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SYSTEMS & RESEARCH DIVISION

15 March 1972

DIELECTRIC RELAXATION AND ROCK GEOPHYSICAL CHARACTERISTICS

Final Report

Submitted to
U.S. Bureau of Mines (ARPA)
Contract No. H0210026

SEE AD 732024

Z9506-3007

Honeywell Document 12288-FR

63

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Honeywell Inc.
Systems and Research Center
2345 Walnut Street, St. Paul, Minnesota 55113

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
DIELECTRIC RELAXATION AND ROCK GEOPHYSICAL CHARACTERISTICS (Final Report)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report 2/19/71 - 2/18/72

5. AUTHOR(S) (First name, middle initial, last name)
Aida S. Khalafalla

6. REPORT DATE
15 March 1972

7a. TOTAL NO. OF PAGES
153

7b. NO. OF REFS
28

8a. CONTRACT OR GRANT NO
H0210026

b. PROJECT NO
ARPA Order No. 1579, Amend. 2

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
12288-FR

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Advanced Research Projects Agency
Washington, D.C., 20301

13. ABSTRACT

Electric and dielectric rock parameters were measured using an analog/digital computer for rapid evolution and data display. In common with many dielectrics, the imaginary part of dielectric constant established a circular arc when plotted against the real part at a series of frequencies. A conformal arc with the same relaxation time was obtained when the reactive component of impedance was plotted as a function of the resistive component. The data were verified on various rock samples of basalt, granite and quartzite in the frequency range 1Hz to 2kHz. Effects of rock pretreatments in water and in sodium hydroxide solutions upon their electric and dielectric parameters were studied. The highest sensitivity for water detection in rocks was realized by extrapolating the circular arc to determine the real dielectric constant at zero frequency limit. Electrode polarization and double layer effects had been explained in terms of an electrical model that also simulated the rock impedance and dielectric relaxation behaviours.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dielectric						
Rock						
Impedance						
Resistivity						
Frequency						
Permittivity						
Relaxation						
Polarization						
Basalt						
Granite						
Quartzite						
Circular-arc						
Argand Diagram						
Cole-Cole						

FINAL REPORT
DIELECTRIC RELAXATION AND ROCK GEOPHYSICAL CHARACTERISTICS

Sponsored By:

Advanced Research Projects Agency
ARPA Order No. 1579, Amend. 2
Program Code 1F10

Contract No. H0210026

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Amount of Contract: $39,642

Effective Date of Contract: 19 February 1971

Contract Expiration Date: 19 February 1972

Contractor:

Honeywell Inc.
Systems and Research Center
Research Department
2345 Walnut Street
St. Paul, Minnesota 55113

ACKNOWLEDGEMENT

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by Bureau of Mines under Contract No. H0210026.

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SECTION I
PROJECT OBJECTIVES AND SIGNIFICANT RESULTS

RESEARCH OBJECTIVES

Objectives of this research were to adopt rock impedance and dielectric parameters as indicators as well as predictors of their geophysical characteristics, of presence of water, entrapped gases, and rock fractures. Dielectric relaxation mechanisms were utilized to describe the impedance and dielectric characteristics of representative rocks. Electrical models to simulate rock impedance and dielectric dispersion were used to correlate rock properties with the model parameters. Data taken at low frequencies (<2kHz) yielded information that is pertinent to rock structure and geophysical characteristics, while the high-frequency data would contribute a valuable input to rock fragmentation by dielectric heating. Research covered in this report was confined to the low-frequency range and to the development of relationships between impedance and dielectric permittivity data on rocks.

SIGNIFICANT RESULTS

Rapid measurement and display of the low-frequency impedance parameters of basalt, granite, and quartzite was accomplished by a novel technique in which the rock under investigation was placed in the feedback path of an operational amplifier, and an analog/digital computer was used for rapid evolution and data display. The data obtained adhered closely to the theoretically predicted circular arc diagram when the equivalent series reactance was plotted as a function of the equivalent series resistance at various frequencies from 0.05 Hz to 2 kHz. The photographs in Figures 1-1, 1-2, and 1-3 show the actual output for the impedance parameters of basalt, granite, and quartzite rock samples as displayed in the Argand diagram.

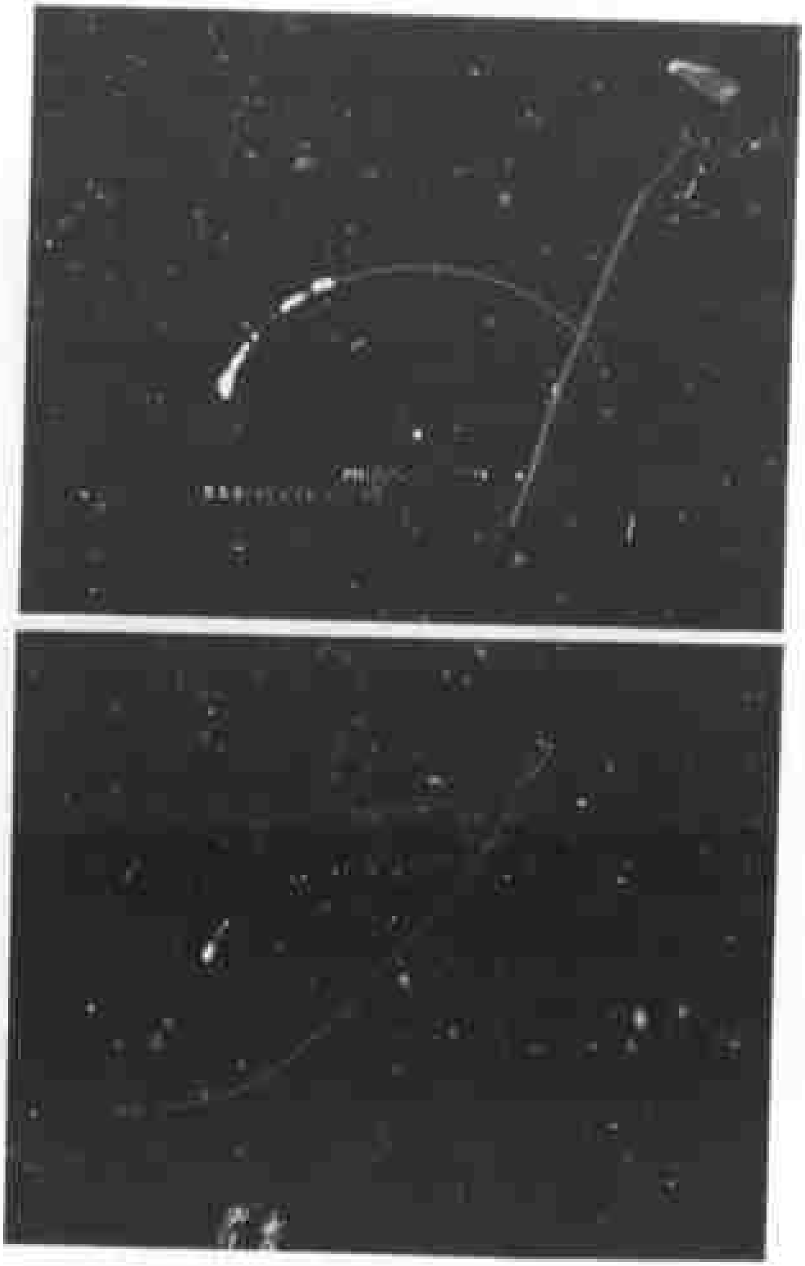

Figure 1-2. Computer Display of the Impedance Circular Arcs for Granite Samples. Top photograph is for a long granite cylinder (4.41 cm). Bottom photograph is for a thin slice of the granite cylinder (0.15 cm). Points (+) represent variation of reactance with resistance at a given frequency. Dotted curves are arcs of the computer data-fitted circle in the least square sense.

Figure 1-3. Computer Display of the Impedance Circular Arc for a Large Diameter Quartzite Disc Sample. Points (+) represent experimental variation of reactance with resistance at a given frequency. Dotted curve is an arc of the computer data-fitted circle in the least square sense.

A new "bracketing" technique was developed to extract the rock dielectric constants from the corrected and normalized impedance parameters. Details of this novel technique are presented in Sections IV and VII.

An electrical model that describes the observed behavior of rock impedance data has been developed and is reported in Section VII. The model permits quantitative evaluation and correlation of observed rock impedance data and their geophysical characteristics. The model also elucidates for the first time the inherent complications that arise from electrode impedance and rock/electrode double layer polarization effects by defining a polarization parameter, g.

The highest sensitivity for water detection in rocks was obtained by extrapolating the real component of the dielectric constant to the zero frequency limit. The effects of rock pretreatment in water and in sodium hydroxide solutions upon their electric and dielectric parameters are covered in Section VI. Variation of the polarization constant, g, for a basalt rock with its sodium (mobile) ion content is shown in Figure 1-4. Lower polarization constants correspond to more significant electrode double-layer polarization artifacts, because this type of double-layer polarization impedance appears to be in parallel with the rock impedance components. Hence, the presence of larger quantities of sodium ions increases the double-layer polarization effects in addition to increasing the rock ohmic conductivity.

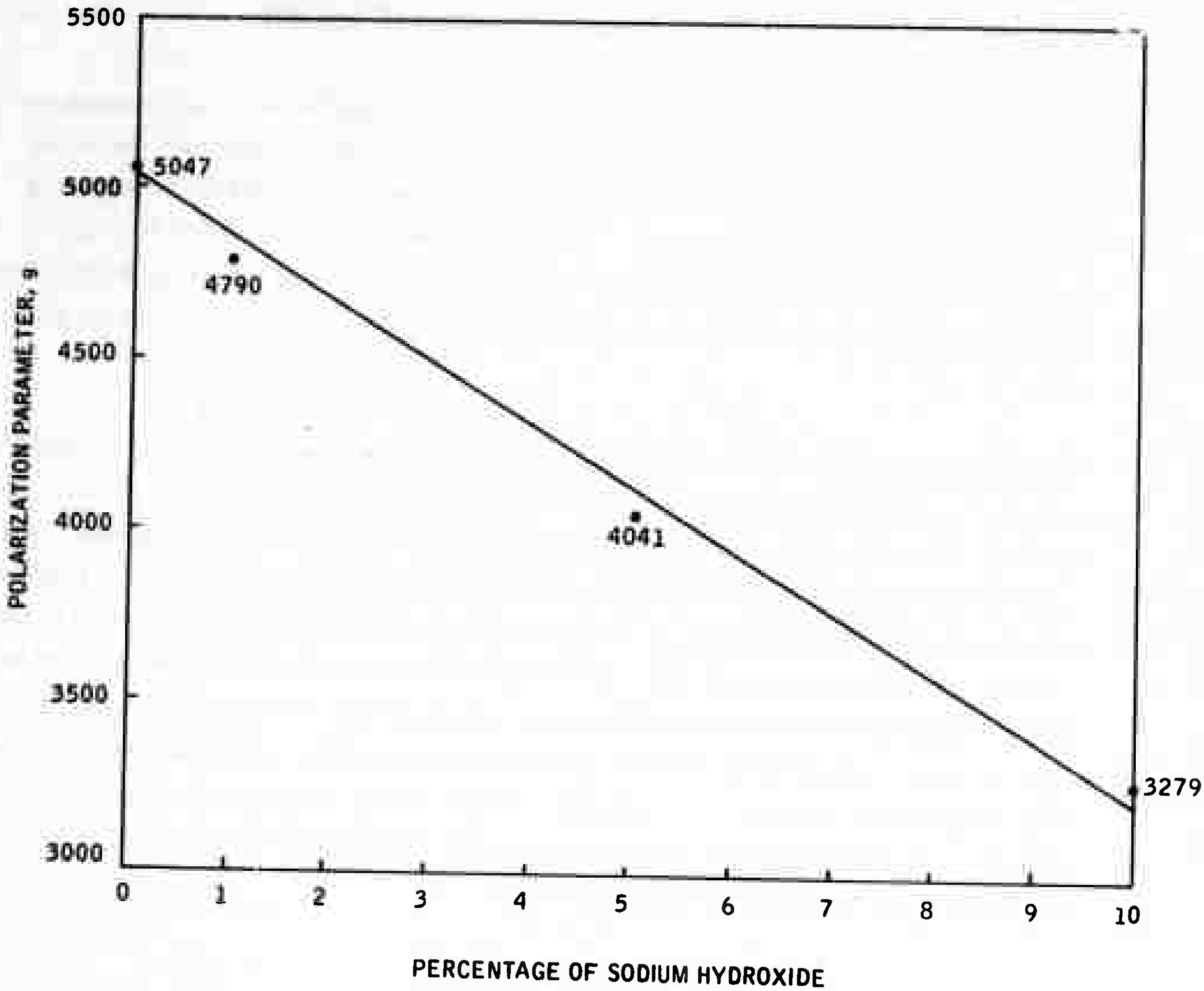

Figure 1-4. Variation of the Polarization Constant g for Basalt Rock with the Percentage of Sodium Hydroxide in the Pretreating Solution. Pretreatment Time = 23 hours.

SECTION II
EXPERIMENTAL TECHNIQUE

The most common methods of determining the electric and dielectric properties of rocks involve bridge, resonance, and heterodyne techniques. A comprehensive description of these and similar techniques is given in References 1 and 2.

During this program a new direct-comparison method was developed that involved placing the rock sample in the feedback loop of an operational amplifier. This method has the advantage that data can be taken at extremely low frequencies where conventional methods become too unstable. Furthermore, the data were processed by a computer and displayed directly. In this technique, impedance data processing involved time-domain sampling and a discrete Fourier transform to the frequency domain.

EXPERIMENTAL SETUP

The basic approach to the experimental determination of the rock impedance is the use of the rock as a feedback impedance in an operational amplifier. Thus, for a known input signal and resistance, the rock impedance can be determined from the amplifier output signal. This technique lends itself to convenient, on-line signal analysis through the use of analog-to-digital conversion equipment.

Figure 2-1 illustrates the experimental setup in simplified form. Basically, a sinusoid at known frequency drives the amplifier containing the rock, while an in-phase square wave generated simultaneously with the sinusoid is used to clearly define the period of the waveform.

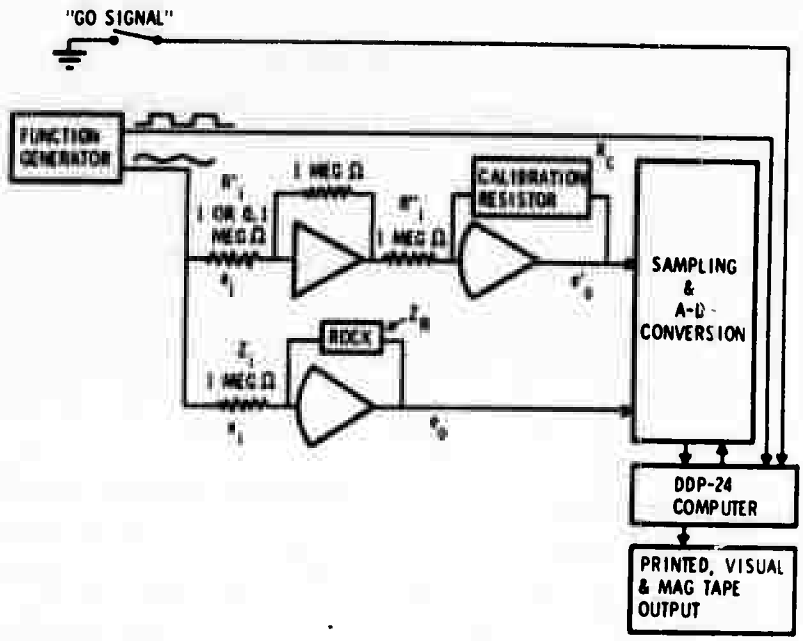

Figure 2-1. Schematic of Experimental Setup

The output from the rock amplifier is sampled over some interval consistent with the signal frequency and converted to digital form. At this stage a DDP-24 computer performs a discrete Fourier transform and computes the equivalent series resistance and reactance for the signal.

Included within the analog circuitry is an amplifier having a known fixed (calibration) resistor in its feedback loop. The signal from this amplifier is analyzed simultaneously with the rock signal and provides a reference signal of known amplitude and phase.

Another amplifier is provided just ahead of the calibration amplifier to provide a means of easily changing the gain through the calibration branch without changing the calibration resistor itself.

The voltage output, e_o (Figure 2-1), from the amplifier having the rock as its feedback impedance is given by

$$e_o = -\frac{Z_R}{Z_i} e_i , \quad e_o = -Z_R e_i \tag{2-1}$$

because Z_i = 1 megohm and Z_R is in megohms.

Similarly, the output e_o' from the calibration amplifier is given by

$$e_o' = -\frac{R_c}{R_i' R_i''} e_i \tag{2-2}$$

The amplitude of the complex impedance Z_R is thus given by

$$|Z_R| = \frac{|e_o|}{|e_o'|} \left(\frac{R_c}{R_i' R_i''}\right) \tag{2-3}$$

where e_o and e_o' are determined from a Fourier analysis of the output voltages e_o and e_o'.

The Fourier analysis also provides the phase angle ϕ between output voltage and current. Thus, the series resistance and reactance are calculated from

$$R_s = |Z_R| \cos \phi, \text{ and } X_s = |Z_R| \sin \phi \tag{2-4}$$

A least-squares circle fit is also automatically made for the R_s and X_s data and displayed along with the R_s and X_s data on a CRT screen. In addition, all data are permanently stored on magnetic tape for future call back.

PROCEDURE

Sinusoidal signals from the function generator of a discrete frequency from 10 Hz to 1 MHz were used to drive the current electrodes. In addition, an in-phase square wave generated simultaneously with the sinusoid served to clearly delineate the period of the waveform so that its frequency could be easily measured. The excitation current, output voltage, square wave, and "go" signal were led directly to the computer for on-line processing, or else stored intermediately on FM magnetic tapes for subsequent playback when off-line processing becomes necessary. The results were printed, punched on paper tape, and digitally recorded on magnetic tape.

All computations were performed in the laboratory on a DDP-24 computer, which has an 8000-core storage memory bank of 24-bit words. Because this computer is oriented in design for process control, it is ideally suited for on-line measurements of the sort described here. Peripheral equipment contained sample and hold circuitry, a multiplexer, and an analog-to-digital converter as input channels, and a typewriter and paper tape punch for hard copy output.

The operation of the program is outlined in Figure 2-2. After the program was loaded and started, it awaited a "go" signal from the operator. Because complete freedom was desired in selecting frequency as an independent variable, it was necessary for the computer to adjust its own sampling rate accordingly every time the "go" signal was given. The excitation period was measured by determining the interval between successive positive sloped zero crossings, using machine cycles as the "yardstick". A minimum-measurement interval of a few milliseconds, measured to the nearest microsecond increment, was set and the number of cycles occurring in it was noted. With the excitation frequency and a sampling period "window" determined, it was possible to specify a sampling rate and the weighting coefficients of a discrete Fourier transform for harmonic analysis of the data. The waveforms across the

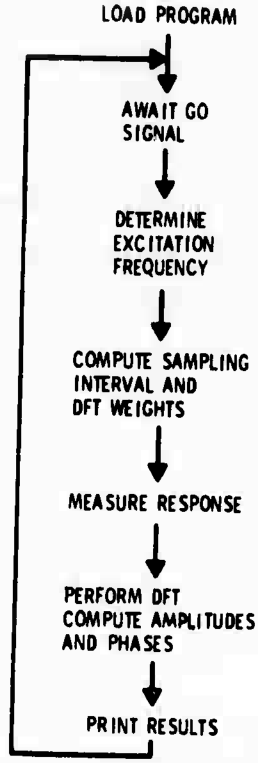

Figure 2-2. Computer Program - Sequence of Events

current source and the rock sample were measured simultaneously and stored internally. From these, the d-c first and second harmonic terms were computed using the above-determined discrete Fourier transform coefficients.

Having determined the frequency, resistance and reactance, a circle was fitted to the data under the condition of minimum deviation (least square calculation). The center of the circle (R_o, X_o) was found such that the square of the deviations, Δ, was a minimum.

$$\Delta = \sum_{i=1}^{n} (r_i - \bar{r})^2 \qquad (2\text{-}5)$$

where n is the number of sampling frequencies at which impedance was measured, $\bar{r}$ is the average circle radius, and r_i is given by

$$r_i = \left[(R_o - R_i)^2 + (X_o - X_i)^2\right]^{1/2} \qquad (2\text{-}6)$$

This was accomplished via a gradient descent in two-dimensional R_o, X_o parameter space. For graphical display, the equivalent series resistances and reactances were computed at each of the sampling frequencies.

Sample Preparation

With the exception of the application of electrode material and the pretreatment experiments in Section VI, all measurements have been made on rocks "as received" from the customer.

The electrodes were applied to the flat surfaces of the cylindrical samples. An epoxy-based conductive adhesive* was applied in a thin coat and allowed to dry for at least two days at room temperature.

Copper leads made from thin sheet stock were laid on top of the electrode material and the rock was clamped tightly between two plates of printed circuit board to secure electrical contact with the rock.

The procedures described here for computing rock electric parameters are valid for isotropic specimens only. It was shown by Spinner and Tefft (Ref. 3) that rock elastic moduli equations can be applied to a polycrystalline material if the individual grains of the material are randomly oriented and distributed, and are not larger than one-third of the smallest dimension of the specimen. Such a material may be considered to be isotropic on a macroscopic scale, even though the individual grains themselves are anisotropic.

*Eccobond Solder V-91, Emerson and Cumming, Inc., Dielectric Materials Division, Canton, Massachusetts.

Validation of the Measurement Technique

To check the validity of rock impedance data obtained with the computer technique, some results were compared with those obtained with traditional compensation techniques using a General Radio-type 1650 CRL bridge. Measurements were performed on a basalt sample (I) at a frequency of 1 kHz. With the bridge technique a series capacitance of 28 picofarads and a dissipation factor, D, of 0.36 at 1 kHz were measured. Transformation from a series domain to an isoimpedic system in the parallel domain yields

$$R_sR_p = X_sX_p = R_s^2 + X_s^2 \qquad (2\text{-}7)$$

The dissipation factor, D, is defined as

$$D = \frac{1}{\omega R_p C_p} = -\frac{X_p}{R_p} = -\frac{R_s}{X_s} \qquad (2\text{-}8)$$

From Equations (2-7) and (2-8) one obtains

$$\frac{X_p}{X_s} = 1 + D^2 = \frac{C_s}{C_p} \qquad (2\text{-}9)$$

Hence

$$C_p = \frac{C_s}{1 + D^2} \qquad (2\text{-}10)$$

From these equations, one calculates a parallel capacitance, C_p, of 25 picofarads and a parallel resistance, R_p, of 17.7 megohms. The series parameters computed at 1 kHz would be -5.72 megohms for the reactance, X_s, and 2.04 megohms for the resistance, R_s.

Measurements with the direct comparison on-line computer technique for the same basaltic rock sample gave the values R_s = 2.77, X_s = -5.28 megohms and ϕ = -62.3 degrees, respectively. The series reactances, -5.72 and -5.28 megohms obtained with the bridge and the new techniques, respectively, differ by about 8 percent. However, the series resistance 2.04 megohms measured with the bridge deviates by about 26 percent from the value 2.77 megohms measured with the present technique.

