11400: GOTO 15000
16680 X =  FRE (0): GOSUB 11500: PRINT : PRINT "FILE NAME WILL BE PRECEDED BY DMSS(P)-": PRINT : INPUT
     "ENTER FILE NAME = DMSS(P)-";ZD$(0):ZF$ = "DMSS(P)-" + ZD$(0):ZD$(0) = ZF$: RETURN
16700  HOME : VTAB 3: PRINT "EXECUTE SET-UP FILE"
16710  FOR II = 1 TO 6: GOSUB 17000: NEXT II
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16720 II = 14: GOSUB 17000: IF ZM(14) = 1 THEN  FOR II = 11 TO 13: GOSUB 17000: NEXT II
16730 II = 20: GOSUB 16900
16740 II = 21: GOSUB 17000:II = 24: IF ZM(23) > 0 THEN II = 23
16750  GOSUB 17000:II = 25: GOSUB 17000:II = 26: GOSUB 17000
16760  FOR II = 27 TO 30: FOR JZN = 1 TO 2: GOSUB 17100: NEXT JZN: NEXT II
16770 II = 34: GOSUB 17000:II = 35: GOSUB 17000:II = 46: GOSUB 17000
16780 ZM(45) = 0201: IF ZM(127) > 0 THEN ZM(45) = 0100: IF ZM(127) > 1 THEN ZM(45) = 0200: IF ZM(127) >
    2 THEN ZM(45) = 0100
16790 II = 45: GOSUB 17000:II = 68: GOSUB 16900
16800 JZN = 0:II = 85:ZM(85) = 1: GOSUB 17200: REM DISPLAY
16802 JZN = 1:ZM(85) = 0: GOSUB 17200
16804 JZN = 2:ZM(85) = 1: GOSUB 17200
16806 JZN = 3:ZM(85) = 1: GOSUB 17200
16810 JZN = 1:II = 86:ZM(86) = 0: GOSUB 17200: REM DISPLAY
16811 JZN = 2:ZM(86) = 0: GOSUB 17200
16812 JZN = 3:ZM(86) = ZM(116): GOSUB 17200
16813 JZN = 4:ZM(86) = 0: GOSUB 17200
16814 JZN = 5:ZM(86) = 0: GOSUB 17200
16816 II = 108: GOSUB 17000:II = 109: GOSUB 17000
16820  GOTO 1000
16900  RESTORE : FOR I = 1 TO II: READ M$: NEXT I:M$ = ":'" + M$ + "'": GOSUB 21000: RETURN
17000  RESTORE : FOR I = 1 TO II: READ M$: NEXT I:M$ = ":'" + M$ +  STR$ (ZM(II)) + "'": GOSUB 21000: RETURN

17100  FOR JZN = 1 TO 2: RESTORE : FOR I = 1 TO II: READ M$: NEXT I:M$ = ":'" + M$ +  STR$ (JZN) + "," +
     STR$ (ZM(II)) + "'": GOSUB 21000: NEXT JZN: RETURN
17200  RESTORE : FOR I = 1 TO II: READ M$: NEXT I:M$ = ":'" + M$ +  STR$ (JZN) + "," +  STR$ (ZM(II)) +
    "'": GOSUB 21000: RETURN
18000  REM CLOCK
18010 ZZ(3) =  PEEK ( - 16384) - 128: REM KEY PUSH
18020  IF ZZ(3) = 1 THEN  GOTO 1000: REM  ABORT
18080  IF ZZ(3) = 19 THEN 18220: REM   STATUS
18090  IF ZZ(3) = 20 THEN ZM(47) = 999: REM  TERMINATE
18100  IF ZZ(3) = 21 THEN ZM(47) = 0
18190  RETURN
18200  REM TIME
18220 II = 1:M$ = ":'?TM0'": GOSUB 24000:ZZ(3) = ZZ(II):M$ = ":'?TM1'": GOSUB 24000:ZZ(4) = ZZ(II):ZD$(
    0) = "TIME IS " +  STR$ (ZZ(3)) + ":":M$ =  STR$ (ZZ(4)): IF ZZ(4) < 9 THEN M$ = "0" + M$
18240 ZD$(0) = ZD$(0) + M$: VTAB 1: HTAB 28: PRINT ZD$(0): RETURN : REM  READ CLOCK
19900  REM CHAIN SUBROUTINE
19920  HOME : VTAB 9:NP% = 1: PRINT "LOADING DMSS."ZD$(0)
19940  PRINT  CHR$ (4);"BLOAD CHAIN,A520,S"SB%;",D1,V"VB%
19960  RETURN
20000 ZZ% = 12
20010 ZD$(4) = "@" +  CHR$ (95) +  CHR$ (ZZ% + 64):ZD$(5) = "@" +  CHR$ (95) + "?" +  CHR$ (ZZ% + 32) +
    ":"
20020 ZD$(6) =  CHR$ (4) + "IN#0":ZD$(7) =  CHR$ (4) + "PR#0"
20030 ZD$(8) =  CHR$ (4) + "PR#3":AA$ = "@" +  CHR$ (95) + "(:'":BB$ = "X'@?;@H:"
20900  RETURN
21000  REM  SEND DATA TO FRA
21030  PRINT ZD$(8): PRINT ZD$(5)
21040  PRINT M$
21050  PRINT ZD$(6)
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21470 PRINT ZD$(7)
21500 RETURN
24000 REM DATA RETRIEVE
24030 PRINT ZD$(8): PRINT ZD$(5)
24040 PRINT  CHR$ (13): PRINT M$: GOSUB 28500: PRINT ZD$(7): PRINT ZD$(6): RETURN
28500 PRINT  CHR$ (13);ZD$(4);":": PRINT ZD$(7): VTAB 23
28501 ON II - 1 GOTO 28504,28506,28508
28502 INPUT ZZ(1): PRINT ZD$(8): RETURN
28504 INPUT ZZ(1),ZZ(2): PRINT ZD$(8): RETURN
28506 INPUT ZZ(1),ZZ(2),ZZ(3): PRINT ZD$(8): RETURN
28508 INPUT ZZ(1),ZZ(2),ZZ(3),ZZ(4): PRINT ZD$(8): RETURN
29000 REM KEITHLEY MODEL 192 SET-UP
29200 ZD$(0) = M$ + "R0K0Q0S3M0Z0W1"
29220 VTAB 23
29240 PRINT ZD$(8): PRINT AA$;ZD$(0);BB$: PRINT ZD$(7): INPUT ZD$(0): PRINT ZD$(6): VTAB 23: PRINT "@"
29260 ZZ(3) =  VAL ( MID$ (ZD$(0),5)): RETURN
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END

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