Despite the large deviation in R_s, and considering the lead impedances and stray capacitances which were not taken into account, these results nevertheless lend credence to the general validity of the new measuring technique. It is generally recognized that bridge balancing methods are difficult at very low frequencies, and hence, their data would be susceptible to gross errors at these frequencies. It appears, therefore, that the new direct-comparison technique yields reliable data in the low-frequency range.

On the assumption that rock impedance can be represented by the simple parallel R_pC_p unit measured with the bridge, we constructed a model from the nearest available components in the laboratory of 18 megohms for R_p and 25 picofarads for C_p. A computer run was performed with this R_pC_p unit replacing the rock. This system gave the data in Table 2-1 for the series parameters at four frequencies.

Table 2-1. Frequency Variation of the Impedance Parameters of the R_pC_p Unit (R_p = 18 megohms, C_p = 25 picofarads)

Frequency (Hz)	R_s (megohms)	$-X_s$ (megohms)	$-\phi$ (degrees)
1000	2.66	4.60	59.9
100	16.22	4.93	16.9
10	17.84	0.61	2.0
1	17.89	0.08	0.2

As predicted, the series resistance approaches the model R_p value of 18 megohms as the frequency approaches zero. The time constant of this unit is equal to R_pC_p = 45 milliseconds. This corresponds to a turnover frequency of about 360 Hz. Around this characteristic frequency, the dispersion in R_s assumes rapidly decreasing values, while the dispersion in X_s assumes a flat maximum (see Figure 3-2). Hence, R_s will be subjected to the greatest error at frequencies between 100 and 1000 ohms by slight changes in the frequency of measurement, while X_s will be somewhat insensitive to such changes. Frequencies reported in this work are the nominal ones; for example, the 1000 Hz was actually sampled by the computer as 1007.33 Hz.

When the simple R_pC_p unit was replaced by the basaltic rock sample in the feedback of the operational amplifier, the data in Table 2-2 were obtained.

Table 2-2. Frequency Variation of Basalt (I) Impedance Parameters

Frequency (Hz)	R_s (megohms)	$-X_s$ (megohms)	$-\phi$ (degrees)
1000	2.77	5.28	62.3
100	16.99	32.15	62.1
10	99.88	110.76	48.0
1	355.84	197.30	29.0

As expected, the values obtained at 1 kHz are in good agreement with those measured with the bridge method. The data at the lower frequencies of 100, 10, and 1 Hz deviated markedly. Thus, a simple R_pC_p model cannot describe the impedance behavior of rocks. More complicated models are therefore needed to simulate the electrical behavior of rocks. One such model is described in Section VII of this report.

SECTION III
ROCK IMPEDANCE AND ELECTRODE EFFECTS

Room-temperature measurements were made on several dry samples of basalt, granite, and quartz. The following results show that impedance data on rocks at audiofrequencies adhere to a circular arc, or series of arcs, when displayed in the Argand diagram. Finite rock resistive and reactive dispersions were evident at characteristic frequencies, which permitted evaluation of rock relaxation time(s).

IMPEDANCE PARAMETERS OF DRESSER BASALT

A disc basaltic sample (II) containing SiO_2, Fe_3O_4, Al_2O_3, TiO_2, CaO, and MgO in the percents* 48.42, 6.6, 15.23, 1.9, 8.35, and 6.4, respectively, and measuring 0.635 cm in length and 6.41 cm^2 in cross-section was supplied to Honeywell by the Thermal Fragmentation Group, Twin Cities Mining Research Center, U.S. Bureau of Mines. Silver electrodes were painted to the circular surfaces of the rock and contact to the electrodes was made with copper wires. Replication of the impedance data at 14 different frequencies and at time intervals ranging from several minutes to three weeks, as well as with repeated electrode applications to the cleaned rock surface gave fairly reproducible results. The standard deviation at the high frequency of 2 kHz was 3.8 percent of the mean in R_s, and 2.6 percent of the mean in X_s. At the low frequency of 0.05 Hz, standard deviations of 3.7 and 8.1 of the mean in R_s and X_s, respectively, were calculated.

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*Chemical analysis of the rock samples are taken from a recent report by Lindroth and Kranze (Reference 4).

The reactive component of the measured impedance is plotted in Figure 3-1 against its corresponding resistive component at a series of frequencies. The least-squares circle fit to the data was determined and plotted in the solid arc of Figure 3-1. The experimental points were found to deviate from the fitted arc by a standard deviation of 2.44 percent of the fitted radius. Inspection of the data in Figure 3-1 suggests a value of 16.4 megohm for the d-c resistance, R_0, of this basalt sample. A rock phase angle, φ, of 29 degrees was also measured for this sample.

When the data were displayed in a log frequency plot, Figure 3-2 was obtained. Curves A and B have been drawn through the series reactance and resistance data, respectively. Careful examination of these curves indicates three dielectric relaxation peaks. The main peak appears at a frequency of 21.8 Hz, which corresponds to a turnover frequency, ω_{max}, of 136.9 radians per second, and to a relaxation time, τ, of 7.3 milliseconds. A second, well-developed relaxation peak appears at a frequency of 1.7 Hz, corresponding to a relaxation time of 93.4 milliseconds. A third relaxation peak appears to be anticipated at frequencies less than 0.01 Hz. In agreement with these observations, the R_s curve shows two definite dispersion regions.

A major emphasis in this work was to represent the process(es) responsible for the impedance or dielectric circular arc by a single time constant, rather than a distribution of time constants. Splitting of the data into 3 overlapping circular arcs will obviously yield three characteristic times, each representing one of the circular arcs, and hence characterize a given relaxation process.

The first dispersion, α_1, appears at a frequency which coincides with the first and main relaxation peak in the series reactance. A second dispersion, α_2, occurs at a frequency of 0.05 Hz, somewhat displaced from the second relaxation peak. A third dispersion may be anticipated at frequencies below 0.01 Hz. In conformity with the adopted notations in dielectric dispersion, we will reserve the symbol α for rock dielectric dispersion in the low-frequency range (below 10 kHz). The symbol β will be used for dispersions in the

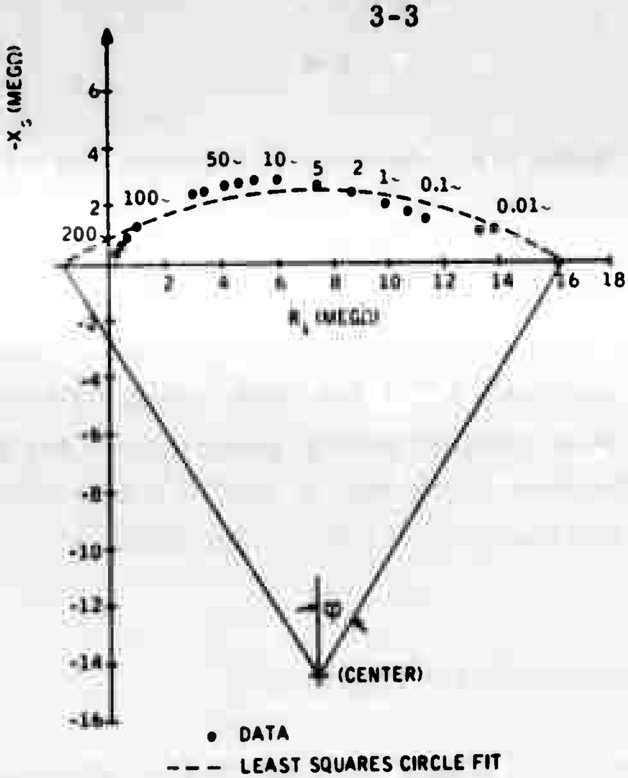


Figure 3-1. Argand Circular-Arc Plot for Dresser Basalt

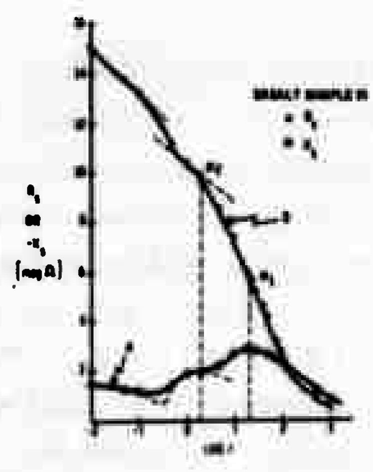


Figure 3-2. Dispersion of Impedance Components of Dresser Basalt and the Relaxation Time(s)

medium frequency range; i.e., between 10 kHz and 100 mHz. The symbol γ will be adopted for dispersions at frequencies beyond 100 mHz. Each of these dispersions may split into more than one subdispersion, such as the α_1, α_2, . . . etc., of the α-dispersion investigated in this project. Each of the discovered dispersions should correspond to a certain relaxation mechanism of a substructure or "structon" within the rock. Huggins and Huggins (Ref. 5) recommended the use of local structural groupings as the basic structural units. They used the term "structon" to signify a specific type of atom(s), with specific kinds and numbers of close neighbors.

IMPEDANCE PARAMETERS OF GRANITE

A sample of charcoal gray granite from St. Cloud, Minnesota, was supplied to Honeywell by personnel from the Thermal Fragmentation Group of the Twin Cities Mining Research Center. The sample analyzed (Ref. 4) 63.5 percent SiO_2, 15.6 percent alumina, 4.1 percent CaO, 3.6 percent Na_2O, 3.6 percent K_2O, 4.2 percent CaO, 2.7 percent FeO, 1.8 percent Fe_2O_3, and smaller quantities of manganese and titanium.

The impedance data of granite followed the same pattern as that of basalt, except that the semicircular arc was not easy to close at the low-frequency side. Resistive and reactive components for a cylindrical granite sample 0.148 cm in length and 3.67 cm^2 in cross-sectional area described a segment of a circular arc when plotted in an Argand diagram. Computer extrapolation of this arc to its point of intersection with the resistive axis yielded a value of 4.8×10^9 ohm (about 5 gigaohm) for R_o. The preceding basaltic sample has an R_o value of 16.4 megohm. If a basalt sample of the same dimension of granite had been used, its R_o value would be

$$16.4 \left(\frac{0.148}{0.635}\right) \left(\frac{6.41}{3.67}\right) = 6.68 \text{ megohm}$$

The d-c resistance value, R_o, as determined by extrapolation of the impedance vector to zero frequency, is therefore about seven hundred times higher for granite than for basalt of similar shape and dimension. This result is consistent with the fact that granite contains 30 percent more of the covalently coordinated, and hence nonconductive, silica tetrahedra. Basalt has more iron, calcium, and titanium, although somewhat less sodium and potassium than granite.

IMPEDANCE PARAMETERS OF QUARTZITE

Sioux quartzite, with a bulk density of 2.64 gram cm^{-3}, was used in the following experiements. The source location of this type of quartzite was Jaspar, Minnesota. Its chemical analysis (Ref. 4) indicated 97.84 percent silica, 0.87 percent Al_2O_3, 0.81 percent CaO, 0.25 percent FeO, and 0.27 percent Fe_2O_3. As with granite, the impedance parameters of quartzite were very large, in the gigaohm range, at low frequencies. A quartzite disc sample of length 0.61 cm and cross-sectional area 18.8 cm^2 gave an extrapolated R_o value of 4.5×10^9 ohms. When corrected to the same dimensions of granite, this value should be modified to

$$4.5 \times 10^9 \left(\frac{0.148}{0.61}\right)\left(\frac{18.8}{3.67}\right) = 5.6 \times 10^9 \text{ ohms}$$

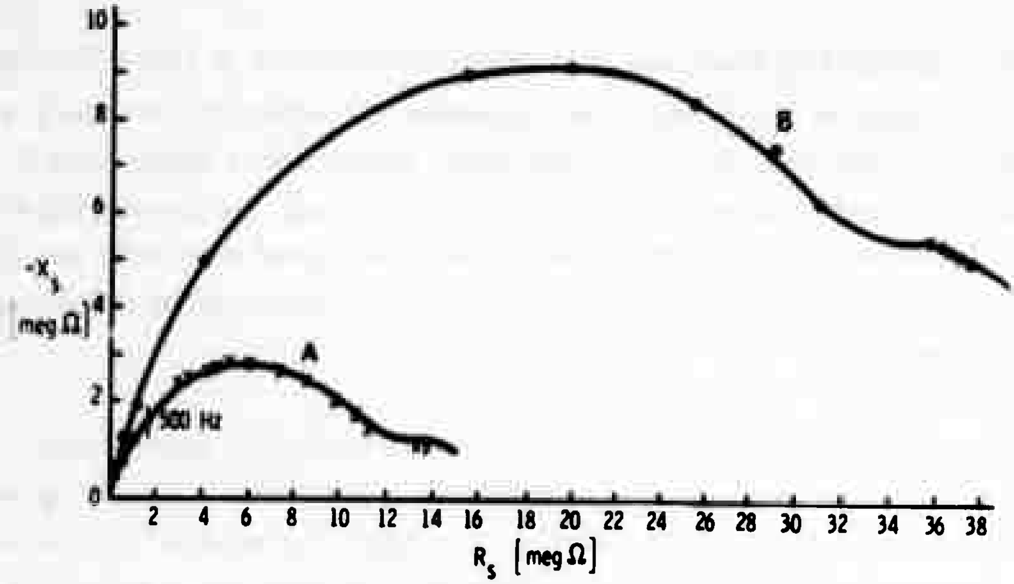
Hence, the quartz d-c resistance is about 20 percent higher than that of granite, and about three orders of magnitude higher than that of basalt. Thus, it appears that the rock's impedance parameters are not only affected by the quantity of silica that it contains, but also by the quantities of volatile oxides within the rock.

Under given environmental conditions, impedance results changed markedly by changes in the rock humidity, despite the reasonable repeatability of impedance data obtained with a given rock sample. In particular, impedance measurements on quartzite were found to be extremely sensitive to ambient air moisture, which contributed a great deal to d-c drifts. With basalt and granite, the data were not as sensitive to room moisture as quartz, and it was possible to study the effect of humidity on their impedance parameters.

EFFECT OF HUMIDITY ON ROCK IMPEDANCE

The effect of moisture content has been examined with a basaltic sample (II) and the data are shown in Figure 3-3. Curve A in this figure was obtained with the rock sample as received from the customer; no attempt was made to control the rock environment. Curve B in Figure 3-3 was obtained when the basalt sample was baked with electrodes attached in a 110°C oven for 19 hours. After baking, the sample was immediately placed in an airtight desiccator and allowed to cool to room temperature for the following 24 hours. The resulting measurements indicated a significant increase in impedance at frequencies up to 500 Hz. Above 500 Hz, the humidity effect on impedance parameters is not very pronounced. While the R_o value for the unbaked basalt was 16.4 megohm, the value determined when the rock was baked is about 45 megohm.

Chemical analysis of Dresser basalt (Ref. 4) indicated the presence of 0.14 percent water in the rock and a loss of ignition (LOI) of 2.26 percent. By contrast, the granite sample and the quartzite sample contained 0.11 and 0.08 percent water, respectively, and showed a loss on ignition of 0.59 and 0.32 percent, respectively. Upon ignition, not only water is lost, but some of the volatile oxides such as Na_2O and K_2O which are not bound in the silicate structure may also sublime. When these volatile oxides are attached to the nonvolatile silica tetrahedron, they are in the form of a solid solution of alkali silicate,



A - Rock at ambient room environment

B - Dry baked rock in desiccator

Figure 3-3. Effect of Moisture on the Impedance Semicircle of Basalt (II)

and the alkali will thereby be prevented from sublimation. A free alkali metal oxide unit in the rock will show a higher LOI ; will also be easily leachable with water, and thus will contribute significantly to the rock conductivity. Thus, the alkali content of a rock as shown by chemical analysis will not be the decisive factor in determining the rock conductivity; rather, the mode by which the alkali oxide enters the rock structure appears to play the predominant role. Because of its higher LOI, Dresser basalt appears to have more of the mobile sodium and potassium ions, which contributes greatly to its higher conductivity relative to granite and quartzite.

ELECTRODE EFFECTS IN IMPEDANCE MEASUREMENT

Measurement of electrical impedance by conventional, two-electrode techniques involves passage of a working current through the sample. At frequencies below 1 kHz, passage of current in the electrode-through-sample junction produces an interfacial phenomenon, which manifests itself as an additional frequency dependent electrode polarization impedance (Ref. 6).

The magnitude of electrode polarization impedance is generally inversely proportional to frequency or some power of frequency. Warburg electrochemical law (Ref. 7) is a special case in which this power is 0.5. In the four-electrode configuration, the current through the measuring electrodes can be minimized when they are properly designed with sufficiently large output impedance, and hence the electrode polarization artifacts can be minimized.

Shedlovsky (Ref. 8) attempted to eliminate electrode polarization by selecting different pairs of electrodes at different separations. Assuming constant polarization effects at each electrode, difference measurements can be made to determine the true sample impedance. At very low frequencies where electrode polarizations are severe, Shedlovsky's method may require finding differences of large numbers with resultant loss of accuracy.

ELECTRODE IMPEDANCE IN CYLINDRICAL ROCKS

Thin slices were cut from a long cylindrical rock sample. The same electrode material was applied to both sides of the rock sample (with the longer length d, and for the thinner rock sample whose length was d'). The total impedance measured with either rock sample is

$$Z_m = Z + Z_e \qquad (3\text{-}1)$$

where Z_m is the measured impedance, Z is the true impedance of the rock, and Z_e is the electrode impedance. For the long example,

$$Z = \xi \left(\frac{d}{A}\right) \qquad (3\text{-}2)$$

and for the thin sample,

$$Z' = \xi \left(\frac{d'}{A}\right) \tag{3-3}$$

where ξ is the rock impedivity and A is the electrode area. Impedivity ξ is the vector summation of resistivity ρ and specific reactance χ, thus

$$\xi = \rho + j\chi \tag{3-4}$$

By separating the real from the imaginary variables, identical relationships to those derived for Z_e will result for electrode resistance R_e and reactance X_e. Substituting from Equation (3-2) and (3-3) into (3-1), one obtains for the long sample

$$Z_m = \xi \left(\frac{d}{A}\right) + Z_e \tag{3-5}$$

and for the thin sample

$$Z_m' = \xi \left(\frac{d'}{A}\right) + Z_e \tag{3-6}$$

therefore,

$$\frac{Z_m - Z_e}{Z'_m - Z_e} = \frac{d}{d'} = \beta \tag{3-7}$$

where β is the ratio of the lengths of the two rock samples. Solving Equation (3-7) for Z_e, one obtains:

$$Z_e = \frac{\beta Z'_m - Z_m}{(\beta - 1)} \tag{3-8}$$

Separating Equation (3-8) into its real and imaginary parts gives

$$R_e = \frac{\beta R'_m - R_m}{(\beta - 1)} \tag{3-9}$$

and

$$X_e = \frac{\beta X'_m - X_m}{(\beta - 1)} \tag{3-10}$$

A thin slice of height 0.152 cm was cut from a basalt cylinder. The length of the remaining long cylinder was 4.08 cm. Hence, $\beta = 26.8$. Circular silver paste electrodes, each of area 3.75 cm^2, were fastened to each side of the two cylinders. The impedance data measured on these two rock specimens are shown in columns 2, 3, 4, and 5 of Table 3-1. R_e and X_e calculated from these data with the aid of Equations (3-9) and (3-10) are given in columns 6 and 7 of Table 3-1.

By subtracting the data in columns 6 and 7 point by point from the corresponding measured impedance data, and multiplying each resulting number into (A/d), the basaltic specific resistance, ρ, and reactance, χ, were calculated and recorded in columns 12 and 13 of Table 3-1.

A check on the validity of this technique was made by cutting a third section of the basalt sample with length 0.150 cm. Repeated measurements on this third sample gave data which agreed closely with those just reported. The specific impedance data for this third sample were calculated and found to be within a 1-percent er or from those recorded in Table 3-1. This agreement supports the technique of correcting for the electrode-impedance artifacts and lends credence to the validity of our impedance measurements.

Table 3-1. Electrode Corrections for Basalt (II)

Frequency (Hz)	Long Cylinder		Small Disc		Electrode		Corrected Cylinder		Corrected Disc		$\rho = (R_S - R_e)\frac{A}{d}$	$\chi = (X_S - X_e)\frac{A}{d}$
	R_{S1}	$-X_{S1}$	R_{S2}	$-X_{S2}$	R_e	$-X_e$	$R_{S1}-R_e$	$-(X_{S1}-X_e)$	$R_{S2}-R_e$	$-(X_{S2}-X_e)$	ρ	$-\chi$
0.502	4059.23	2854.57	164.63	66.46	12.90	-42.17	4046.32	2896.74	151.74	108.63	37.10	26.56
0.995	2661.09	2455.49	130.13	70.75	31.52	-22.16	2629.57	2477.65	98.61	92.91	24.11	22.72
2.00	1731.15	2085.56	95.27	70.44	31.53	-8.07	1699.62	2093.63	63.74	78.51	15.59	19.20
4.02	936.03	1441.44	63.12	59.37	29.10	5.53	906.93	1435.91	34.01	53.85	8.32	13.17
6.03	652.78	1152.74	48.42	52.24	24.88	9.36	627.88	1143.37	23.55	42.88	5.76	10.48
9.95	407.08	831.64	57.48	70.53	43.86	40.88	365.22	790.76	13.62	29.65	3.33	7.25
20.06	286.68	493.78	19.71	29.22	9.31	11.12	277.38	482.65	10.40	18.10	2.54	4.43
50.15	123.52	293.68	9.48	16.99	5.03	6.21	118.49	287.46	4.44	10.78	1.09	2.64
99.50	46.56	200.34	5.26	10.83	3.65	3.45	42.91	196.59	1.61	7.38	0.39	1.81
504	6.13	45.59	1.34	3.20	1.16	1.55	4.97	44.04	0.19	1.65	0.05	0.40
1000	3.84	23.48	0.83	1.83	0.72	0.99	3.12	22.44	0.12	0.84	0.03	0.21
2028	2.93	11.91	0.48	0.97	0.39	0.54	2.55	11.37	0.10	0.43	0.02	0.10

Table 3-2. Electrode Corrections for Granite

Frequency (Hz)	Long Cylinder		Small Disc		Electrode		Corrected Cylinder		Corrected Disc		$\rho = (R_S - R_e)\frac{A}{d}$	$\chi = (X_S - X_e)\frac{A}{d}$
	R_{S1}	$-X_{S1}$	R_{S2}	$-X_{S2}$	R_e	$-X_e$	$R_{S1}-R_e$	$-(X_{S1}-X_e)$	$R_{S2}-R_e$	$-(X_{S2}-X_e)$	ρ	$-\chi$
5.027	921.7	3152	248.6	483.9	225.3	391.8	696.4	2760	23.3	92.1	6.40	25.6
6.013	720.8	2755	205.8	430.5	188.0	350.3	522.8	2405	17.8	80.3	4.90	22.3
7.96	544.0	2280	152.2	353.5	138.7	287.0	405.3	1993	13.5	66.5	3.80	18.5
9.96	421.4	1775	119.5	297.5	109.1	246.5	31[illegible].3	1528.5	10.4	51.0	3.00	14.2
20.07	465.8	944.9	63.01	173.8	49.1	147.2	418.7	797.7	13.9	26.6	3.90	7.4
40.20	240.2	688.8	28.91	103.0	21.6	82.78	218.8	606	7.3	20.2	2.03	5.6
60.10	183.0	525.8	17.07	73.69	12.0	58.1	151.0	467.7	5.04	15.6	1.40	4.3
1000	1.172	31.71	1.503	5.65	---	4.7	---	26.96	---	0.9	---	0.3
2028	1.920	15.91	1.154	2.97	1.128	2.5	0.792	13.39	0.026	0.4	0.01	0.1

In nearly all the measurement in this report each rock sample was cut into two unequal lengths and the ratio β of the two lengths was accurately determined. The computer program was modified to automatically correct for electrodes by Equations (3-9) and (3-10) before the final data of ρ and χ were displayed.

In a similar manner, the electrode corrections for granite were applied and the data in Table 3-2 were obtained. The plots of the specific reactance χ against the specific resistance ρ at a series of frequencies for basalt, granite, and quartzite are shown in Figure 3-4. The impedivity of each of these three rocks expressed in (ohms x meter) is thus determined at frequencies between 1 and 2000 Hz.

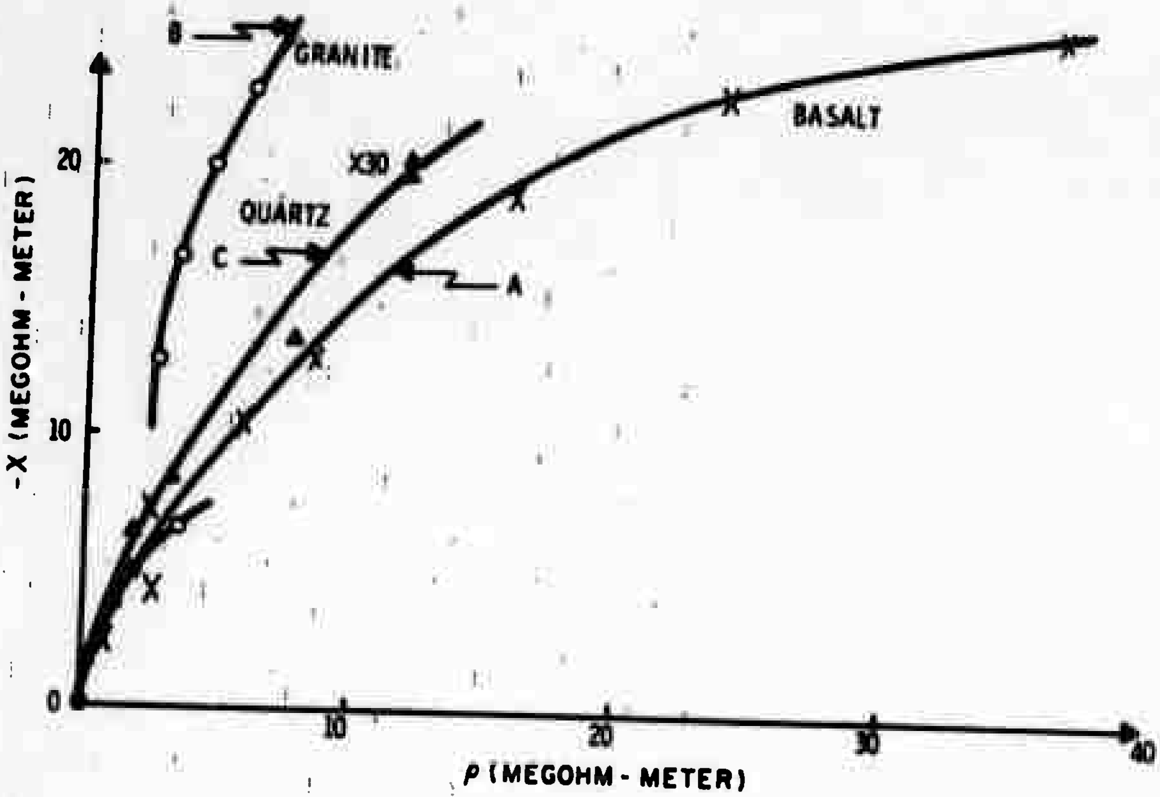


Figure 3-4. Specific Impedance Parameters for: (A) Basalt; (B) Granite; and (C) Quartzite

SECTION IV
TRANSFORMATION OF COMPLEX IMPEDANCE DATA TO COMPLEX PERMITTIVITY DATA

An important phase of this research has been concerned with the development of techniques for the extraction of the real and imaginary parts of the complex permittivity, ϵ^*, from their impedance counterparts, namely the imaginary and real parts of the electric impedance, Z.

The admittance vector, $\vec{Y}$, is defined as

$$\vec{Y} = G + j\omega C_p \tag{4-1}$$

where G is the conductance, ω is the angular frequency, and C_p is the parallel capacitance of the medium. Hence, admittance is conceptually related to parallel circuit components. In terms of this vector, one can define the admittivity, $\vec{y}$, of the medium by

$$\vec{I} = \vec{y}\, E = (\sigma + j\omega\epsilon')\, E \tag{4-2}$$

Admittivity, therefore, relates the current density vector, $\vec{I}$, to the scalar potential difference, E. If the medium is simulated by a simple parallel R_pC_p combination, then the parallel resistance, R_p, would be inversely related to the rock conductance, G, and per unit volume to the rock conductivity, σ. The parallel capacitance, C_p, is similarly related to the dielectric permittivity (its real component ϵ'). In this report the dielectric constant, K, of the rock is defined as the ratio of its dielectric permittivity, ϵ, to the dielectric permittivity of free space, ϵ_r.

By contrast, the impedance vector, $\vec{Z}$, is related to the series resistance, R_s, and series reactance, X_s, of the medium; thus,

$$\vec{Z} = R_s + jX_s \tag{4-3}$$

Ohm's law may be written in terms of an impedivity vector, $\vec{\xi}$; thus,

$$\vec{I} \cdot \vec{\xi} = E \tag{4-4}$$

where $\vec{\xi} = \rho + j\chi$, ρ being the rock resistivity, and χ its specific reactance. Impedance is, therefore, defined as that vector whose dot product into the current vector yields the potential difference, a scalar quantity. Comparing Equations (4-1) and (4-3), and remembering that impedance is the inverse vector of admittance, it becomes apparent that both R_s and X_s are necessarily frequency dependent.

Rock impedance data are presented in terms of the series equivalent circuit parameters because these are the parameters that are easy to measure without previous commitment to an exact electrical analog or model to simulate the medium. In addition, the series parameters can elegantly display a circular arc in the Argand diagram when X_s is plotted as a function of R_s, both measured at the same frequency.

The parallel-to-series transformation with frequency-independent components of an R-C network provides the proof of the determined semicircular arc in the Argand diagram. This is explained in detail in Appendix A.

In the transformation of complex impedance to complex permittivity data for an ideal system (Debye case), the impedance vector for the system is given by Equation (4-3).

Assuming that the rock system can be represented by the simple R_pC_p unit, one can use Equation (A4) in Appendix A and (4-3) to obtain

$$\vec{Z} = \frac{R_s^2 + X_s^2}{R_p} + j\,\frac{R_s^2 + X_s^2}{X_p}$$

$$= (R_s^2 + X_s^2)\left[\frac{1}{R_p} + j\,\frac{1}{X_p}\right]$$

$$\therefore \quad \vec{Z} = |Z|^2\,[G_p + j\omega C_p] \qquad (4\text{-}5)$$

For normalization purposes, one must use specific quantities for the rock system. This is achieved by multiplying both sides of Equation (4-5) into A/d, where A is the area of the electrodes attached to the rock and d is their distance apart. This will transform impedance to impedivity ξ; thus,

$$\vec{\xi} = |\xi|^2\left[G_p\left(\frac{d}{A}\right) + j\omega C_p\left(\frac{d}{A}\right)\right]$$

$$= |\xi|^2\,[\sigma + j\omega\epsilon']$$

$$= j\omega\,|\xi|^2\,[-jK''\epsilon_r + K'\epsilon_r] \qquad (4\text{-}6)$$

$$= j\omega\,|\xi|^2\,[\epsilon' - j\epsilon'']$$

$$= j\omega\,|\xi|^2\,\epsilon_r\,[K'' - jK'']$$

Here ϵ_r is the permittivity of free space (8.85×10^{-12} farad per meter), and the rock conductivity σ defines (Ref. 9) the imaginary part of the dielectric permittivity, ϵ'', according to

$$\sigma = \omega\epsilon'' = \omega K''\epsilon_r \qquad (4\text{-}7)$$

Using the complex dielectric permittivity, ϵ^*, as

$$\epsilon^* = \epsilon' - j\epsilon'' \tag{4-8}$$

and complex dielectric constant, K^*, as

$$K^* = K' - jK'' \tag{4-9}$$

Equation (4-6) becomes

$$\vec{\xi} = j\omega\,|\xi|^2\,(\epsilon' - j\epsilon'')$$

$$= j\omega\,|\xi|^2\,\epsilon^*$$

Equation (4-10) gives the relation between the impedivity vector and the dielectric permittivity vector. Using the vectorial notation

$$\vec{\xi} = |\xi|\,e^{j\theta} \tag{4-10}$$

Into Equation (4-10) one obtains

$$\epsilon^* = \frac{\xi}{j\omega\,|\xi|^2} = -\frac{j\,e^{j\theta}}{\omega\,|\xi|}$$

$$= \frac{j^3\,e^{j\theta}}{\omega\,|\xi|} \tag{4-11}$$

Equation (4-11) signifies that the permittivity vector can be obtained from the impedivity vector by rotating the latter through $(3\pi/2)$ and dividing through $\omega\,|\xi|^2$. These operations are diagramatically illustrated in Figure 4-1.

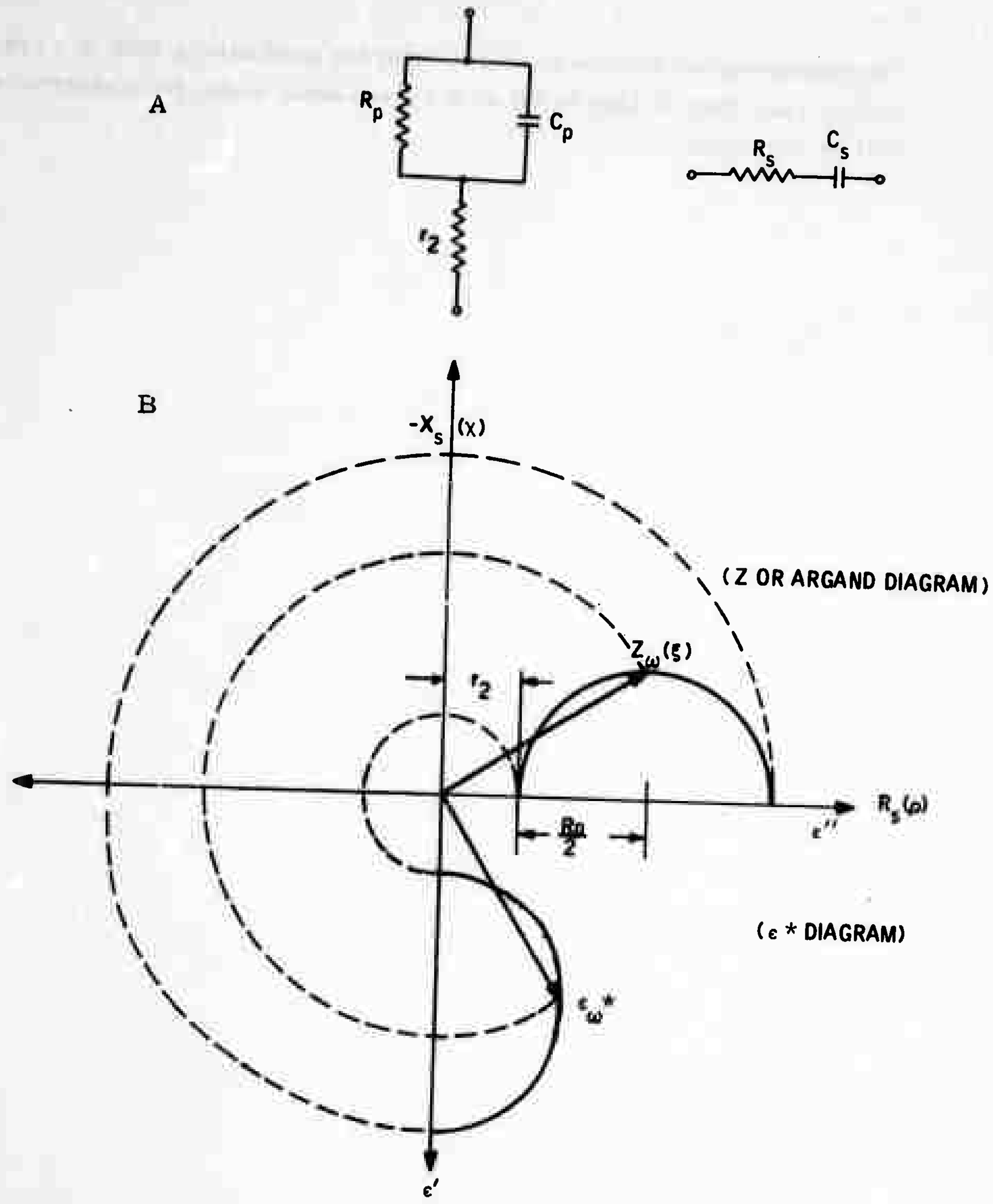


Figure 4-1. A. Transformation of parallel circuit with frequency independent parameters to isoimpedic series circuit gives a semicircle in the Argand diagram.
B. Diagram to show rotation of impedance vector to give dielectric permittivity vector.

The conversion of impedivity data to complex permittivity data in a real system will be described in Section VII where a workable model for dielectric relaxation will be developed.

SECTION V
RESISTIVITY AND DIELECTRIC CONSTANT OF ROCKS

The principles presented in Section IV and implemented in Section VII to include real systems, were used to compute values for the dielectric constant of two basaltic rock samples and one quartzite rock from the experimentally measured impedance parameters.

Basaltic sample (III) was obtained in the form of a cylinder with diameter 2.17 cm. Thin slices that measured 0.30 and 0.61 cm in length were cut from this sample. The ratio A/d for the thinner slice was 0.1232 meter and for the thicker slice 0.0618 meter. The electrode impedances were calculated with the aid of Equations (3-9) and (3-10) for the two slices. The electrode impedances were subtracted point by point from the corresponding measured impedance values. The resulting data were then multiplied into (A/d) to give the specific resistance and reactance of basalt. Photostatic copies of the computer output for the two basaltic slices are shown in Tables 5-1 and 5-2.

Dielectric permittivity at each frequency was calculated by the procedure described in Section VII. The Cole-Cole plots resulting from these data are shown in Figures 5-1 and 5-3 for the 0.30- and 0.61-cm slices of basalt, respectively. These figures can be considered to be in satisfactory agreement within experimental error. The dielectric dispersion curves for basalt are shown in Figures 5-2 and 5-4 for the 0.30- and 0.61-cm slices of basalt. The relaxation times calculated from either the maximum in the loss factor, ϵ'', or the inflection point in the ϵ' curve were found to be 16.6 and 13.4 milliseconds for the two basalt slices. Since the experimental measurements on both slices were completely independent of each other, the derived values of relaxation time are considered to be in reasonable agreement.

Table 5-1. Impedance and Dielectric Data on Basalt (III).
0.30 cm slice

```
ENTER NS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION

069.12317

      K4-1 7/2/71              AOD=  0.12317     PHASE AND AMPLITUDE CORRECTED
```

FRQ	RS	XS	RAOD	XAOD	PH1	Z
0.099	931.0156	-122.4131	114.6732	-13.0776	-7.4910	939.0288
0.130	433.0498	-197.6160	33.3387	-24.3404	-24.5307	476.0006
0.201	376.8926	-214.2601	46.4219	-26.3904	-29.6201	433.3383
0.403	307.3906	-273.3842	37.8839	-33.9437	-41.8617	412.9874
0.601	227.0444	-224.0116	27.9631	-27.3913	-44.6181	318.9320
0.801	267.1763	-253.4711	32.9081	-31.4664	-43.7203	369.6602
1.002	236.3063	-210.7373	29.1303	-23.9363	-41.7033	316.7733
2.012	131.219	-169.7444	18.6014	-20.9074	-48.3440	227.2020
4.022	89.2898	-120.6417	10.9978	-14.8394	-33.4979	130.0903
6.009	66.2687	-99.1330	8.1623	-12.2129	-36.2480	119.2613
10.032	41.1296	-67.2230	3.0639	-8.2799	-38.3444	78.8073
20.072	28.0718	-41.7083	3.4376	-3.1372	-36.0617	30.2753
60.096	10.7081	-23.1228	1.3189	-2.8480	-65.1361	25.4819
100.604	7.0602	-17.3937	0.8696	-2.1426	-67.9147	18.7739
201.342	3.4133	-10.0660	0.207	-1.2398	-71.2624	10.6297
603.448	1.3968	-3.7563	0.1720	-0.4627	-69.6079	4.0076
1009.174	1.1344	-2.2427	0.1422	-0.2762	-62.7682	2.5223
1309.434	1.0483	-1.3610	0.1291	-0.1923	-36.1132	1.8804
2023.783	0.9039	-1.1397	0.1113	-0.1404	-31.3830	1.4346

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER =  311.1931  370.7380
                                  RADIUS =  638.4723
                                  FIT    =    3.4732

R0=  1030.9866          RINF=    -8.6003

MODEL PARAMETERS -    R1 =  1343.4873/FRQ
                      RP =  1039.3872
                      CP = 0.1701E-03

CP= 0.130032E-04

TAU=  16.60434MSEC          E0=1771.1337          EINF=  14.77477
```

FRQ	EP	EPP
0.099	-0.168186E 04	-0.831248E 02
0.130	-0.163781E 04	-0.106640E 03
0.201	-0.163703E 04	-0.124742E 03
0.403	-0.137142E 04	-0.178948E 03
0.601	-0.132132E 04	-0.217142E 03
0.801	-0.147941E 04	-0.247313E 03
1.002	-0.144237E 04	-0.272144E 03
2.012	-0.130321E 04	-0.352604E 03
4.022	-0.112932E 04	-0.422121E 03
6.009	-0.101618E 04	-0.448484E 03
10.032	-0.864007E 03	-0.459783E 03
20.072	-0.662333E 03	-0.432068E 03
60.096	-0.393816E 03	-0.320979E 03
100.604	-0.298123E 03	-0.261763E 03
201.342	-0.199427E 03	-0.190306E 03
603.448	-0.994948E 02	-0.107468E 03
1009.174	-0.697422E 02	-0.807933E 02
1309.434	-0.318329E 02	-0.642934E 02
2023.783	-0.411467E 02	-0.342893E 02

```
*********** STOP ***********
```

Table 5-2. Impedance and Dielectric Data on Basalt (III).
0. 61 cm slice.

MORE
DONE

ENTER NS, AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
068.06184

K2-1 7/2/71 ADD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z
0.099	1400.6572	-292.5101	86.6166	-18.0765	-11.7890	1450.8542
0.201	650.5455	-296.0410	58.9804	-18.3072	-25.1590	696.5999
0.402	551.9665	-568.5069	32.8968	-22.7761	-54.6994	647.0226
0.602	552.7695	-412.9792	52.9464	-25.5586	-57.7840	674.0884
0.801	459.8779	-345.4170	27.2020	-21.2569	-57.9825	558.0571
1.005	542.4744	-552.4679	55.5466	-54.1646	-45.5262	774.2755
2.008	518.4526	-425.5148	19.6951	-26.1902	-55.0654	529.8858
4.025	184.9092	-297.8154	11.4548	-18.4169	-58.1687	350.5502
6.010	150.7422	-228.6871	8.0051	-14.1420	-60.2475	265.4224
7.999	90.7915	-172.8500	5.6145	-10.6878	-62.2906	195.2262
10.026	80.4771	-151.9040	4.9767	-9.5957	-62.0904	171.9052
20.048	54.5092	-80.4668	5.5708	-5.4708	-58.5648	105.9116
60.096	20.5684	-46.5154	1.2719	-2.8641	-66.0591	50.6771
100.200	14.1226	-55.6855	0.8755	-2.2067	-68.4127	58.5766
200.555	5.9685	-19.9417	0.5691	-1.2552	-75.5451	20.8157
605.448	2.4719	-7.5750	0.1529	-0.4561	-71.4755	7.7785
1009.174	2.0572	-4.4140	0.1260	-0.2750	-65.2502	4.8614
1512.288	1.9527	-5.0550	0.1208	-0.2077	-57.2467	5.6089
2025.785	1.8259	-2.1429	0.1129	-0.1525	-49.5692	2.8155

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 817.1544 512.9148
RADIUS = 978.6765
FIT = 5.4205

R0= 1650.6567 RINF= -16.5679

MODEL PARAMETERS - R1 = 4016.5664/FRQ
RP = 1667.0046
CP = 0.8516E-04

CP= 0.685079E-05

TAU= 15.40942MSEC E0=1496.9577 EINF= 14.84582

FRQ	EP	EPP
0.099	-0.144029E 04	-0.555150E 02
0.201	-0.140918E 04	-0.845058E 02
0.402	-0.136220E 04	-0.126864E 05
0.602	-0.152522E 04	-0.158669E 05
0.801	-0.129566E 04	-0.184666E 05
1.005	-0.126515E 04	-0.207210E 03
2.008	-0.115659E 04	-0.284185E 05
4.025	-0.101591E 04	-0.561508E 05

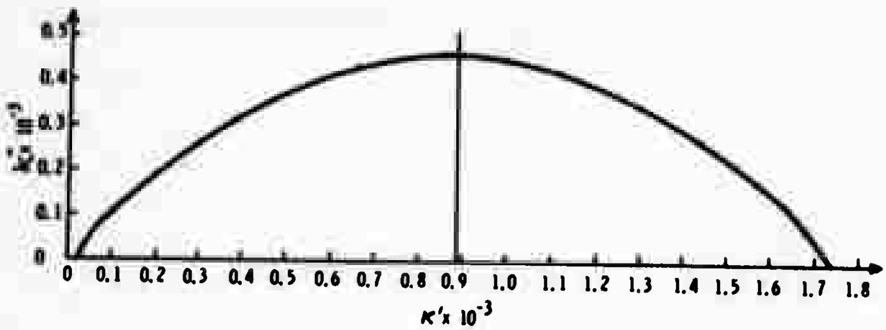


Figure 5-1. Cole-Cole Plot of Dresser Basalt Data on 0. 30-cm Slice

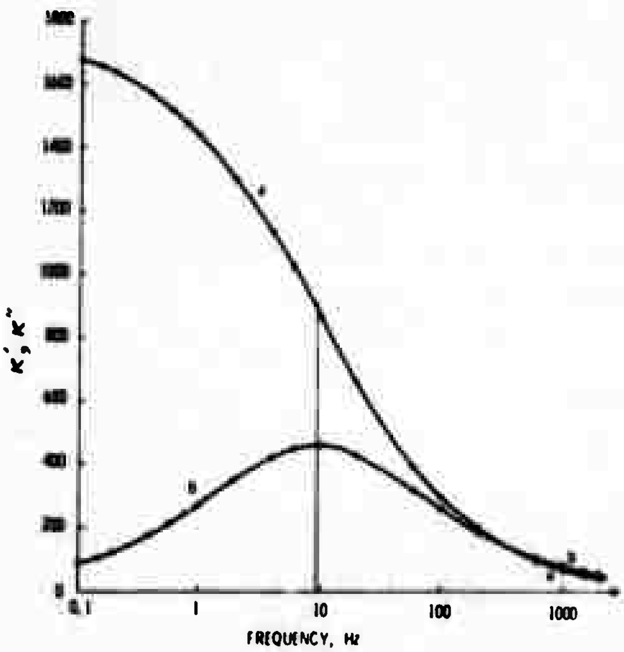


Figure 5-2. Dielectric Constant of Dresser Basalt as a Function of Frequency [(a) Real Part of Dielectric Constant, k'; (b) Imaginary Part, k'']. Data on the 0. 30-cm Slice; Relaxation Time, τ = 16. 6 msec.

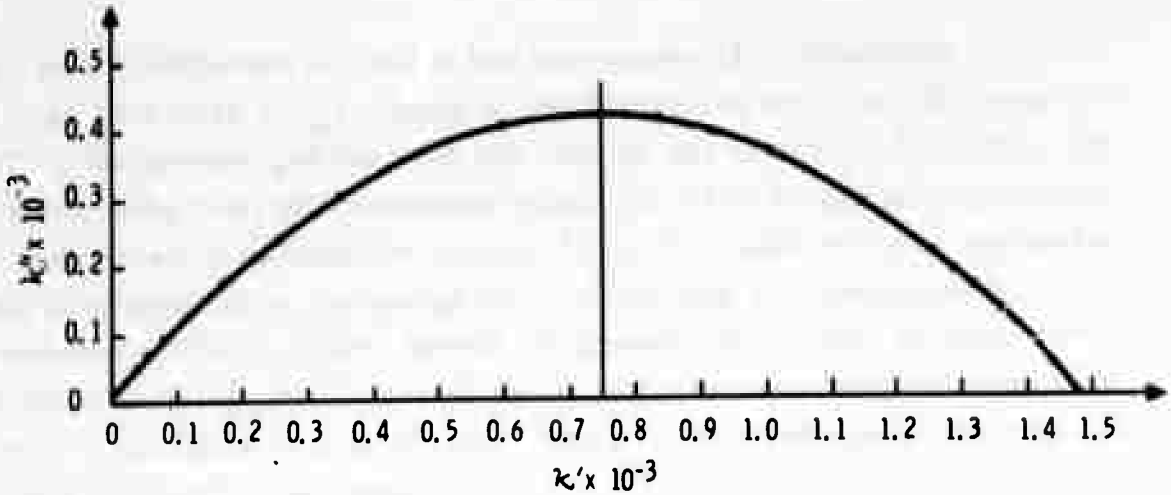


Figure 5-3. Cole-Cole Plot of Dresser Basalt Data on 0.61-cm Slice

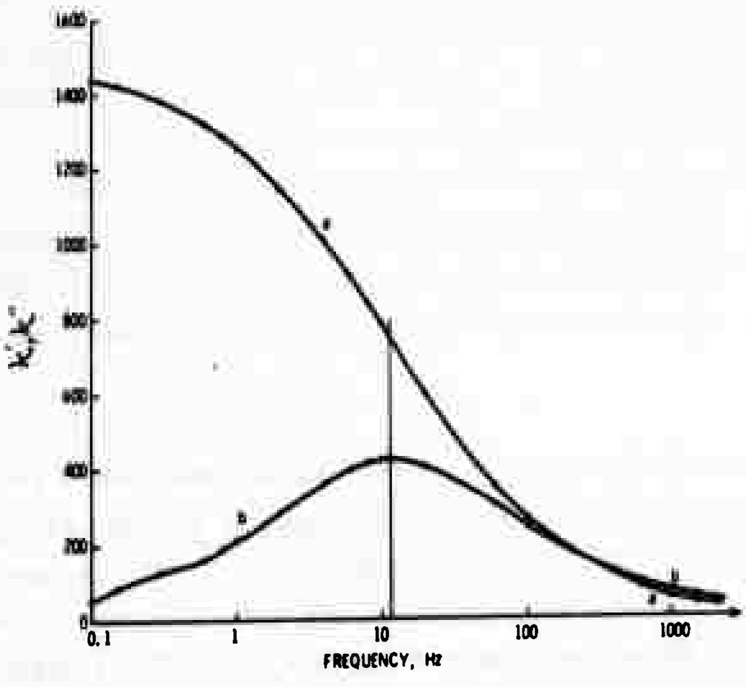


Figure 5-4. Dielectric Constant of Dresser Basalt as a Function of Frequency [(a) Real Part of Dielectric Constant, κ'; (b) Imaginary Part, κ'']. Data on the 0.61-cm Slice; Relaxation Time, τ = 13.4 msec.

Table 5-3 summarizes the impedivity and dielectric permittivity data on the two basalt slices. The d-c resistivity of basalt, ρ_o, is estimated as 1.27×10^8 and 1.00×10^8 ohmmeter for the thin and thick slices, respectively. These resistivity data appear to be internally consistent with each other and are in agreement with the value 1.26×10^8 ohmmeter reported in Parkhomenko (Ref. 10) monograph for dry basalt. The agreement is surprising in view of the anticipated differences between the Dresser basalt and Parkhomenko's most probably Russian basalt (origin not given). Table 5-3 also shows that the zero frequency dielectric constant of basalt is 1.77×10^3 and 1.50×10^3 for the thin and thick slices. The internal agreement in this case is also acceptable. Parkhomenko (Ref. 10) reports that at low frequencies of 10^2 to 10^4 Hz the dielectric constant may assume very large values (10^3 to 10^5).

Keller (Ref. 11) observed that the product of the dielectric permittivity at low frequency, ϵ_o, into the resistivity at low frequency, ρ_o, is nearly a constant characteristic of a particular type of rock. For rhyolite and basalt, the average value of $\rho_o \epsilon_o$ is 0.63 sec with the range of 19 values from 0.25 to 26 sec. Average values of this product varied from 1.4×10^{-3} for basic igneous rocks such as gabbro and chromite to 10.8 for the hematite ore from Minnesota, which contains appreciable quantities of electronically conducting materials. The data in Table 5-3 also show that the products $\rho_o K'_\infty \epsilon_r$ and $\rho_\infty K_o \epsilon_r$ are equal to the relaxation time for both the thin and thick samples of basalt.

Similar experiments to those performed on basalt were run on a cylindrical quartzite sample (II) of 2.22 cm diameter, 0.955 cm length, and an (A/d) ratio of 0.0406 meter. The computer output data on this sample are shown in Table 5-4. From the present data, one can calculate the d-c resistivity of quartzite, ρ_o, from the observed value R_o of 31737.9 megohm, thus

$$\rho_o = R_o \left(\frac{A}{d}\right) = 3.17 \times 0.041 \times 10^{10} = 1.29 \times 10^9 \text{ ohm-meter}$$

The relaxation time of this quartzite sample is also calculated to be 60.3 milliseconds. The real component of the dielectric constant at infinite frequency, κ'_∞, is determined as 5.29. Also, the real component of the quartzite dielectric constant at the time of zero frequency, κ'_o, is found to be 3.95×10^3.

Table 5-3. Electric and Dielectric Parameters of Dresser Basalt (III)

Parameter	0.30 cm Slice	0.61 cm Slice
dc resistivity, ρ_o, ohm meter	1.27×10^8	1.00×10^8
infinite frequency resistivity, ρ_∞, ohm meter	1.06×10^6	1.01×10^6
model parallel resistance, R_p, ohm/(meter)^3	8.89×10^{14}	6.87×10^{14}
model capacitance, C_p, farad	1.3×10^{-5}	6.8×10^{-6}
relaxation time, τ, second	16.6×10^{-3}	13.4×10^{-3}
zero frequency dielectric constant, κ_o	1.77×10^3	1.50×10^3
infinite frequency dielectric constant, κ_∞	14.8	14.8
maximum dielectric constant, κ''_{max}	4.6×10^2	4.2×10^2
$\rho_o \kappa'_\infty \epsilon_r$, second	16.4×10^{-3}	13.1×10^{-3}
$\rho_\infty \kappa'_o \epsilon_r$ second	16.6×10^{-3}	13.2×10^{-3}

Table 5-4. Impedance and Dielectric Data on Quartzite (II). 0.96 cm Slice

```
ENTER NS,AOD    PUT SSW1 UP FOR ELECTRODE CORRECTION
076.04062

M3 08/26/71                AOD=  0.04062     PHASE AND AMPLITUDE CORRECTED
```

FRQ	RS	XS	RAOD	XAOD	PHI	Z
1.001	906.0527	-4305.7520	36.8039	-174.8996	-78.1225	4400.0498
2.004	858.0356	-3565.0869	34.8534	-144.8138	-76.4732	3666.8882
4.030	473.6096	-1959.4707	19.2380	-79.5937	-76.4177	2015.8948
6.017	329.4869	-1296.3813	13.3838	-52.6590	-75.7453	1337.5972
8.026	299.3496	-1046.7861	12.1596	-42.5205	-74.0465	1088.7478
10.008	285.1741	-825.8511	11.5838	-33.5461	-70.9549	873.7014
20.153	294.2329	-513.6184	11.9517	-20.8632	-60.1976	591.9265
40.161	137.3826	-395.5394	5.5805	-16.0668	-70.8516	418.7188
60.168	26.0835	-291.0387	1.0595	-11.8220	-84.8850	292.2051
79.872	-43.7361	-229.9436	-1.7766	-9.3403	-100.7766	234.0660
99.800	-32.5157	-183.0712	-1.3208	-7.4364	-100.0787	185.9364
201.884	-14.8709	-75.4577	-0.6041	-3.0651	-101.1562	76.9091
504.202	-2.9886	-24.6946	-0.1214	-1.0031	-96.9075	24.8748
998.185	0.6537	-11.1146	0.0265	-0.4515	-86.6404	11.1338
1506.591	1.7666	-7.0809	0.0717	-0.2876	-75.9968	7.2979
2022.059	2.0117	-5.2798	0.0817	-0.2145	-69.1470	5.6501
2537.594	1.2796	-4.3307	0.0519	-0.1759	-73.5441	4.5158

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER =15890.1699 1622.5833
                                  RADIUS =15930.5625
                                  FIT    =      0.6057

R0= 31737.8828
MODEL PARAMETERS -        RINF=    42.4551
                          R1 =268343.750/FRQ
                          RP =  31695.4258
                          CP =  0.9060E-05

CP= 0.189275E-05

TAU=  60.30515MSEC          E0=3951.31494        EINF=   5.28559
```

FRQ	EP	EPP
1.001	0.281805E 04	0.127285E 04
2.004	0.223135E 04	0.172910E 04
4.030	0.159191E 04	0.166165E 04
6.017	0.125202E 04	0.138837E 04
8.026	0.103396E 04	0.115927E 04
10.008	0.884613E 03	0.989096E 03
20.153	0.516610E 03	0.557240E 03
40.161	0.291078E 03	0.301209E 03
60.168	0.205644E 03	0.208085E 03
79.872	0.160841E 03	0.160254E 03
99.800	0.132528E 03	0.130402E 03
201.884	0.721628E 02	0.677588E 02
504.202	0.339802E 02	0.288582E 02
998.185	0.204895E 02	0.152495E 02
1506.591	0.156443E 02	0.103800E 02
2022.059	0.131578E 02	0.788417E 01
2537.594	0.116534E 02	0.637630E 01

```
*********** STOP ***********
```

SECTION VI
EFFECT OF WATER AND SODIUM HYDROXIDE PRETREATMENT ON ROCK ELECTRIC AND DIELECTRIC PARAMETERS

The presence of underground water ahead of excavation can be detected in principal by electrical resistivity probes. A major emphasis of Honeywell's rock impedance research is to determine the impedance or dielectric parameter that exhibits the largest change in value by the presence of small quantities of entrapped water. To define these parameters, basaltic rock samples were subjected to planned water treatments. Their impedance and dielectric parameters were measured before and after these pretreatments, so that each sample acted as its own control standard.

Previous workers (Refs. 12 and 15) have shown that the resistivity of a rock completely saturated with saline is determined by the rock porosity to a first approximation. However, the pore spaces in a rock may not always be saturated with aqueous electrolytes. In oil reservoirs, for example, oil may partially replace water in the pore spaces. The presence of oil, natural gas, or air in the pore structure of a rock may increase the resistivity significantly over what it would be in a completely water-saturated rock.

Rock resistivity is greatly affected by the quantity of water present. Letting ρ be the bulk resistivity of the rock, ρ_w the resistivity of water as it actually exists in the pore space of the rock, and θ the rock porosity , then

$$\rho = \rho_w/\theta^n \qquad (6\text{-}1)$$

This relationship is commonly known as Archies' law (Ref. 12). The exponent n is an empirically derived parameter characteristic of the texture of the rock. Its value varies from about 1.3 in loosely packed granular material to about 2.2 in well-cemented granular rocks (Refs. 13 and 14).

Pirson (Ref. 15) modified Archies' relationship by introducing a second empirical parameter, m, which multiplies the porosity term; thus,

$$\rho/\rho_w = m\,\theta^{-n} \tag{6-2}$$

The value of m varies from 0.6 to 1.3 in marine sedimentary rocks, and appears to be related to the texture of the rock. For rocks with less than 4 percent porosity, including dense igneous rocks and metamorphosed sedimentary rocks, $m = 1.4$ and $n = 1.6$. These expressions apply only when a rock is completely saturated with water. Keller (Ref. 16) observed that the resistivity of a rock increases proportionately to the inverse square of the fraction, S, of the pore space filled with water, provided the water which remains coats the grains uniformly. Accordingly, Archies' relationship becomes

$$\rho = \rho_w\,\theta^{-n}\,S^{-2} \tag{6-3}$$

Scott et al. (Ref. 17) used this relationship in the form

$$\sigma = \sigma_w\,\theta^n\,S^m \tag{6-4}$$

where σ is the rock conductivity, σ_w is the conductivity of the pore fluid at the same frequency, and the constants m and n are approximately equal to 2. The product of the fractional saturation of the rock, S, into the fractional porosity, θ, should yield the fractional water content of the rock, w. Under these conditions, Archies' law becomes

$$\sigma \approx \sigma_w \times w^2 \tag{6-5}$$

It should also be remembered that σ_w is approximately proportional to the salinity of the pore fluid.

WATER TREATMENT OF BASALT

To investigate the effect of rock water content on its electric properties, a series of experiments were performed with three slices of basalt. The slices were cut from the one long cylinder of basalt (III), hence they possessed the same diameter of 2.18 cm, but were of different lengths. Slices K_1, K_2, and K_4 were of lengths 0.956, 0.605, and 0.304 cm, respectively. The rock samples were pretreated simultaneously in distilled water for periods of 23 and 77 hours. After each soak, the rocks were dried in an 80°C oven for two hours, then cooled in a dessicator before the impedance circular arcs were determined.

Typical results on samples K_1, K_2, and K_4 before and after the water pretreatment are shown in Tables 6-1 to 6-9. These results show that R_o decreased, after soaking the sample in water for 23 hours, to about one third of its value before soaking. Further soaking to 77 hours increased R_o slightly, but it still remained smaller than the baseline value before water pretreatment. Typical values of R_o for sample K_1 before water pretreatment, after 23 hours, and after 77 hours of pretreatment were 1031, 328, and 447 megohms, respectively. This same trend can be noticed in the results obtained with the rest of the basaltic rock samples.

By contrast, the dielectric constant at zero frequency, κ_o, increased monotonally with increase in water soak time. Typical values of κ_o were 1770, 60200, and 146000 before water soak, after 23 hours, and after 77 hours of water pretreatment, respectively. The infinite frequency parameters R_∞ and κ_∞ did not change significantly with the water pretreatments. Furthermore, the impedance arc plots were very close and actually tangenial to each other down to a frequency of 300 Hz. Below that frequency, the arcs began to separate from each other following each water soak. Typical data on sample

Table 6-1. Computer Output for Electric and Dielectric Data of Untreated Basalt (Sample K1)

```
ENTER RS,ADD   PUT SENS UP FOR ELECTRODE CORRECTION
007.03916

K1-1 7/2/71             ADD=  0.03916     PHASE AND AMPLITUDE CORRECTED
```

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
0.999	984.4177	-1115.1220	30.5490	-43.6002	-40.5659	1487.4731	30.2494
2.009	533.2920	-823.3362	20.9021	-32.3209	-37.0304	903.7435	30.5234
4.016	304.0719	-500.2336	11.9300	-22.1737	-61.7056	643.0920	23.1033
6.012	203.1134	-410.3913	8.0322	-16.3920	-63.0994	466.1440	18.2542
8.000	133.0310	-333.0290	6.0240	-23.1432	-65.3011	369.2029	14.4500
10.016	121.6247	-270.3243	4.7620	-18.5937	-63.7967	296.6077	11.6152
20.004	82.5505	-154.2740	3.2329	-6.0414	-61.0321	174.9731	6.0520
40.120	43.7045	-100.0014	1.7115	-3.9396	-66.5232	109.6047	4.2933
60.100	29.0049	-73.5033	1.1393	-2.0007	-60.0031	79.2969	3.1033
79.072.	23.1794	-66.4192	0.9060	-2.0010	-69.2434	71.0316	2.7016
100.301	22.0176	-30.4022	0.0935	-2.2111	-60.0003	60.0905	2.3040
200.333	7.0934	-31.0434	0.3092	-1.2157	-73.7350	32.0317	1.2544
402.376	4.2007	-15.0029	0.1390	-0.6100	-73.3267	16.3212	0.6391
602.410	3.3013	-11.3412	0.1297	-0.4441	-73.7740	11.0120	0.4626
802.133	3.2334	-8.4962	0.1196	-0.3327	-70.2373	9.0202	0.3533
1005.404	2.9011	-6.0031	0.1136	-0.2696	-67.1563	7.4713	0.2926
2512.200	2.6479	-4.4001	0.1037	-0.1739	-59.4640	5.2110	0.2641
2049.520	2.3737	-3.1301	0.0929	-0.1220	-52.0025	3.9331	0.1540

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 1034.5062  610.6073
                                  RADIUS = 1933.5234
                                  FIT    =    0.2607

R0=  3666.4536          RINF=     2.7163

MODEL PARAMETERS -   R1 = 16392.2109/FRQ
                     RP =  3663.7349

RHO = 0.143560 11 OHM-CM

CP= 0.24335076-04

TAU= 94.0002709SEC         E0=399006.107          EINF=  74.04716
```

FRQ	EP	EPP
0.999	0.6049423E 03	0.3356000E 03
2.009	0.4040077E 03	0.3556030E 03
4.016	0.3311516E 03	0.3022140E 03
6.012	0.2032440E 03	0.2324910E 03
8.000	0.2210031E 03	0.2109240E 03
10.016	0.1914720E 03	0.1090640E 03
20.004	0.1195016E 03	0.1199350E 03
40.120	0.7203340E 02	0.7459190E 02
60.100	0.5303042E 02	0.5353090E 02
79.072	0.4350910E 02	0.4313020E 02
100.301	0.3072370E 02	0.3020900E 02
200.333	0.2100310E 02	0.2114910E 02
402.376	0.1290210E 02	0.1223140E 02
602.410	0.9040040E 01	0.6921900E 01
802.139	0.7049306E 01	0.7119260E 01
1005.404	0.6009046E 01	0.5930720E 01
2512.200	0.3031740E 01	0.4315[illegible]40E 01
2049.520	0.4137730E 01	0.3419760E 01

```
DET. G,H FOR RINF/FRQ
```

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 1977.0006  735.4393
                                  RADIUS = 2106.7949
                                  FIT    =    0.2964

R0=  3952.0713          RINF=     3.5437

MODEL PARAMETERS -   R1 = 26449.2691/FRQ
                     RP =  3940.5234
```

F	F-2/4	R1	XP	CP
0.9993	2.0003	6502.7744	-2363.5615	-0.67370-04
2.0000	0.7036	3003.4044	-1467.6523	-0.33990-04
4.0164	0.4990	2330.9097	-907.6223	-0.43650-04
6.0110	0.4070	1709.9367	-667.6130	-0.39640-04
8.0000	0.3336	1303.0004	-333.1701	-0.37310-04
10.0166	0.3139	1126.0092	-437.9725	-0.36270-04
20.0042	0.2232	600.4770	-266.4937	-0.29770-0[illegible]
40.1204	0.1579	442.6544	-164.6505	-0.24090[illegible]
60.1005	0.1269	354.3106	-110.4162	-0.2234[illegible]
79.0742	0.1119	331.1202	-100.1311	-0.19900-0[illegible]
100.3009	0.0990	271.9107	-02.2441	-0.19290-04
200.3347	0.0700	215.5207	-43.9914	-0.10040-04
402.5704	0.0490	140.3049	-23.0901	-0.17120-04
602.4097	0.0407	129.5507	-13.7074	-0.16740-04
802.1392	0.0353	100.0330	-11.0424	-0.16750-04
2003.4044	0.0315	106.0202.	-9.4630	-0.16730-04
1512.2076	0.0237	101.2369	-6.3130	-0.16670-04
2049.5200	0.0222	902.2102	-4.3363	-0.17290-04

```
G= 0.362020 00 H= 0.474430 00
*********** STOP ***********
```

Table 6-2. Computer Output for Electric and Dielectric Data of Untreated Basalt (Sample K_2)

ENTER RS,ADD PUT SSW1 UP FOR ELECTRODE CORRECTION
068.08184

K2-1 7/2/71 ADD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	2	2ADD
0.099	1400.0572	-292.3101	80.6108	-18.0765	-11.7890	1450.8342	88.4828
0.201	630.3455	-290.0410	58.9004	-18.5072	-25.1590	696.5999	43.0654
0.402	531.9065	-368.3069	52.8968	-22.7761	-54.6994	647.0226	40.0119
0.602	532.7895	-412.9792	52.9464	-25.5386	-37.7840	674.0084	41.6856
0.801	439.8779	-345.4170	27.2020	-21.2369	-37.9823	558.0571	34.5105
1.005	542.4744	-532.4679	53.5466	-34.1646	-45.5262	774.2733	47.8811
2.008	318.4526	-425.3148	19.8951	-26.1902	-53.0634	529.8838	32.7680
4.023	184.9092	-297.8154	11.4348	-18.4169	-58.1687	350.5502	21.6780
6.010	130.7422	-228.6871	8.0851	-14.1420	-60.2475	265.4224	16.2900
7.999	90.7913	-172.8300	5.6145	-10.6878	-62.2906	193.2262	12.0728
10.020	80.4771	-151.9040	4.9767	-9.5937	-62.0904	171.9052	10.6306
20.048	54.5092	-88.4668	3.5708	-5.4700	-58.3648	103.9116	6.4259
60.096	20.5684	-46.3154	1.2719	-2.8641	-66.0591	50.6771	3.1339
100.200	14.1220	-35.6835	0.8735	-2.2067	-68.4127	38.5766	2.3752.
200.535	5.9685	-19.9417	0.5691	-1.2332	-73.3431	20.8157	1.2872
605.448	2.4719	-7.3730	0.1529	-0.4561	-71.4755	7.7783	0.4810
1009.174	2.0372	-4.4140	0.1260	-0.2730	-65.2302	4.8614	0.3006
1512.288	1.9527	-3.0350	0.1208	-0.1877	-57.2467	3.6089	0.2232
2025.783	1.8259	-2.1429	0.1129	-0.1325	-49.5692	2.8155	0.1741

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 817.1344 512.9148
RADIUS = 978.6765
FIT = 5.4205

R0= 1650.0307 RINF= -16.5679

MODEL PARAMETERS - R1 = 4016.5864/FRQ
RP = 1667.0046

RHO = 0.10200E 11 OHM-CM

CP= 0.08507 9E-05

TAU= 15.40942MSEC E0=1496.9577 EINF= 14.84302.

FRQ	EP	EPP
0.099	-0.144029E 04	-0.555150E 02.
0.201	-0.140918E 04	-0.845038E 02.
0.402	-0.150220E 04	-0.120864E 03
0.602	-0.152522E 04	-0.138669E 05
0.801	-0.129306E 04	-0.184066E 05
1.005	-0.120515E 04	-0.207210E 03
2.008	-0.115059E 04	-0.284185E 03
4.023	-0.101591E 04	-0.361508E 05
6.010	-0.917736E 05	-0.390814E 03
7.999	-0.844870E 03	-0.415448E 05
10.020	-0.785090E 05	-0.420734E 05
20.048	-0.603847E 03	-0.400805E 03
60.096	-0.354357E 05	-0.502114E 05
100.200	-0.265449E 03	-0.243398E 05
200.535	-0.175384E 03	-0.172403E 05
605.448	-0.815975E 02	-0.924918E 02
1009.174	-0.530925E 02.	-0.678890E 02
1512.288	-0.393322E 02	-0.529560E 02
2025.785	-0.301547E 02	-0.441023E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 2065.1525 1464.8105
RADIUS = 2548.6143
FIT = 1.5794

R0= 4148.7607 RINF= -22.4565

MODEL PARAMETERS - R1 = 5459.4727/FRQ
RP = 4171.2178

F	F-1/2.	R1	XP	CP
0.0999	3.1630	13938.5918	-8406.1975	-0.1894E-03
0.2006	2.2327	4899.2344	-4024.6152	-0.1971E-05
0.4022	1.5768	5700.7007	-2799.7119	-0.1415E-05
0.6017	1.2891	3324.5472	-2555.1325	-0.1154E-05
0.8008	1.1174	2565.0308	-1845.0853	-0.1077E-05
1.0045	0.9978	2524.4844	-1815.1167	-0.9810E-04
2.0084	0.7056	1650.0144	-1054.5010	-0.7515E-04
4.0229	0.4988	1095.6938	-656.9392	-0.6022E-04
6.0103	0.4079	805.5264	-502.3894	-0.5271E-04
7.9987	0.3556	680.6456	-593.4688	-0.5057E-04
10.0201	0.3158	601.5801	-544.4452	-0.4609E-04
20.0481	0.2233	547.5172	-225.6909	-0.3549E-04
60.0902	0.1290	171.4776	-115.0658	-0.2302E-04
100.2004	0.0999	115.9562	-85.8875	-0.1849E-04
200.5347	0.0706	62.5205	-65.5655	-0.1214E-04
603.4484	0.0407	32.0642	-74.0[illegible]81	-0.5552E-05
1009.1743	0.0314	27.9266	-105.6890	-0.1518E-05
1512.2876	0.0257	26.5571	-142.1658	-0.7403E-06
2025.7827	0.0222	25.9122	-189.1053	-0.4155E-06

G= 0.23751E 04 N= 0.65421E 00
########### STOP ###########

Table 6-3. Computer Output for Electric and Dielectric Data of Untreated Basalt (Sample K_4)

ENTER NS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
069.12317

K4-1 7/2/71 AOD= 0.12317 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
0.099	931.0130	-122.4131	114.6732.	-13.0776	-7.4910	939.0288	113.6600
0.150	433.0490	-197.8160	33.3387	-24.3404	-24.3307	476.0088	38.6300
0.201	376.0926	-214.2601	46.4219	-26.3904	-28.6201	433.3383	33.3989
0.403	307.3906	-273.3842	37.8839	-33.9437	-41.8617	412.9874	30.8677
0.601	227.0444	-224.0118	27.9831	-27.3913	-44.6181	318.9930	39.8033
0.801	207.1703	-233.4711	32.8081	-31.4864	-43.7203	369.6602	45.3310
1.002	230.3083	-210.7373	29.1303	-23.9363	-41.7033	316.7733	39.0170
2.012	131.0219	-169.7444	18.8014	-20.8074	-48.3440	227.2020	87.9843
4.022	09.2090	-120.6417	10.9978	-14.8394	-53.4979	130.0903	18.4886
6.009	60.2087	-99.1350	8.1823	-12.2129	-36.2480	119.2613	14.6894
10.052.	41.1290	-07.2230	3.0888	-8.2799	-58.3444	78.0073	[illegible]
20.072	28.0718	-41.7083	3.4378	-3.1372.	-56.0617	90.2735	6.1904
60.096	10.7081	-23.1228	1.3189	-2.8480	-83.1381	28.4819	3.1306
100.604	7.0602	-17.3957	0.8696	-2.1428	-87.9147	18.7738	2.3124
201.342	3.4135	-10.0600	0.4207	-1.2388	-71.2824	10.6297	1.3093
603.448	1.3968	-3.7363	0.1720	-0.4827	-69.8079	4.0076	0.4936
1009.174	1.1344	-2.2427	0.1422	-0.2782	-82.7882	8.5223	0.3107
1309.434	1.0403	-1.3610	0.1291	-0.1823	-38.1132	1.8804	0.0336
2023.703	0.9039	-1.1397	0.1113	-0.1404	-31.3830	1.4346	0.1798

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 311.1931 370.7380
RADIUS = 638.4723
FIT = 3.4732

R0= 1030.9006 RINF= -8.6005

MODEL PARAMETERS - R1 = 1545.4873/FRQ
RP = 1039.3872

RHO = 0.12699E 11 OHM-CM

CP= 0.130032E-04

TAU= 16.60434MSEC E0=1771.1357 EINF= 14.77477

FRQ	EP	EPP
0.099	-0.168186E 04	-0.031248E 02
0.130	-0.163781E 04	-0.100640E 03
0.201	-0.163703E 04	-0.124742E 03
0.403	-0.137142E 04	-0.178940E 03
0.601	-0.132132E 04	-0.217142E 03
0.801	-0.147941E 04	-0.247313E 03
1.002	-0.144257E 04	-0.272144E 03
2.012	-0.130321E 04	-0.332604E 03
4.022	-0.112932E 04	-0.422121E 03
6.009	-0.101610E 04	-0.444404E 03
10.032	-0.864007E 03	-0.439783E 03
20.072	-0.662333E 03	-0.432068E 03
60.096	-0.393816E 03	-0.320979E 03
100.604	-0.298123E 03	-0.261763E 03
201.342	-0.199427E 03	-0.190306E 03
603.448	-0.994940E 02	-0.107468E 03
1009.174	-0.697422E 02	-0.007933E 02
1509.434	-0.310329E 02	-0.642934E 02
2023.703	-0.411467E 02	-0.542893E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1833.3384 1009.3773
RADIUS = 1946.0640
FIT = 1.2160

R0= 3319.1660 RINF= -8.4893

MODEL PARAMETERS - R1 = 4223.6465/FRQ
RP = 3327.6333

F	F-1/2	R1	XP	CP
0.0999	3.1633	13231.9102	-6869.2339	-0.2319E-03
0.1301	2.3010	6650.3010	-3870.3408	-0.2733E-03
0.2006	2.2329	4871.9629	-3263.0364	-0.2431E-03
0.4028	1.5737	3324.9424	-2220.1641	-0.1773E-03
0.6014	1.2095	2318.4209	-1647.0713	-0.1607E-03
0.8011	1.1172	2390.0361	-1432.6421	-0.1368E-03
1.0016	0.9992	1933.3244	-1194.3003	-0.1331E-03
2.0123	0.7049	1331.4703	-762.8210	-0.1037E-03
4.0222	0.4906	914.1420	-473.3183	-0.8337E-04
6.0089	0.4079	703.2791	-331.4971	-0.7336E-04
10.0523	0.3134	301.5943	-240.2769	-0.6390E-04
20.0723	0.2232	292.9998	-140.1288	-0.3333E-04
60.0962	0.1290	130.6039	-69.7721	-0.3796E-04
100.6036	0.0997	87.9140	-48.4283	-0.3267E-04
201.3423	0.0704	44.2342	-31.2719	-0.2528E-04
603.4484	0.0407	16.6172	-24.3889	-0.1073E-04
1009.1743	0.0314	12.7990	-29.3046	-0.3345E-03
1309.4341	0.0237	11.3673	-37.8633	-0.2783E-03
2025.7027	0.0222	10.0583	-49.7118	-0.1380E-03

G= 0.20477E 04 N= 0.70373E 00
************ STOP ************

Table 6-4. Computer Output for Electric and Dielectric Data of Basalt Sample K_1 Following 23-Hour Water Soak

ENTER NS,ADD   PUT 0001 UP FOR ELECTRODE CORRECTION
879.03916

K1 9/10/71   ADD= 0.03916   PHASE AND AMPLITUDE CORRECTED

FRQ	RP	XS	RADD	XADD	PHI	Z	ZADD
1.005	279.4092	48.9736	10.9417	1.9178	9.9423	283.6687	11.1005
2.025	290.7750	-59.7574	11.6217	-2.3401	-11.3854	302.7315	11.0550
4.032	241.9583	-125.0030	9.4751	-4.9186	-27.4363	272.6168	10.6757
8.096	165.9746	-147.5070	6.4996	-5.7764	-41.6316	222.0493	8.6954
10.075	143.0486	-140.5651	5.6018	-5.7395	-45.6990	204.0029	8.0201
20.268	91.3979	-107.9236	3.5791	-4.2263	-49.7432	141.4252	5.5582
40.480	54.5153	-84.8701	2.1548	-3.3235	-57.2900	100.8704	3.9501
80.775	33.3246	-56.6761	1.3050	-2.2194	-59.5496	65.7474	2.5747
100.705	23.4282	-40.4393	0.9171	-1.8969	-64.2011	53.0040	2.1070
202.130	9.0530	-28.8129	0.3859	-1.1283	-71.1253	30.4512	1.1925
405.044	5.1202	-15.6243	0.2009	-0.6118	-71.8310	16.4447	0.6440
810.811	3.4972	-8.1451	0.1369	-0.3190	-66.7681	8.8641	0.3471
1009.174	3.2733	-6.6239	0.1282	-0.2594	-63.7080	7.5886	0.2895
1520.913	2.9259	-4.3883	0.1146	-0.1718	-56.3109	5.[illegible]43	0.2065
2029.520	2.6082	-3.3450	0.1021	-0.1310	-52.0587	4.2417	0.1661

RP,XP CIRCLE FIT RESULTS- CIRCLE CENTER = 155.2299 4.2558
RADIUS = 146.6115
FIT = 6.0611

R0= 301.7795   RINF= 8.6801

MODEL PARAMETERS - R1 = 26507.3359/FRQ
RP = 293.0994

RHO = 0.11018E 10 OHM-CM

CP= 0.101091E-04

TAU= 4.74114MSEC   E0=1576.05029   EINF= 45.33224

FRQ	EP	EPP
1.005	0.152078E 04	0.407153E 02
2.025	0.140465E 04	0.964506E 02
4.032	0.140614E 04	0.106842E 03
8.096	0.127234E 04	0.332177E 03
10.075	0.121069E 04	0.422234E 03
20.268	0.990481E 03	0.662824E 03
40.480	0.740515E 03	0.731409E 03
80.775	0.499848E 03	0.537263E 03
100.705	0.433822E 03	0.438407E 03
202.130	0.269543E 03	0.252691E 03
405.044	0.167308E 03	0.130088E 03
810.811	0.109699E 03	0.660901E 02
1009.174	0.970016E 02	0.540227E 02
1520.913	0.807329E 02	0.361682E 02
2029.520	0.721562E 02	0.272650E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 569.0011 256.6362
RADIUS = 624.9592
FIT = 0.4400

R0= 1130.8359   RINF= -0.8339

MODEL PARAMETERS - R1 = 17693.5623/FRQ
RP = 1139.6699

F	F-1/2	R1	XP	CP
1.0040	0.9977	3738.3309	-1640.1948	-0.9659E-04
2.0240	0.7028	2304.5439	-1006.1207	-0.7238E-04
4.0319	0.4980	1510.5762	-703.0687	-0.5608E-04
8.0959	0.3515	990.0929	-444.5887	-0.4422E-04
10.0740	0.3151	808.4542	-381.0447	-0.4137E-04
20.2075	0.2221	496.3653	-242.0605	-0.3244E-04
40.4030	0.1572	340.0243	-151.9793	-0.2587E-04
80.7755	0.1113	219.0772	-91.4100	-0.2155E-04
100.7849	0.0996	190.9601	-75.6945	-0.2088E-04
202.1504	0.0703	128.9946	-41.0712	-0.1880E-04
405.0442	0.0496	61.4349	-23.3549	-0.1679E-04
810.8180	0.0351	26.3507	-13.6238	-0.1441E-04
1009.1743	0.0314	19.0292	-11.7680	-0.1340E-04
1520.9120	0.0256	11.9225	-9.7023	-0.1079E-04
2029.5200	0.0221	0.3359	-8.6064	-0.9028E-05

G= 0.50150E 04 N= 0.77800E 00
*********** STOP ***********

Table 6-5. Computer Output for Electric and Dielectric Data of Basalt Sample K_2 Following 23-Hour Water Soak

ENTER RS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
077.00184

K2 9/10/71 AOD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.005	208.5029	-122.7792	17.8410	-7.5947	-23.0550	315.5421	19.3894
2.020	220.3037	-120.4530	14.1103	-7.9435	-29.3661	261.9595	16.1996
4.027	115.5096	-127.0088	7.1431	-7.8579	-47.7316	171.7236	10.6194
8.022	108.8884	-115.0280	6.7337	-7.1134	-46.5742	158.3927	9.7950
10.040	92.3354	-56.3097	5.7108	-3.4871	-31.4149	180.1926	6.6906
20.178	59.2947	-74.9708	3.6668	-4.6362	-51.6632	95.5849	5.9110
40.258	34.7834	-55.9064	2.1510	-3.4573	-58.1155	65.8438	4.0718
80.380	19.3853	-36.7395	1.1988	-2.2720	-62.1865	41.5401	2.5688
100.503	15.2341	-31.4196	0.9421	-1.9430	-64.1378	34.9181	2.1595
201.072	6.0852	-18.0410	0.4134	-1.1528	-70.2765	19.8041	1.2247
402.570	3.4990	-10.2656	0.2164	-0.6348	-71.1838	10.8456	0.6707
809.353	2.4321	-5.3338	0.1504	-0.3298	-65.4928	3.8621	0.5625
1007.320	2.1127	-4.3080	0.1306	-0.2702	-64.1963	4.8527	0.3001
1512.288	1.7342	-2.9589	0.1072.	-0.1830	-59.6303	3.4297	0.2121
2033.272	1.7901	-2.1744	0.1107	-0.1345	-50.5401	2.8165	0.1742

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 219.2023 116.4595
RADIUS = 248.6751
FIT = 4.0902

R0= 438.9214 RINF= -0.5169

MODEL PARAMETERS - R1 = 8810.5195/FRQ
RP = 439.4383

RHO = 0.27143E 10 OHM-CM

CP= 0.202045E-04

TAU= 14.027520SEC E0=49588.593 EINF= 58.39580

FRQ	EP	EPP
1.005	-0.422706E 05	-0.680620E 04
2.020	-0.385849E 05	-0.968684E 04
4.027	-0.337339E 05	-0.120449E 05
8.022	-0.274991E 05	-0.140508E 05
10.040	-0.258705E 05	-0.149017E 05
20.178	-0.190121E 05	-0.141008E 05
40.258	-0.140450E 05	-0.116996E 05
80.380	-0.958090E 04	-0.867790E 04
100.503	-0.839851E 04	-0.774937E 04
201.072.	-0.547204E 04	-0.520143E 04
402.570	-0.348469E 04	-0.344168E 04
809.353	-0.217059E 04	-0.219092E 04
1007.320	-0.187200E 04	-0.190297E 04
1512.288	-0.141103E 04	-0.145354E 04
2033.272	-0.114451E 04	-0.119239E 04

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 675.1211 293.2156
RADIUS = 733.8569
FIT = 0.9575

R0= 1347.0547 RINF= 2.3873

MODEL PARAMETERS - R1 = 14489.4062/FRQ
RP = 1345.4673

F	F-1/2.	R1	XP	CP
1.0054	0.9973	3351.1836	-1326.0083	-0.1194E-03
2.0204	0.7035	1837.7493	-844.7229	-0.9325E-04
4.0274	0.4983	1104.3674	-534.5367	-0.7393E-04
8.0216	0.3531	698.8958	-330.3651	-0.6006E-04
10.0402	0.3155	593.0262	-279.6208	-0.5666E-04
20.1770	0.2226	357.2649	-173.5365	-0.4545E-04
40.2570	0.1576	252.0451	-105.9010	-0.3733E-04
80.3859	0.1115	150.2855	-60.6456	-0.3265E-04
100.5025	0.0997	119.0897	-51.5415	-0.3073E-04
201.0724	0.0705	107.7498	-28.2352	-0.2805E-04
402.5704	0.0498	75.2745	-15.2304	-0.2596E-04
809.3525	0.0351	51.1665	-7.9341	-0.2479E-04
1007.3202	0.0315	50.2423	-6.3773	-0.2478E-04
1512.2870	0.0257	57.4750	-4.3865	-0.2399E-04
2033.2720	0.0221	48.4960	-3.0878	-0.2535E-04

G= 0.23313E 04 N= 0.55359E 00
*********** STOP ***********

Table 6-6. Computer Output for Electric and Dielectric Data of Basalt Sample K_4 Following 23-Hour Water Soak

ENTER RS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
078.12317

K4 9/10/71 AOD= 0.12317 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.000	193.0283	-103.2272	23.7753	-12.7145	-28.1389	218.8967	26.9615
2.013	132.3356	-104.3148	16.2990	-12.8484	-38.2501	168.5059	20.7549
4.040	89.2910	-84.1705	10.9981	-10.3673	-43.3121	122.7098	15.1142
8.060	55.7010	-66.4763	8.8608	-8.1879	-50.0435	86.7281	10.6823
10.002	40.8967	-59.0026	5.7783	-7.2772	-51.5630	75.4324	9.2910
20.227	30.2582	-40.0012	3.7269	-4.9269	-52.8989	50.1563	6.1777
40.323	17.5454	-29.0573	2.1611	-3.5790	-58.8000	33.9436	4.1888
80.045	9.0423	-18.7059	1.1137	-2.3139	-64.3016	20.8488	2.5679
100.301	7.8072	-16.0585	0.9616	-1.9779	-64.0770	17.8558	2.1993
201.084	3.8151	-9.4997	0.4453	-1.1701	-69.1707	10.1643	1.2519
403.877	1.8829	-5.3380	0.2295	-0.6576	-70.7695	5.6545	0.6965
807.099	1.2600	-2.7341	0.1580	-0.3368	-65.1453	3.0133	0.3712
1009.174	1.1092	-2.2486	0.1368	-0.2770	-63.7495	2.5073	0.3088
1420.455	0.8894	-1.5519	0.1095	-0.1912	-60.1887	1.7887	0.2203
2037.037	0.9130	-1.1181	0.1128	-0.1377	-50.6913	1.4451	0.1780

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 364.4427 76.8911
RADIUS = 181.1940
FIT = 0.9165

R0= 320.5128 RINF= 0.3725

MODEL PARAMETERS - R1 = 4607.1875/FRQ
RP = 320.1402

RHO = 0.40403E 10 OHM-CM

CP= 0.074179E-04

TAU= 24.43145MSEC E0=560164.734 EINF= 68.22583

FRQ	EP	EPP
1.000	0.483100E 05	0.109967E 05
2.013	0.426271E 05	0.150747E 05
4.040	0.354877E 05	0.183311E 05
8.060	0.278498E 05	0.189437E 05
10.002	0.252059E 05	0.184775E 05
20.227	0.179960E 05	0.153118E 05
40.323	0.122300E 05	0.112444E 05
80.045	0.798008E 04	0.761403E 04
100.301	0.694497E 04	0.660217E 04
201.084	0.438257E 04	0.424391E 04
403.877	0.274039E 04	0.265432E 04
807.099	0.171507E 04	0.163938E 04
1009.174	0.147028E 04	0.140212E 04
1420.455	0.117315E 04	0.110139E 04
2037.037	0.923078E 03	0.852782E 03

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 364.4236 139.3846
RADIUS = 388.8536
FIT = 0.6445

R0= 727.4375 RINF= 1.4098

MODEL PARAMETERS - R1 = 9414.4453/FRQ
RP = 726.0277

F	F-1/2	R1	XP	CP
1.0002	0.9959	2277.5112	-837.4116	-0.1885E-03
2.0126	0.7049	1431.3850	-546.0271	-0.1448E-03
4.0401	0.4975	840.4938	-346.3225	-0.1138E-03
8.0604	0.3521	510.1658	-212.5725	-0.9280E-04
10.0020	0.3162	437.0799	-182.0284	-0.8742E-04
20.2265	0.2224	261.8143	-110.7184	-0.7107E-04
40.3226	0.1575	177.4755	-60.9308	-0.5897E-04
80.0452	0.1114	118.7027	-38.9754	-0.5064E-04
100.3009	0.0998	102.7803	-32.3585	-0.4304E-04
201.0842	0.0703	69.8307	-17.7851	-0.4433E-04
403.8772	0.0497	45.3987	-9.6001	-0.4105E-04
807.0994	0.0351	30.4916	-5.0030	-0.3876E-04
1009.1743	0.0314	23.7440	-4.0725	-0.3873E-04
1420.4546	0.0265	22.4012	-2.9025	-0.3860E-04
2037.0371	0.0221	16.5356	-1.9660	-0.3973E-04

G= 0.20178E 04 N= 0.63535E 00
*********** STOP ***********

Table 6-7. Computer Output for Electric and Dielectric Data of Basalt Sample K_1 Following 72-Hour Water Soak

ENTER RS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
002.03916

K1 9/17/71 77 HR AOD= 0.03916 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZADD
1.011	1012.1704	-833.7279	39.6366	-32.6488	-39.4813	1311.3318	31.3318
2.013	640.3005	-688.8183	23.0742	-26.8958	-47.0109	938.9912	36.7709
4.042	365.7009	-305.1570	14.3234	-19.7020	-34.0970	623.6743	24.4231
8.080	191.1057	-342.1343	7.4837	-13.3988	-60.8195	391.9069	19.9471
10.054	152.9525	-295.4302	5.9896	-11.5690	-62.6327	332.6762	19.0276
20.145	90.5029	-174.2307	3.3441	-6.8229	-62.5553	196.5342	7.6804
40.225	52.9494	-113.0870	2.0733	-4.4398	-65.0699	125.5949	4.9183
80.645	31.8339	-71.1370	1.2308	-2.7857	-66.0306	77.8535	3.0487
100.604	16.7475	-59.3730	0.6358	-2.3231	-74.2337	61.6918	2.4158
201.013	9.9012	-32.9723	0.3877	-1.2912	-73.2910	34.4268	1.3482
403.220	5.2777	-17.0320	0.2067	-0.6991	-73.5399	18.6198	0.7290
807.899	3.4049	-9.1037	0.1333	-0.3366	-69.3027	9.7215	0.9807
1007.320	3.3604	-7.2723	0.1316	-0.2848	-65.2036	8.0111	0.3197
1515.131	3.2039	-4.9486	0.1286	-0.1938	-36.4360	3.9390	0.2326
2033.272	2.7261	-3.2877	0.1068	-0.1287	-30.3382	4.2709	0.1672

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1257.4980 311.3094
RADIUS = 1358.9213
FIT = 0.[illegible]048

R0= 2510.4492 RINF= -1.4331

MODEL PARAMETERS - R1 = 18199.4102/FRQ
RP = 2517.9023

RHO = 0.98344E 10 OHM-CM

CP= 0.156479E-04

TAU= 42.52533MSEC E0=84442.062 EINF= 48.76112

FRQ	EP	EPP
1.011	-0.820938E 03	-0.205449E 05
2.013	-0.522494E 05	-0.283099E 05
4.042	-0.409250E 05	-0.284044E 03
8.080	-0.298087E 05	-0.252581E 05
10.054	-0.266417E 05	-0.234756E 05
20.145	-0.178670E 05	-0.170417E 05
40.225	-0.114713E 05	-0.113183E 05
80.645	-0.711827E 04	-0.712408E 04
100.604	-0.808438E 04	-0.610931E 04
201.013	-0.367590E 04	-0.372101E 04
403.220	-0.219334E 04	-0.224186E 04
807.899	-0.129077E 04	-0.133968E 04
1007.320	-0.108770E 04	-0.113861E 04
1515.151	-0.708985E 03	-0.837880E 03
2033.272	-0.625300E 03	-0.672232E 03

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 883.6303 417.9223
RADIUS = 978 1311
FIT = 0.4849

R0= 1766.0039 RINF= -0.7033

MODEL PARAMETERS - R1 = 15961.8437/FRQ
RP = 1768.7075

F	F-1/2	R1	XP	CP
1.0105	0.9948	3922.7334	-1737.1453	-0.8964E-04
2.0134	0.7047	2338.0403	-1133.9956	-0.6971E-04
4.0417	0.4974	1430.6592	-710.9470	-0.3539E-04
8.0802	0.3518	914.9569	-435.3304	-0.4523E-04
10.0545	0.3154	790.6863	-369.4814	-0.4284E-04
20.1450	0.2228	449.5347	-220.3885	-0.3459E-04
40.2255	0.1577	304.1602	-143.4758	-0.2758E-04
80.6452	0.1114	197.9356	-87.0238	-0.2268E-04
100.6036	0.0997	107.6031	-69.6103	-0.2273E-04
201.0129	0.0704	107.0280	-40.0049	-0.1973E-04
403.2258	0.0498	56.1489	-22.5607	-0.1750E-04
807.0994	0.0351	25.0158	-13.0719	-0.1507E-04
1007.3262	0.0313	18.9504	-11.2510	-0.1404E-04
1515.1514	0.0256	11.6742	-9.2134	-0.1140E-04
2033.2720	0.0221	8.2137	-8.2597	-0.9477E-05

G= 0.47747E 04 N= 0.78137E 00
************ STOP ************

Table 6-8. Computer Output for Electric and Dielectric Data of Basalt Sample K_2 Following 72-Hour Water Soak

ENTER RS,AOD POT SSW1 UP FOR ELECTRODE CORRECTION
000,06184

K2 9/17/71 77 HR AOD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZADD
1.002	529.0524	-400.2118	32.7166	-24.7491	-37.1091	663.5746	41.0231
2.011	347.2244	-336.3760	21.4724	-20.8139	-44.1111	483.3786	29.9043
4.043	209.1399	-256.0068	17.9332	-15.8313	-50.7373	330.3737	20.4427
8.041	117.3779	-180.0921	7.2387	-11.1864	-37.0233	213.6373	13.3350
10.036	95.7040	-103.1648	5.9183	-10.0901	-39.6107	189.1613	11.6977
20.137	57.0289	-97.4923	3.3761	-6.0289	-39.3294	113.3551	7.0098
40.250	33.9951	-65.3471	2.1023	-4.0534	-62.3917	73.8382	4.3662
80.775	19.1599	-41.7323	1.1848	-2.3820	-65.3347	43.9387	2.8400
100.503	12.6530	-35.2892	0.7823	-2.1823	-70.2797	37.4890	2.3183
201.884	6.0413	-20.0026	0.4231	-1.2407	-71.1754	21.1970	1.5108
401.929	3.7131	-10.9801	0.2297	-0.6794	-71.3214	11.5973	0.7172
807.099	2.4917	-5.7334	0.1541	-0.3347	-66.3229	6.2333	0.3867
1003.404	2.2116	-4.7243	0.1368	-0.2922	-64.9193	3.2163	0.3226
1512.280	1.9329	-3.2193	0.1193	-0.1991	-39.0242	3.7332	0.2322
2025.783	1.0773	-2.3532	0.1161	-0.1433	-31.4224	3.0103	0.1862

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 603.8373 261.2600
RADIUS = 637.7368
FIT = 0.3839

R0= 1207.4807 RINF= 0.2344

MODEL PARAMETERS - R1 = 9877.5664/FRQ
RP = 1207.2463

RHO = 0.74671E 10 OHM-CM

CP= 0.297500E-04

TAU= 39.135360MSEC E0=5305102.18 EINF= 39.22110

FRQ	EP	EPP
1.002	0.227628E 06	0.703371E 03
2.011	0.192995E 06	0.911249E 03
4.043	0.152932E 06	0.100179E 06
8.041	0.113395E 06	0.916560E 03
10.050	0.101430E 06	0.058671E 05
20.137	0.699930E 05	0.641053E 05
40.250	0.450001E 05	0.433276E 05
80.775	0.283532E 05	0.278997E 03
100.503	0.244151E 05	0.240919E 03
201.884	0.149993E 05	0.148652E 03
401.929	0.910297E 04	0.910123E 04
807.099	0.555650E 04	0.549030E 04
1005.404	0.474319E 04	0.468109E 04
1512.288	0.333507E 04	0.347332E 04
2025.783	0.206400E 04	0.200323E 04

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 333.6002 176.3403
RADIUS = 578.0610
FIT = 0.5473

R0= 660.0244 RINF= -0.8001

MODEL PARAMETERS - R1 = 9040.9633/FRQ
RP = 668.8325

F	F-1/2	R1	XP	CP
1.0019	0.9990	1950.7134	-980.0205	-0.1621E-03
2.0112	0.7051	1213.9211	-648.8845	-0.1220E-03
4.0427	0.4974	767.0601	-422.8733	-0.9310E-04
8.0412	0.3526	500.9435	-270.0319	-0.7330E-04
10.0503	0.3153	435.7302	-231.7460	-0.6829E-04
20.1369	0.2220	267.2646	-146.4672	-0.3396E-04
40.2576	0.1576	101.2016	-91.6665	-0.4313E-04
80.7753	0.1113	121.8577	-34.4156	-0.3621E-04
100.5025	0.0997	101.6069	-46.9402	-0.3374E-04
201.8842	0.0703	62.33'2	-27.0119	-0.2919E-04
401.9293	0.0490	32.9214	-13.7629	-0.2512E-04
807.0994	0.0351	15.3646	-9.6673	-0.2036E-04
1005.4844	0.0315	12.2091	-8.3360	-0.1894E-04
1512.2076	0.0257	0.0346	-6.7673	-0.1533E-04
2025.7827	0.0222	3.9933	-6.6082	-0.1189E-04

G= 0.24041E 04 N= 0.74404E 00
************ STOP ************

Table 6-9. Computer Output for Electric and Dielectric Data of Basalt Sample K_4 Following 72-Hour Water Soak

ENTER NS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION
001.12317

K4 9/17/71 77 HR   AOD= 0.12517   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.007	217.1331	-146.2850	26.7445	-18.0177	-55.9705	261.8156	32.2476
2.022	149.7510	-126.3896	18.4424	-13.3920	-40.2157	196.0721	24.1502
4.050	93.4650	-101.1523	11.7384	-12.4563	-46.6546	139.0750	17.1296
8.091	37.2352	-75.4501	7.0497	-9.2907	-32.0152	94.6867	11.6626
10.064	47.4825	-86.9405	5.0460	-8.2451	-34.6665	82.0392	10.1072
20.170	29.3177	-45.4969	3.6111	-3.5575	-36.0254	32.4548	6.4609
40.230	17.5133	-30.0500	2.1327	-5.7022	-60.0395	34.6888	4.2726
80.773	9.5402	-19.8448	1.1504	-2.4197	-64.5760	21.7522	2.6792
100.806	7.2944	-17.1468	0.0985	-2.1120	-66.9596	18.6538	2.2951
201.015	5.0378	-9.7208	0.4503	-1.1975	-69.5842	10.5862	1.2795
402.376	2.8667	-3.5688	0.2346	-0.6613	-68.9509	5.7329	0.7066
807.099	1.4200	-2.8737	0.1749	-0.3539	-65.7087	5.2054	0.3948
1012.891	1.2536	-2.5874	0.1319	-0.2941	-62.6785	2.6873	0.3510
1320.915	0.9279	-1.6462	0.1143	-0.2028	-60.3969	1.8896	0.2327
2037.037	0.9378	-1.2237	0.1100	-0.1507	-51.9541	1.3540	0.1914

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 223.4990 106.2981
RADIUS = 247.3219
FIT = 0.8181

R0= 446.8124   RINF= 0.1857

MODEL PARAMETERS - R1 = 4802.6133/FRQ
RP = 446.6267

RHO = 0.33854E 10 OHM-CM

CP= 0.397770E-04

TAU= 29.56855MSEC   E0=8146096.37   EINF= 60.70906

FRQ	EP	EPP
1.007	0.115734E 06	0.293029E 03
2.022	0.980181E 03	0.390894E 03
4.036	0.809715E 03	0.434510E 03
8.091	0.619537E 03	0.447643E 03
10.084	0.561826E 03	0.430290E 03
20.170	0.393464E 03	0.344561E 03
40.238	0.263694E 03	0.247426E 03
80.773	0.171807E 03	0.165265E 03
100.806	0.148771E 03	0.143971E 03
201.615	0.937327E 04	0.917197E 04
402.576	0.384879E 04	0.375832E 04
807.099	0.361673E 04	0.353862E 04
1012.891	0.389510E 04	0.381992E 04
1520.913	0.233362E 04	0.226807E 04
2057.037	0.199980E 04	0.184464E 04

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 194.2527 95.4422
RADIUS = 215.2560
FIT = 0.6200

R0= 388.1494   RINF= 0.3160

MODEL PARAMETERS - R1 = 5894.1033/FRQ
RP = 587.8334

F	F-1/2	R1	XP	CP
1.0069	0.9966	1234.5152	-578.7021	-0.2731E-03
2.0220	0.7032	810.8369	-583.7461	-0.2041E-03
4.0358	0.4978	489.4203	-249.8445	-0.1578E-03
8.0980	0.3516	318.3516	-138.0434	-0.1245E-03
10.0644	0.3132	271.2822	-136.1979	-0.1161E-03
20.1776	0.2226	166.9179	-84.7639	-0.9506E-04
40.2376	0.1376	111.5041	-52.3894	-0.7346E-04
80.7735	0.1113	72.9378	-51.0837	-0.6339E-04
100.8063	0.0993	63.9032	-26.0274	-0.6066E-04
201.6129	0.0704	39.2328	-13.1506	-0.5217E-04
402.3764	0.0498	22.0331	-8.6318	-0.4580E-04
807.0994	0.0331	11.3239	-4.8726	-0.4043E-04
1012.0914	0.0314	8.4798	-4.0834	-0.5848E-04
1520.9126	0.0236	5.0026	-3.0778	-0.5400E-04
2057.0371	0.0221	3.3376	-2.4840	-0.5145E-04

G= 0.15167E 04 N= 0.74106E 00
********** STOP **********

K1 are given in Table 6-10. The significant conclusion indicated by these results is that the highest sensitivity for water detection in rocks can only be achieved by data extrapolation to the static or zero frequency dielectric constant.

Table 6-10. Effect of Water Pretreatment on Selected Electric and Dielectric Parameters of Basalt

Parameter↓ / Soak Time (Hours) →	0 (Baseline)	23	77
R_o, megohm	1,031.0	328.0	447.0
τ, millisecond	16.6	24.4	29.6
$\epsilon_o \epsilon_r = K_o$	1,770.0	60200.0	146000.0
$\epsilon_\infty \epsilon_r = K_\infty$	14.8	68.2	60.7

The highest selectivity for water detection is obtained by choosing the real component of the dielectric constant at the limit of zero frequency from among the impedance and the dielectric parameters.

The variations of the impedivity vectors for three basalt samples with frequency are shown in Figure 6-1. After the three rocks were soaked for 23 hours in distilled water, their impedivity variation with frequency are shown by the curves in Figure 6-2. Figure 6-3 gives the same relationships for the rocks following a 77-hour soak period.

Here again, the impedivity vectors are the most separated at low frequencies, and approach each other as the frequency increases.

The variation of rock impedivity at 1 Hz with the duration of water pretreatment is shown in Table 6-11 and Figure 6-4 for the three basalt rocks.

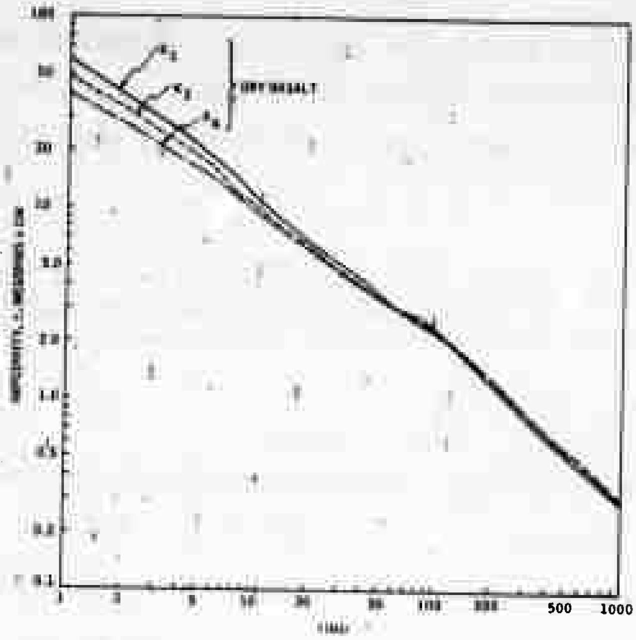


Figure 6-1. Variation of Impedivity with Frequency for an Untreated Basalt Sample

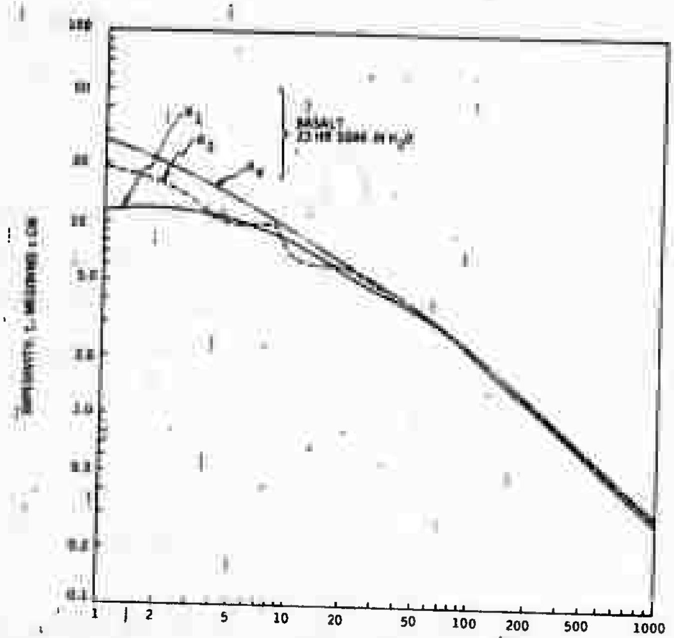


Figure 6-2. Variation of Impedivity with Frequency for Basalt Samples Following a 23-hour Water Soak

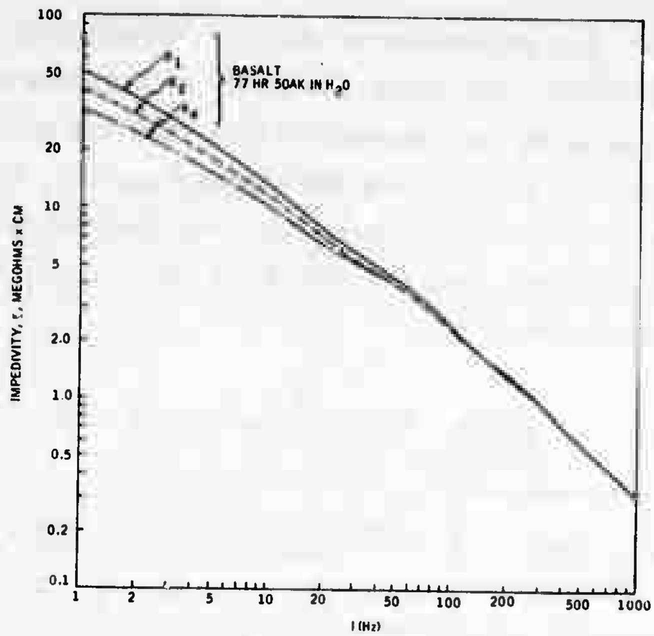


Figure 6-3. Variation of Impedivity with Frequency for Basalt Samples Following a 77-hour Water Soak

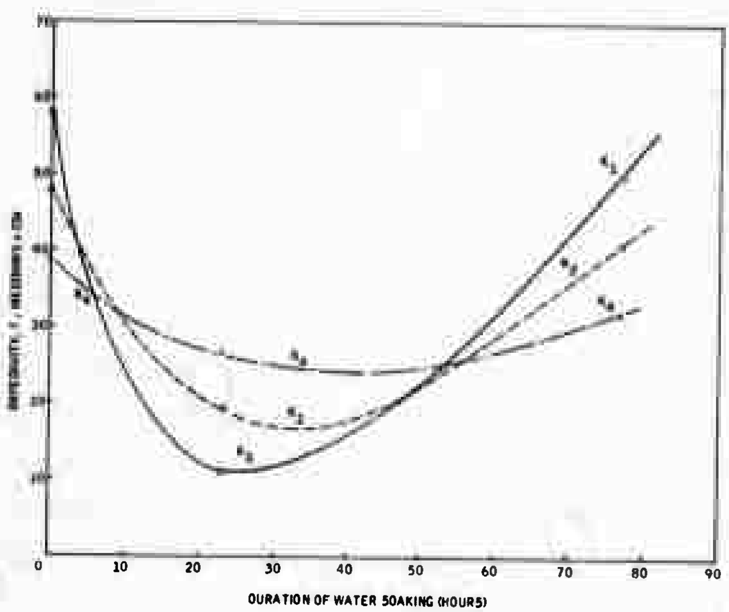


Figure 6-4. Variation of Rock Impedivity with the Duration Time of Water Treatment for Three Samples of Basalt

Generally speaking, the impedance versus time-of-soaking decreases initially, goes through a minimum, and increases again with longer soak times. This behavior is explainable by the assumption that the first portions of water that diffuse through the rock pores leach the adjacent sodium and potassium ions, and thus decrease the rock impedance. Further introduction of water into the pores will begin to leach out the dissolved alkali ions, thus resulting in an increase in rock impedance.

Table 6-11. Effect of Water Soaking on Impedivity of Basalt at 1 Hz

Time of Soaking (hours)	Impedivity at 1 Hz, megohm x cm		
	K_1	K_2	K_4
0	58	48	39
23	11	19	27
77	50	41	32

PRETREATMENT OF BASALT IN SODIUM HYDROXIDE

To further investigate the effects of environmental conditions on rock impeditivity, other series of tests were conducted on basalt that had been pretreated in solutions of sodium hydroxide. The three samples K_1, K_2, and K_4 of basalt were soaked for 23 hours in 1, 5, and 10 percent solutions of sodium hydroxide in water. The impedance data of these experiments were grouped with those obtained while soaking the same rock samples in distilled water (zero percent NaOH) for 23 hours. Computer output data of these experiments are given in Tables 6-12 to 6-20. Variations of the magnitude of impeditivity vector with frequency as a result of the various soaking solutions are shown in Figures 6-5, 6-6, and 6-7. Here again, the impedance arcs for various NaOH concentrations seem to overlap and become indistinguishable at frequencies greater than 100 Hz.

Table 6-12. Computer Output for Electric and Dielectric Data of Basalt Sample K_1 Pretreated in 1% NaOH for 23 Hours

ENTER NS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
003.03910

K1 9/27/71 1PC   AOD= 0.05918   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.000	-46.8450	225.4504	-1.8544	8.8288	101.7451	250.2654	9.0172
2.005	60.5096	174.8752	2.8828	8.8480	88.6114	187.8143	7.5548
4.020	155.9631	89.3441	5.5245	5.4987	53.5122	162.8909	8.5710
8.008	140.1420	4.9909	5.4800	0.1954	2.0598	140.2509	5.4914
10.028	131.1049	-15.8528	5.1541	-0.5425	-6.0520	151.8547	5.1826
20.161	98.4211	-42.4405	5.8542	-1.8820	-25.5282	107.1817	4.1972
40.225	65.0090	-53.1601	2.5489	-2.0810	-39.2425	84.0591	5.2910
80.257	51.5885	-41.8259	1.2570	-1.7555	-54.8507	54.8562	2.1474
100.301	26.7956	-39.6400	1.0492	-1.5525	-55.9484	47.8459	1.8758
201.072	15.0709	-25.7145	0.5119	-1.0070	-85.0599	28.8459	1.1298
402.576	6.4465	-15.0297	0.2524	-0.5886	-86.7894	18.5558	0.6404
805.572	5.8108	-8.1242	0.1492	-0.5181	-84.8751	8.9758	0.5524
1005.484	5.5162	-6.4839	0.1577	-0.2559	-51.5558	7.5780	0.2888
1512.288	2.9548	-4.4106	0.1157	-0.1727	-58.1847	5.5089	0.2079
2025.785	2.6284	-5.5321	0.1029	-0.1505	-51.7572	4.2440	0.1662

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 41.5851 89.0127
RADIUS = 120.0228
FIT = 17.4001

R0= 121.8755   RINF= -39.1491

MODEL PARAMETERS - R1 = 20705.8516/FRQ
RP = 161.0244

RHO = 0.47726E 09 OHM-CM

CP= 0.145554E-05

TAU= 0.54887MSEC   E0= -25.71297   EINF= 8.25958

FRQ	EP	EPP
1.000	-0.244097E 02	-0.119245E 01
2.005	-0.259077E 02	-0.159938E 01
4.020	-0.232160E 02.	-0.211921E 01
8.008	-0.222789E 02	-0.275500E 01
10.028	-0.219061E 02	-0.298975E 01
20.161	-0.204959E 02	-0.378434E 01
40.225	-0.186658E 02	-0.463112E 01
80.257	-0.163456E 02	-0.544896E 01
100.501	-0.154955E 02	-0.580659E 01
201.072	-0.125516E 02	-0.627421E 01
402.576	-0.952172E 01	-0.655538E 01
805.372	-0.805745E 01	-0.641258E 01
1005.484	-0.503255E 01	-0.629258E 01
1512.288	-0.524915E 01	-0.598716E 01
2025.785	-0.205470E 01	-0.571100E 01

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 259.2518 125.1585
RADIUS = 289.2081
FIT = 0.9550

R0= 519.9550   RINF= -1.4918

MODEL PARAMETERS - R1 = 17781.2891/FRQ
RP = 521.4468

F	F-1/2	R1	XP	CP
0.9999	1.0001	3934.5721	-1718.5688	-0.9262E-04
2.0051	0.7062	2395.5915	-1121.0417	-0.7081E-04
4.0196	0.4988	1468.5708	-717.5768	-0.5518E-04
8.0077	0.3554	915.6278	-444.6910	-0.44708-04
10.0281	0.3158	778.4894	-380.1547	-0.41758-04
20.1613	0.2227	465.7562	-244.0275	-0.5224E-04
40.2255	0.1577	322.8907	-152.5859	-0.2595E-04
80.2568	0.1116	221.8252	-88.4447	-0.2242E-04
100.3009	0.0998	185.5672	-75.2488	-0.2109E-04
201.0724	0.0703	109.9158	-42.9241	-0.1844E-04
402.5764	0.0498	56.9755	-24.5256	-0.1612E-04
805.5715	0.0552	25.1147	-14.6844	-0.1549E-04
1005.4844	0.0515	18.9547	-12.8555	-0.1251E-04
1512.2876	0.0257	12.0268	-10.8965	-0.9659E-05
2025.7827	0.0222	8.8846	-10.1782	-0.7719E-05

G= 0.48169E 04 N= 0.77814E 00
*********** STOP ***********

Table 6-13. Computer Output for Electric and Dielectric Data of Basalt Sample K_2 Pretreated in 1% NaOH for 23 Hours

ENTER NS,ADD PUT 66W1 UP FOR ELECTRODE CORRECTION
003.06184

K2 8/27/71 1PC ADD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
0.899	113.4325	3.6031	7.0139	0.2270	1.8605	113.5105	7.0396
2.010	120.0020	-10.3338	7.4733	-0.6329	-4.9900	121.3918	7.5038
4.023	113.7433	-20.3816	7.1579	-1.0170	-14.2440	119.4149	7.9849
8.033	93.1602	-43.1041	3.7615	-3.7942	-23.8741	103.3467	6.4033
10.060	89.0046	-48.0038	5.1000	-0.9735	-29.0811	96.6971	[illegible]
20.121	60.1012	-44.0270	3.7222	-2.7721	-36.6794	79.0495	4.6011
40.238	30.4400	-40.0019	2.3776	-2.5949	-40.0309	59.2937	3.4738
80.313	19.3242	-31.0399	1.1950	-1.9193	-38.0970	39.3611	0.2609
100.402	16.3334	-27.2106	1.0224	-1.6027	-38.7211	31.0397	1.9690
201.613	7.9731	-17.0700	0.4931	-1.0337	-94.9693	18.0411	1.1651
402.376	4.0769	-8.0590	0.2521	-0.6003	-67.3385	30.0633	[illegible]
807.898	2.9011	-9.2034	0.1547	-0.5067	-84.6702	5.0456	0.9019
1009.174	2.2022	-4.2257	0.1417	-0.0615	-61.5271	4.0073	0.2973
1310.027	1.0904	-2.9209	0.1199	-0.1011	-37.1646	9.4060	0.2156
2033.272	1.0391	-2.1424	0.1133	-0.1325	-49.4073	2.0215	0.1745

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 91.0001 10.5096
RADIUS = 90.4099
FIT = 3.7094

R0= 121.3734 RINF= 2.4028

MODEL PARAMETERS - R1 = 13977.4640/FRQ
RP = 118.9706

RHO = 0.730378 04 OHM-CM

CP= 0.300178E-04

TAU= 4.32305MSEC E0=3492.72949 EINF= 69.14598

FRQ	EP	EPP
0.999	0.3354180 04	0.1410420 03
2.010	0.3243220 04	0.2396730 03
4.023	0.3036890 04	0.4635910 03
8.033	0.2764000 04	0.7069130 03
10.060	0.2042030 04	0.8133030 03
20.121	0.2109300 04	0.1303740 04
40.250	0.1666190 04	0.1423000 04
80.313	0.1163980 04	0.1140290 04
100.402	0.1022430 04	0.1010430 04
201.613	0.6363110 03	0.6314000 03
403.376	0.4133000 03	0.3624030 03
807.899	0.2631730 03	0.2003340 03
1009.174	0.2239300 03	0.1653000 03
1310.027	0.1026000 03	0.1139020 03
2033.272	0.1572990 03	0.0951130 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 435.3424 216.9901
RADIUS = 487.3000
FIT = 0.4277

R0= 871.6740 RINF= -0.9891

MODEL PARAMETERS - R1 = 22332.5701/FRQ
RP = 872.6931

F	F-1/2	R1	XP	CP
0.9987	1.0006	3613.3027	-1267.0030	-0.12570-03
2.0102	.7053	1647.0103	-823.1321	-0.93030-04
4.0233	0.4983	1037.1060	-328.6429	-0.74890-04
8.0334	0.3328	633.7011	-329.4938	-0.90130-04
10.0604	0.3133	337.0709	-281.3319	-0.36190-04
20.1207	0.2223	339.0793	-170.5989	-0.44420-04
40.2376	0.1376	230.7323	-100.0699	-0.39310-04
80.3133	0.1114	133.0770	-94.3879	-0.30700-04
100.4016	0.0998	130.1234	-54.4269	-0.20130-04
201.6120	0.0794	70.4897	-30.0004	-0.33920-04
402.3764	0.0498	40.3439	-17.6617	-0.22300-04
807.0004	0.0331	17.9007	-10.3071	-0.10300-04
1009.1743	0.0314	13.7103	-9.2134	-0.17110-04
1310.0260	0.0256	8.7303	-7.7300	-0.13310-04
2033.2720	0.0221	6.3400	-7.3913	-0.10390-04

G= 0.333330 04 N= 0.772100 00
********** STOP **********

Table 6-14. Computer Output for Electric and Dielectric Data of Basalt Sample K_4 Pretreated in 1% NaOH for 23 Hours

ENTER NS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION
Ø84.12517

K4 9/27/71 1PC   AOD= Ø.12517   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XADD	PH1	Z	ZADD
1.ØØ4	118.6592	-38.Ø375	14.6132	-7.1485	-26.Ø657	132.Ø922	16.2698
2.Ø19	94.3437	-37.3Ø47	11.62Ø5	-7.Ø382	-51.277Ø	11Ø.3838	15.396Ø
4.Ø5Ø	7Ø.7654	-31.9217	8.7162	-6.3952	-36.27Ø8	87.77Ø1	1Ø.81Ø6
8.Ø17	48.6585	-43.7294	5.9952	-5.5861	-41.9492	65.42Ø9	8.Ø579
1Ø.Ø28	42.4959	-4Ø.6498	3.254Ø	-5.ØØ68	-45.7527	38.8Ø39	7.2431
2Ø.Ø88	29.55Ø2	-3Ø.2313	5.6151	-3.7261	-45.8696	42.1495	3.1915
4Ø.161	18.1461	-25.7146	2.2351	-2.92Ø9	-52.3811	29.86Ø8	5.6779
8Ø.313	9.4Ø75	-16.7869	1.1587	-2.Ø676	-6Ø.758Ø	19.2452	2.57Ø2
1ØØ.4Ø2	8.1115	-14.5846	Ø.9991	-1.7964	-6Ø.9255	16.6884	2.Ø355
2Ø1.613	3.8677	-8.9159	Ø.4764	-1.Ø982.	-66.5559	9.7187	1.197Ø
4Ø2.376	2.Ø588	-5.Ø963	Ø.2311	-Ø.6277	-68.2Ø15	5.489Ø	Ø.6761
8Ø9.355	1.2989	-2.7117	Ø.16ØØ	-Ø.554Ø	-64.4Ø99	5.ØØ68	Ø.57Ø5
1Ø12.891	1.1819	-2.1599	Ø.1456	-Ø.2673	-61.4285	2.47Ø9	Ø.3Ø45
1512.288	Ø.9378	-1.3539	Ø.118Ø	-Ø.1889	-58.Ø252	1.8Ø84	Ø.2227
2Ø29.52Ø	Ø.9962	-1.Ø897	Ø.1227	-Ø.1542	-47.5697	1.4764	Ø.1818

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 96.723Ø 55.4681
RADIUS = 11Ø.4367
FIT = 1.4339

RØ= 195.3554   RINF= Ø.Ø926

MODEL PARAMETERS - R1 = 4ØØ5.9922/FRQ
RP = 193.26Ø8

RHO = Ø.23813E 1Ø OHM-CM

CP= Ø.614124E-Ø4

TAU= 15.56457MSEC   EØ=$154331.59   EINF= 64.3576Ø

FRQ	EP	EPP
1.ØØ4	Ø.11462ØE Ø6	Ø.181965E Ø5
2.Ø19	Ø.1Ø4793E Ø6	Ø.257Ø65E Ø5
4.Ø3Ø	Ø.918867E Ø5	Ø.554Ø77E Ø5
8.Ø17	Ø.763991E Ø5	Ø.387Ø91E Ø5
1Ø.Ø28	Ø.71Ø187E Ø3	Ø.394336E Ø5
2Ø.Ø88	Ø.343193E Ø3	Ø.378689E Ø3
4Ø.161	Ø.592349E Ø5	Ø.317Ø39E Ø5
8Ø.513	Ø.269936E Ø5	Ø.258233E Ø3
1ØØ.4Ø2	Ø.2579Ø4E Ø3	Ø.214Ø11E Ø5
2Ø1.613	Ø.156746E Ø5	Ø.146938E Ø3
4Ø2.576	Ø.1Ø1632E Ø5	Ø.97433ØE Ø4
8Ø9.333	Ø.64892ØE Ø4	Ø.628681E Ø4
1Ø12.891	Ø.36Ø963E Ø4	Ø.34456ØE Ø4
1312.288	Ø.431984E Ø4	Ø.419661E Ø4
2Ø29.32Ø	Ø.356446E Ø4	Ø.346Ø68E Ø4

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 242.Ø772 121.Ø511
RADIUS = 271.9834
FIT = Ø.3391

RØ= 485.6497   RINF= -1.4953

MODEL PARAMETERS - R1 = 8154.8477/FRQ
RP = 487.143Ø

F	F-1/2	R1	XP	CP
1.ØØ36	Ø.9982.	1917.8881	-911.2679	-Ø.174ØE-Ø5
2.Ø187	Ø.7Ø38	1162.5181	-585.8918	-Ø.133ØE-Ø3
4.Ø3ØØ	Ø.4981	718.7581	-566.5549	-Ø.1Ø78E-Ø5
8.Ø167	Ø.5352	436.8784	-227.Ø554	-Ø.8744E-Ø4
1Ø.Ø281	Ø.3138	389.7518	-193.5584	-Ø.82ØØE-Ø4
2Ø.Ø384	Ø.2231	241.93Ø6	-119.6719	-Ø.6621E-Ø4
4Ø.16Ø6	Ø.1378	16Ø.1624	-72.2Ø3Ø	-Ø.5489E-Ø4
8Ø.3135	Ø.1114	1Ø1.3481	-42.4442	-Ø.4657E-Ø4
1ØØ.4Ø16	Ø.Ø998	86.4976	-53.3226	-Ø.4465E-Ø4
2Ø1.6129	Ø.Ø7Ø4	47.6977	-2Ø.3789	-Ø.5856E-Ø4
4Ø2.3764	Ø.Ø498	25.3962	-12.25Ø4	-Ø.5233E-Ø4
8Ø9.3523	Ø.Ø351	1Ø.3631	-7.9871	-Ø.2462E-Ø4
1Ø12.8914	Ø.Ø314	8.3449	-7.2569	-Ø.2171E-Ø4
1512.2876	Ø.Ø237	3.6483	-6.9753	-Ø.15Ø9E-Ø4
2Ø29.52ØØ	Ø.Ø221	4.4389	-6.7278	-Ø.1166E-Ø4

G= Ø.24221E Ø4 N= Ø.79574E ØØ
********** STOP **********

Table 6-15. Computer Output for Electric and Dielectric Data of Basalt Sample K_1 Pretreated in 5% NaOH for 23 Hours

ENTER NS,ADD   PUT SSW1 UP FOR ELECTRODE CORRECTION
006.05916

K1 9/20/71 5PC   ADD= 0.03916   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
1.004	-157.1950	102.5416	-6.1537	4.0077	146.9445	187.3732	7.3454
2.009	-113.0080	125.4922	-4.4285	4.9143	132.0535	168.9295	6.6153
4.021	-41.4929	120.4851	-1.6249	4.7182	109.0108	127.4297	4.9901
8.030	22.2226	88.1223	0.8702	3.4509	75.8519	90.8812	3.5589
10.042	56.7930	73.1545	1.4408	2.8659	63.2983	81.8681	5.2060
20.169	58.5265	28.9186	2.2919	1.1325	26.2964	65.2812	2.5364
40.225	55.7110	-4.2177	2.1816	-0.1652	-4.3297	55.8704	2.1879
80.257	38.7504	-20.5966	1.5178	-0.8066	-27.9887	43.8911	1.7188
100.402	31.5901	-22.5054	1.2292	-0.8812	-35.6393	38.6231	1.3123
201.615	16.5455	-19.4906	0.6478	-0.7633	-49.6791	25.5650	1.0011
402.576	7.9485	-13.1213	0.5113	-0.5138	-58.7979	15.3410	0.6008
805.009	4.2782	-7.6000	0.1675	-0.2976	-60.6283	8.7214	0.5415
1007.526	3.6688	-6.2931	0.1457	-0.2464	-59.7629	7.2845	0.2853
1515.151	5.5592	-4.0508	0.1515	-0.1589	-50.3916	3.2686	0.2063
2029.520	2.8229	-5.1213	0.1105	-0.1222	-47.8771	4.2084	0.1648

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 875.9071 1090.9680
RADIUS = 1378.3042
FIT = 2.4599

R0= 1716.2319   RINF= 51.5825

MODEL PARAMETERS - R1 = 5550.2773/FRQ
RP = 1684.6497

RHO = 0.67208E 10 OHM-CM

CP= 0.469278E-05

TAU= 12.93616MSEC   E0=1181.88794   EINF= 21.74922

FRQ	EP	EPP
1.004	0.929929E 05	0.140083E 05
2.009	0.854565E 05	0.169344E 05
4.021	0.765252E 03	0.186274E 05
8.050	0.665850E 05	0.196125E 03
10.042	0.652595E 05	0.197975E 05
20.169	0.527785E 05	0.195550E 03
40.225	0.429525E 05	0.184925E 03
80.257	0.541651E 05	0.167550E 05
100.402	0.516118E 03	0.160910E 05
201.613	0.246486E 05	0.158559E 03
402.576	0.191605E 05	0.115827E 05
805.009	0.149090E 05	0.943866E 02
1007.526	0.157641E 05	0.879401E 02
1515.151	0.119295E 05	.769576E 02
2029.520	0.107955E 05	0.696751E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 89.7714 35.8754
RADIUS = 95.9456
FIT = 1.1576

R0= 178.7581   RINF= 0.7846

MODEL PARAMETERS - R1 = 16416.9453/FRQ
RP = 177.9736

F	F-1/2	R1	XP	CP
1.0040	0.9980	2359.8872	-1195.5615	-0.1326E-05
2.0087	0.7050	2139.8452	-860.5085	-0.9208E-04
4.0212.	0.4987	1505.1824	-586.4468	-0.6749E-04
8.0295	0.3529	975.3585	-579.8451	-0.5218E-04
10.0422	0.3156	824.8989	-327.5205	-0.4859E-04
20.1694	0.2227	473.8918	-212.9669	-0.5705E-04
40.2255	0.1577	508.5551	-135.6855	-0.2960E-04
80.2568	0.1116	205.5284	-81.2527	-0.2441E-04
100.4016	0.0998	176.5287	-67.5950	-0.2345E-04
201.6129	0.0704	109.5883	-58.3949	-0.2056E-04
402.5764	0.0498	62.6188	-21.5471	-0.1855E-04
805.0090	0.0352	30.5905	-12.0024	-0.1647E-04
1007.3262	0.0515	25.4178	-9.9496	-0.1588E-04
1515.1514	0.0256	15.5512	-7.4479	-0.1410E-04
2029.5200	0.0221	9.0077	-5.9746	-0.1313E-04

G= 0.40225E 04 N= 0.73464E 00
*********** STOP ***********

Table 6-16. Computer Output for Electric and Dielectric Data of Basalt Sample K_2 Pretreated in 5% NaOH for 23 Hours

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ENTER NS,ADD PUT SSW1 UP FOR ELECTRODE CORRECTION
007.06184

K2 9/28/71 5PC ADD= 0.06184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
1.003	-58.6750	57.5107	-3.6285	3.5565	135.5841	82.1599	5.0808
2.017	-26.9062	63.1087	-1.6639	3.9026	113.0991	68.6050	4.2425
4.029	9.2421	54.6287	0.5715	3.3782	80.4035	55.4050	3.4262
8.045	35.9742	31.8358	2.2246	1.9687	41.5107	48.0301	2.9707
10.002.	40.2682	23.9611	2.4902	1.4818	30.7565	45.8579	2.8977
20.129	43.2346	2.6133	2.6736	0.1616	3.4593	4[illegible].3136	2.6785
40.225	35.9017	-11.8715	2.2202	-0.7341	-18.2987	37.8135	2.3384
80.257	23.7954	-17.1684	1.4715	-1.0617	-35.8131	29.3423	1.8145
100.705	19.6201	-16.9979	1.2133	-1.0512	-40.9071	25.9592	1.6053
201.342	10.0314	-13.3597	0.6203	-0.8262	-53.1021	16.7066	1.0331
401.929	5.0108	-8.6320	0.3099	-0.5338	-59.8695	9.9810	0.6172
805.009	2.7789	-4.9539	0.1718	-0.3064	-60.7147	5.6801	0.3513
1007.320	2.4226	-4.0854	0.1498	-0.2526	-59.3365	4.7497	0.2937
1512.288	2.1869	-2.6422	0.1352.	-0.1634	-50.3896	3.4298	0.2121
2018.349	1.8420	-2.0604	0.1139	-0.1274	-48.2071	2.7637	0.1709

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 292.4046 301.6920
RADIUS = 407.3560
FIT = 4.7200

R0= 566.1212 RINF= 18.6080

MODEL PARAMETERS - R1 = 5695.1484/FRQ
RP = 547.4332

RHO = 0.35009E 10 OHM-CM

CP= 0.831733E-05

TAU= 6.77622MSEC E0= 662.54065 EINF= 21.87085

FRQ	EP	EPP
1.003	0.565852E 03	0.705828E 02
2.017	0.531279E 03	0.867885E 02
4.029	0.487812E 03	0.102378E 03
8.045	0.435413E 03	0.115129E 03
10.002	0.417345E 03	0.118144E 03
20.129	0.356067E 03	0.123474E 03
40.225	0.294257E 03	0.121426E 03
80.257	0.236368E 03	0.112613E 03
100.705	0.218851E 03	0.108548E 03
201.342	0.171212E 03	0.938731E 02
401.929	0.132973E 03	0.777892E 02
805.009	0.103339E 03	0.622100E 02
1007.320	0.954363E 02	0.575296E 02
1512.288	0.829145E 02	0.496109E 02
2018.349	0.752828E 02.	0.444619E 02.

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 148.3072 62.1715
RADIUS = 159.8824
FIT = 1.3765

R0= 295.6066 RINF= 1.0078

MODEL PARAMETERS - R1 = 11225.9102/FRQ
RP = 294.5987

F	F-1/2	R1	XP	CP
1.0027	0.9986	2029.2983	-980.7141	-0.1618E-03
2.0173	0.7041	1877.2017	-671.1392	-0.1176E-03
4.0293	0.4982	1065.8247	-439.7712	-0.8982E-04
8.0451	0.3526	642.1090	-279.4643	-0.7079E-04
10.0020	0.3162	539.8024	-240.3228	-0.6621E-04
20.1288	0.2229	313.6195	-152.0536	-0.5200E-04
40.2253	0.1577	206.6049	-94.1823	-0.4201E-04
80.2568	0.1116	139.6487	-55.8460	-0.3551E-04
100.7049	0.0996	120.7985	-46.4138	-0.3405E-04
201.3423	0.0704	76.4019	-26.8541	-0.2944E-04
01.9293	0.0498	44.5304	-15.0485	-0.2631E-04
805.0090	0.0352	22.9930	-8.2768	-0.2389E-04
1007.3262	0.0315	17.7110	-6.7862	-0.2328E-04
1512.2876	0.0257	10.9527	-4.8815	-0.2156E-04
2018.3486	0.0222	7.1653	-3.7649	-0.2095E-04

G= 0.29328E 04 N= 0.73460E 00
*********** STOP ***********

Table 6-17. Computer Output for Electric and Dielectric Data of Basalt Sample K_4 Pretreated in 5% NaOH for 23 Hours

ENTER NS,ADD PUT SSW1 UP FOR ELECTRODE CORRECTION
088.12317

K4 9/20/71 3PC ADD= 0.12317 PHASE AND AMPLITUDE CORRECTED

FRQ	R3	XS	RADD	XADD	PH1	Z	ZADD
1.007	-11.1869	23.8777	-1.3779	3.1874	113.3871	28.1923	3.4724
2.012	6.4092	24.0411	0.7894	3.0397	73.3383	23.6346	3.1399
4.023	20.3482	17.6013	2.3309	2.1679	40.3839	27.0361	3.3323
8.036	27.4643	3.8038	3.3828	0.7149	11.9332	28.0709	3.4373
10.044	27.3324	2.4336	3.3936	0.3000	3.0321	27.6398	3.4069
20.137	24.3600	-3.3920	3.0004	-0.6641	-12.4819	24.9496	3.0730
40.290	18.3064	-9.9308	2.2348	-1.2232	-28.4810	20.8263	2.3632.
80.386	11.2623	-10.3699	1.3872	-1.2773	-42.6409	13.3093	1.8836
100.604	9.2219	-9.6970	1.1339	1.1944	-46.4420	13.3819	1.6482
201.884	4.0404	-7.1321	0.3962	-0.8809	-33.9149	8.6361	1.0637
402.376	2.3009	-4.4766	0.3000	-0.3314	-60.8136	3.1278	0.6316
809.333	1.4196	-2.3434	0.1749	-0.3133	-60.8334	2.9143	0.3390
1011.030	1.2394	-2.0973	0.1331	-0.2383	-39.0199	2.4463	0.3013
1313.131	1.1229	-1.3360	0.1383	-0.1670	30.3769	1.7606	0.2168
2033.272	0.9400	-1.0701	0.1168	-0.1318	-48.4673	1.4296	0.1761

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 10.6066 9.9038
RADIUS = 17.8203
FIT = 19.4934

R0= 23.4204 RINF= -4.2071

MODEL PARAMETERS - R1 = 7409.3781/FRQ
RP = 29.6273

RHO = 0.31310E 09 OHM-CM

CP= 0.113070E-04

TAU= 0.41012MSEC E0= -89.42863 EINF= 14.80070

FRQ	EP	EPP
1.007	-0.873324E 02	-0.204368E 01
2.012	-0.862493E 02	-0.310231E 01
4.023	-0.843742E 02.	-0.467403E 01
8.036	-0.820664E 02	-0.694610E 01
10.044	-0.810223E 02	-0.786209E 01
20.137	-0.768130E 02	-0.113713E 02.
40.290	-0.708391E 02	-0.130343E 02
80.386	-0.627614E 02	-0.208283E 02
100.604	-0.396619E 02	-0.224093E 02.
201.884	-0.407320E 02	-0.264094E 02
402.376	-0.366619E 02	-0.270393E 02
809.333	-0.243302E 02	-0.260473E 02
1011.030	-0.209072E 02	-8.248943E 02
1313.131	-0.147940E 02	-0.223268E 02
2033.272.	-0.107934E 02	-0.202369E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 138.6480 70.6484
RADIUS = 173.7294
FIT = 0.3396

R0= 317.3637 RINF= -0.0677

MODEL PARAMETERS - R1 = 7408.2031/FRQ
RP = 317.4313

F	F-1/2	R1	XP	CP
1.0073	0.9964	1396.2349	-713.8491	-0.2207E-03
2.0122	0.7030	1131.0634	-478.8938	-0.1632E-03
4.0248	0.4983	687.4030	-306.6374	-0.1290E-03
8.0360	0.3328	418.7403	-192.0294	-0.1031E-03
10.0442	0.3133	339.3662	-164.6832	-0.9622E-04
20.1369	0.2220	217.9398	-102.3693	-0.7721E-04
40.2901	0.1373	142.2237	-62.3217	-0.6339E-04
80.3839	0.1113	92.1638	-36.9969	-0.3332E-04
100.6036	0.0997	79.2181	-30.7379	-0.3144E-04
201.8842	0.0703	46.8037	-17.6424	-0.4469E-04
402.5764	0.0498	24.9922	-10.0818	-0.3921E-04
809.3323	0.0331	11.3314	-3.8776	-0.3346E-04
1011.0293	0.0314	8.7587	-4.9384	-0.3188E-04
1313.1314	0.0236	3.8049	-3.8378	-0.2723E-04
2033.2720	0.0221	3.6838	-3.3679	-0.2324E-04

G= 0.21394E 04 N= 0.77879E 00
*********** STOP ***********

Table 6-18. Computer Output for Electric and Dielectric Data of Basalt Sample K_1 Pretreated in 10% NaOH for 23 Hours

ENTER NS,AOD   PUT S5W1 UP FOR ELECTRODE CORRECTION
089.05916

K1 9/29/71 10PC   AOD= 0.05916   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.000	59.4852.	6.9506	2.5294	0.2722	6.6651	59.8899	2.3453
2.010	41.5985	18.1095	1.6290	0.7092	23.5272	45.3693	1.7767
4.018	46.4519	21.7561	1.8185	0.8520	25.1077	51.2762	2.0000
8.026	56.5688	16.7120	2.2152	0.6544	16.4598	58.9058	[illegible]
10.058	58.2242	13.5717	2.2801	0.3315	13.1220	59.7850	[illegible]
20.155	60.9485	0.0402	2.3867	0.0013	0.0378	60.9483	2.3867
40.258	55.6060	-15.9153	2.1775	-0.6252	-15.9712	57.8383	2.2649
80.257	40.5458	-25.3645	1.5877	-0.9953	-32.0527	47.8243	1.8728
100.402.	55.5752	-25.8068	1.5069	-1.0106	-37.7168	42.1872	1.6521
202.156	17.0245	-21.6903	0.6667	-0.8494	-51.8757	87.3736	[illegible]
403.877	8.1538	-14.1124	0.5195	-0.5526	-59.9862	16.2986	0.6383
806.452	4.6554	-7.8564	0.1815	-0.5077	-59.4671	9.1219	0.3578
1005.484	5.8574	-6.5246	0.1503	-0.2555	-59.5426	7.5694	0.2964
1518.027	3.2261	2.6455	0.1265	0.1036	59.3558	4.1722	0.1634
2029.520	2.9661	-5.1608	0.1162	-0.1258	-46.8235	4.5545	0.1697

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 51.8487 -0.4295
RADIUS = 27.5527
FIT = 8.0840

R0= 59.5980   RINF= 4.2994

MODEL PARAMETERS - R1 =216537.6875/FRQ
RP = 55.0986

RHO = 0.25260E 09 OHM-CM

CP= 0.777601E-05

TAU= 0.42850MSEC   E0= 287.57928   EINF= 20.81576

FRQ	EP	EPP
1.000	0.286820E 05	0.761711E 00
2.010	0.286068E 05	0.151966E 01
4.018	0.284595E 05	0.501654E 01
8.026	0.281724E 05	0.597985E 01
10.058	0.280297E 05	0.747412E 01
20.155	0.273470E 05	0.148250E 02
40.258	0.260972E 05	0.290966E 02
80.257	0.259588E 05	0.554675E 02
100.402	0.250255E 03	0.674112E 02
202.156	0.193195E 03	0.110905E 05
405.877	0.148671E 05	0.150874E 03
806.452.	0.105578E 05	0.100658E 05
1005.484	0.952951E 02	0.864701E 02
1518.027	0.758451E 02	0.618956E 02
2019.520	0.626757E 02	0.477162E 02

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 75.9658 42.4923
RADIUS = 88.0760
FIT = 1.6498

R0= 155.1117   RINF= -1.1841

MODEL PARAMETERS - R1 = 13460.5059/FRQ
RP = 154.2958

F	F-1/2	R1	XP	CP
1.0005	0.9999	2711.5076	-1151.9424	-0.1581E-05
2.0097	0.7054	1641.2422	-858.9255	-0.9440E-04
4.0177	0.4989	1054.4907	-573.8958	-0.6903E-04
8.0257	0.5550	667.6863	-574.6154	-0.5294E-04
10.0585	0.5155	585.9577	-522.9716	-0.4899E-04
20.1552.	0.2228	558.5120	-21[illegible].9011	-0.5745E-04
40.2576	0.1576	247.5275	-154.5008	-0.2959E-04
80.2568	0.1116	169.1596	-82.7553	-0.2596E-04
100.4016	0.0998	145.6857	-68.9052	-0.2501E-04
202.1564	0.0705	90.7404	-39.8980	-0.1973E-04
405.8772	0.0497	49.0474	-23.1757	-0.1700E-04
806.4517	0.0552	22.8451	-14.0806	-0.1402E-04
1005.4844	0.0515	17.9178	-12.1758	-0.1500E-04
1518.0269	0.0256	11.5225	-10.5571	-0.1014E-04
2029.5200	0.0221	8.2850	-9.6710	-0.8109E-05

G= 0.52225E 04 N= 0.75407E 00
*********** STOP ***********

Table 6-19. Computer Output for Electric and Dielectric Data of Basalt Sample K_2 Pretreated in 10% NaOH for 23 Hours

ENTER NS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
Ø9Ø.Ø6184

K2 9/29/71 1ØPC ADD= Ø.Ø6184 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZADD
1.ØØØ	6.212Ø	15.4181	Ø.5842	Ø.8298	65.16ØØ	14.7866	Ø.9144
2.Ø24	13.2251	17.4562	Ø.8178	1.Ø783	52.Ø242	21.8844	1.5533
4.Ø24	21.2575	19.1558	1.3146	1.1846	42.Ø262	28.6152	1.7696
8.Ø53	31.2877	14.29Ø8	1.954Ø	Ø.8837	24.55Ø5	34.3969	2.1271
9.99Ø	53.9513	1Ø.775Ø	2.Ø985	Ø.6662	17.6156	35.6ØØ4	2.2Ø15
2Ø.145	36.5922	Ø.ØØ66	2.2629	Ø.ØØØ4	Ø.Ø1Ø3	36.5922	2.2629
4Ø.29Ø	52.6115	-9.8252	2.Ø167	-Ø.6Ø76	-16.7677	54.Ø594	2.1Ø62
8Ø.586	25.2928	-14.9661	1.44Ø4	-Ø.9255	-52.724Ø	27.6865	1.7121
1ØØ.4Ø2	19.5Ø69	-15.1233	1.2115	-Ø.9552	-37.6749	24.7459	1.5393
2Ø2.156	1Ø.3285	-12.6937	Ø.63Ø7	-Ø.7Ø5Ø	-5Ø.Ø695	16.364Ø	1.Ø12Ø
4Ø3.226	5.256Ø	-8.3981	Ø.325Ø	-Ø.5193	-57.9655	9.9Ø73	Ø.6127
ØØ7.Ø99	5.Ø1Ø6	-4.8Ø45	Ø.1862	-Ø.2971	-57.95Ø8	5.6697	Ø.35Ø6
1Ø11.Ø5Ø	2.5Ø95	-3.9951	Ø.1552	-Ø.2469	-57.8589	4.7161	Ø.2916
1518.Ø27	2.Ø795	-2.7915	Ø.1286	-Ø.1726	-53.32Ø2	5.48Ø6	Ø.2152
2Ø57.Ø37	1.9898	-1.951Ø	Ø.125Ø	-Ø.1194	-44.1447	2.7727	Ø.1715

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 19.1747 1.7855
RADIUS = 17.3574
FIT = 1.64Ø8

RØ= 56.44ØØ RINF= 1.9Ø95

MODEL PARAMETERS - R1 = 55Ø88.8125/FRQ
RP = 34.53Ø7

RHO = Ø.22555E Ø9 OHM-CM

CP= Ø.314665E-Ø4

TAU= 1.Ø9255MSEC EØ=1Ø45.56743 EINF= 54.77335

FRQ	EP	EPP
1.ØØØ	Ø.1Ø56Ø8E Ø4	Ø.955844E Ø1
2.Ø24	Ø.1Ø2757E Ø4	Ø.18Ø5ØØE Ø2
4.Ø24	Ø.1Ø12Ø8E Ø4	Ø.541495E Ø2
8.Ø55	Ø.985715E Ø5	Ø.6453Ø6E Ø2
9.99Ø	Ø.97Ø823E Ø5	Ø.786958E Ø2
2Ø.145	Ø.911Ø84E Ø3	Ø.146728E Ø3
4Ø.29Ø	Ø.816773E Ø5	Ø.257235E Ø5
ØØ.386	Ø.684589E Ø5	Ø.39Ø6Ø4E Ø5
1ØØ.4Ø2	Ø.6556Ø5E Ø5	Ø.425246E Ø5
2Ø2.156	Ø.474686E Ø5	Ø.42859ØE Ø5
4Ø5.226	Ø.35Ø54ØE Ø5	Ø.5Ø9787E Ø5
ØØ7.899	Ø.22Ø62ØE Ø5	Ø.18575ØE Ø3
1Ø11.Ø5Ø	Ø.195625E Ø5	Ø.152Ø54E Ø5
1518.Ø27	Ø.154113E Ø3	Ø.1Ø65Ø7E Ø3
2Ø37.Ø57	Ø.152Ø91E Ø3	Ø.Ø17719E Ø2

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 62.9858 19.9821
RADIUS = 64.4255
FIT = 4.8657

RØ= 124.2519 RINF= 1.7597

MODEL PARAMETERS - R1 = 1Ø626.582Ø/FRQ
RP = 122.4922

F	F-1/2	R1	XP	CP
1.ØØØ1	Ø.9999	6Ø8.8Ø57	-67Ø.459Ø	-Ø.2574E-Ø5
2.Ø245	Ø.7Ø28	2265.1558	-496.1249	-Ø.1585E-Ø3
4.Ø258	Ø.4985	14Ø2.4895	-538.258Ø	-Ø.1169E-Ø5
8.Ø354	Ø.5528	757.4973	-22Ø.5851	-Ø.899ØE-Ø4
9.99ØØ	Ø.5164	654.99Ø6	-192.Ø256	-Ø.8297E-Ø4
2Ø.145Ø	Ø.2228	358.7Ø12	-125.484Ø	-Ø.6398E-Ø4
4Ø.29Ø1	Ø.1575	2Ø2.8852.	-77.3645	-Ø.51Ø6E-Ø4
8Ø.5859	Ø.1115	13Ø.2266	-46.865Ø	-Ø.4225E-Ø4
1ØØ.4Ø16	Ø.Ø998	11Ø.1134	-59.6155	-Ø.4ØØ2E-Ø4
2Ø2.1564	Ø.Ø7Ø3	7Ø.6751	-23.Ø775	-Ø.5412E-Ø4
4Ø5.2258	Ø.Ø498	45.6954	-15.Ø775	-Ø.3Ø18E-Ø4
8Ø7.Ø994	Ø.Ø351	26.8472	-7.Ø727	-Ø.2785E-Ø4
1Ø11.Ø295	Ø.Ø314	22.7199	-5.7318	-Ø.2746E-Ø4
1518.Ø269	Ø.Ø256	14.984Ø	-3.9569	-Ø.265ØE-Ø4
2Ø37.Ø571	Ø.Ø221	1Ø.6717	-2.8797	-Ø.2713E-Ø4

G= Ø.25459E Ø4 N= Ø.66952E ØØ
*********** STOP ***********

Table 6-20. Computer Output for Electric and Dielectric Data of Basalt Sample K_4 Pretreated in 10% NaOH for 23 Hours

ENTER NS,AUD   PUT SSW1 UP FOR ELECTRODE CORRECTION
Ø91.12317

K4 9/29/71 1ØPC   ADD= Ø.12317   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XADD	PHI	Z	ZADD
1.ØØ1	-9.9475	1Ø.622Ø	-1.2232	1.3Ø83	133.1316	14.3327	1.7923
2.Ø16	Ø.3441	11.2683	Ø.Ø423	1.3879	88.2373	11.2733	1.3886
4.Ø32	7.1366	11.9394	Ø.8813	1.47Ø6	39.Ø634	13.92ØØ	1.7143
8.Ø39	13.7Ø39	8.7Ø49	1.6879	1.Ø722	32.4263	16.2349	1.9997
1Ø.Ø42	13.8Ø34	6.3483	1.9468	Ø.7819	21.8843	17.Ø327	2.Ø979
2Ø.129	17.3382	-Ø.Ø438	2.16Ø2	-Ø.ØØ33	-Ø.1431	17.3383	2.16Ø2
4Ø.238	13.2932	-4.7833	1.Ø839	-Ø.3892	-17.3673	16.Ø237	1.9739
8Ø.313	1Ø.6617	-7.1398	1.3132	-Ø.8794	-33.8114	12.8313	1.38Ø3
1ØØ.3Ø3	9.1638	-7.Ø432	1.1287	-Ø.8673	-37.3483	11.3378	1.4236
2Ø1.613	4.99Ø4	-3.9232	Ø.6147	-Ø.7296	-49.8888	7.7432	Ø.934Ø
4Ø2.376	2.6843	-3.9796	Ø.33Ø6	-Ø.49Ø2	-36.ØØ34	4.8ØØ3	Ø.3912
8Ø7.Ø99	1.3431	-2.3423	Ø.19Ø1	-Ø.2883	-36.6267	2.8Ø49	Ø.3433
1Ø11.Ø3Ø	1.2926	-1.9494	Ø.1392	-Ø.24Ø1	-36.4378	2.339Ø	Ø.2881
132Ø.913	1.Ø391	-1.3612	Ø.13Ø4	-Ø.1677	-32.1184	1.7247	Ø.2124
2Ø22.Ø39	1.Ø466	-Ø.939Ø	Ø.1289	-Ø.1137	-41.899Ø	1.4Ø61	Ø.1732.

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 21.9436 39.Ø331
RADIUS = 42.Ø324
FIT = 14.4431

RØ= 37.4883   R1NF= 6.4Ø27

MUUEL PARAMETERS - R1 = 2733.7339/FRQ
RP = 31.Ø838

RHU = Ø.46173E Ø9 UHM-CM

CP= Ø.2Ø3112E-Ø4

TAU= 1.7Ø743MSEC   EØ= 244.64394   E1NF= 41.78333

FRQ	EP	EPP
1.ØØ1	Ø.2Ø9413E Ø3	Ø.144887E Ø2
2.Ø16	Ø.2Ø2122E Ø3	Ø.137Ø84E Ø2
4.Ø32	Ø.193723E Ø3	Ø.1682Ø4E Ø2
8.Ø39	Ø.184188E Ø3	Ø.177835E Ø2
1Ø.Ø42	Ø.18Ø877E Ø3	Ø.18Ø388E Ø2
2Ø.129	Ø.169867E Ø3	Ø.1877Ø3E Ø2
4Ø.238	Ø.138ØØ6E Ø3	Ø.192376E Ø2
8Ø.313	Ø.143829E Ø3	Ø.194364E Ø2
1ØØ.3Ø3	Ø.141871E Ø3	Ø.194411E Ø2
2Ø1.613	Ø.129334E Ø3	Ø.192694E Ø2
4Ø2.376	Ø.117717E Ø3	Ø.18829ØE Ø2
8Ø7.Ø99	Ø.1Ø6393E Ø3	Ø.181388E Ø2
1Ø11.Ø3Ø	Ø.1Ø3224E Ø3	Ø.178697E Ø2
132Ø.913	Ø.9738ØØE Ø2	Ø.173286E Ø2
2Ø22.Ø39	Ø.933395E Ø2	Ø.169162E Ø2

DET. G,N FUR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 76.9643 3Ø.4Ø73
RADIUS = 82.2643
FIT = Ø.8112

RØ= 133.4Ø27   R1NF= Ø.5263

MOUEL PARAMETERS - R1 = 6763.3839/FRQ
RP = 132.8764

F	F-1/2	R1	XP	CP
1.ØØ1Ø	Ø.9993	1279.7668	-37Ø.9148	-Ø.2783E-Ø3
2.Ø162	Ø.7Ø43	983.9623	-388.Ø86Ø	-Ø.2Ø34E-Ø3
4.Ø316	Ø.498Ø	679.4182	-236.1473	-Ø.1341E-Ø3
8.Ø386	Ø.3327	411.3693	-163.1936	-Ø.1213E-Ø3
1Ø.Ø422	Ø.3136	347.7717	-14Ø.3596	-Ø.1129E-Ø3
2Ø.1288	Ø.2229	199.3332	-87.6288	-Ø.9Ø23E-Ø4
4Ø.2376	Ø.1376	129.12Ø1	-33.9399	-Ø.7329E-Ø4
8Ø.5133	Ø.1114	83.8437	-32.3Ø43	-Ø.6119E-Ø4
1ØØ.3Ø23	Ø.Ø997	72.778Ø	-26.9Ø71	-Ø.3886E-Ø4
2Ø1.6129	Ø.Ø7Ø4	44.327Ø	-13.3819	-Ø.3Ø66E-Ø4
4Ø2.3764	.Ø498	23.4143	-8.7877	-Ø.4499E-Ø4
8Ø7.8994	Ø.Ø331	12.9489	-4.8648	-Ø.4Ø3ØE-Ø4
1Ø11.Ø293	Ø.Ø314	9.9692	-4.Ø292	-Ø.39Ø7E-Ø4
132Ø.9126	Ø.Ø236	3.9Ø26	-2.9726	-Ø.332ØE-Ø4
2Ø22.Ø391	Ø.Ø222	4.4384	-2.2127	-Ø.3557E-Ø4

G= Ø.1831ØE Ø4 N= Ø.74494E ØØ
*********** STOP ***********

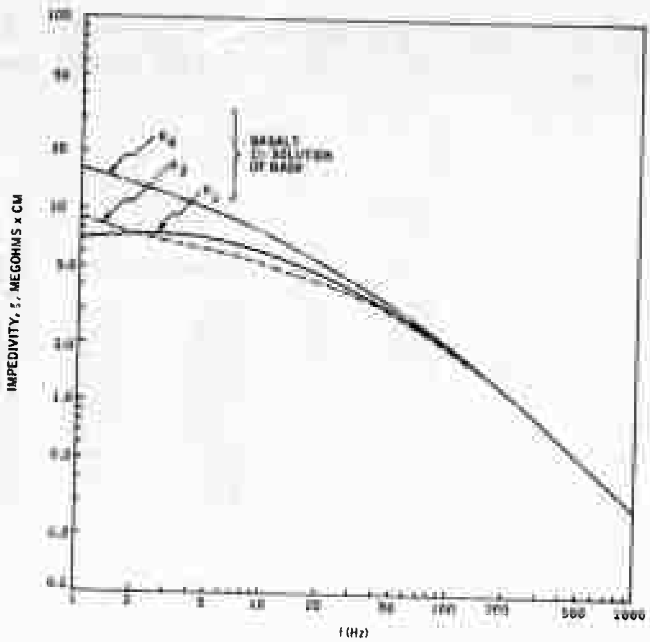


Figure 6-5. Variation of Impedivity with Frequency for the Basalt Samples after 23-hour Pretreatment in 1% NaOH

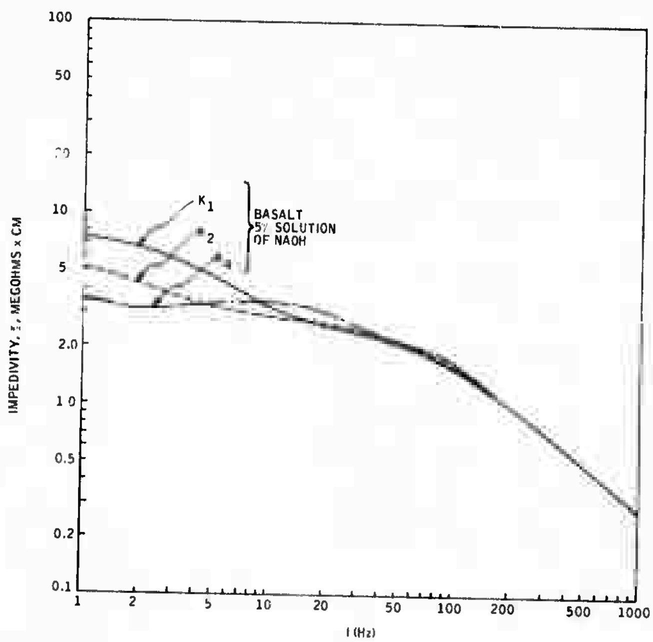


Figure 6-6. Variation of Impedivity with Frequency for Basalt Samples Following a 23-hour Pretreatment in 5% NaOH

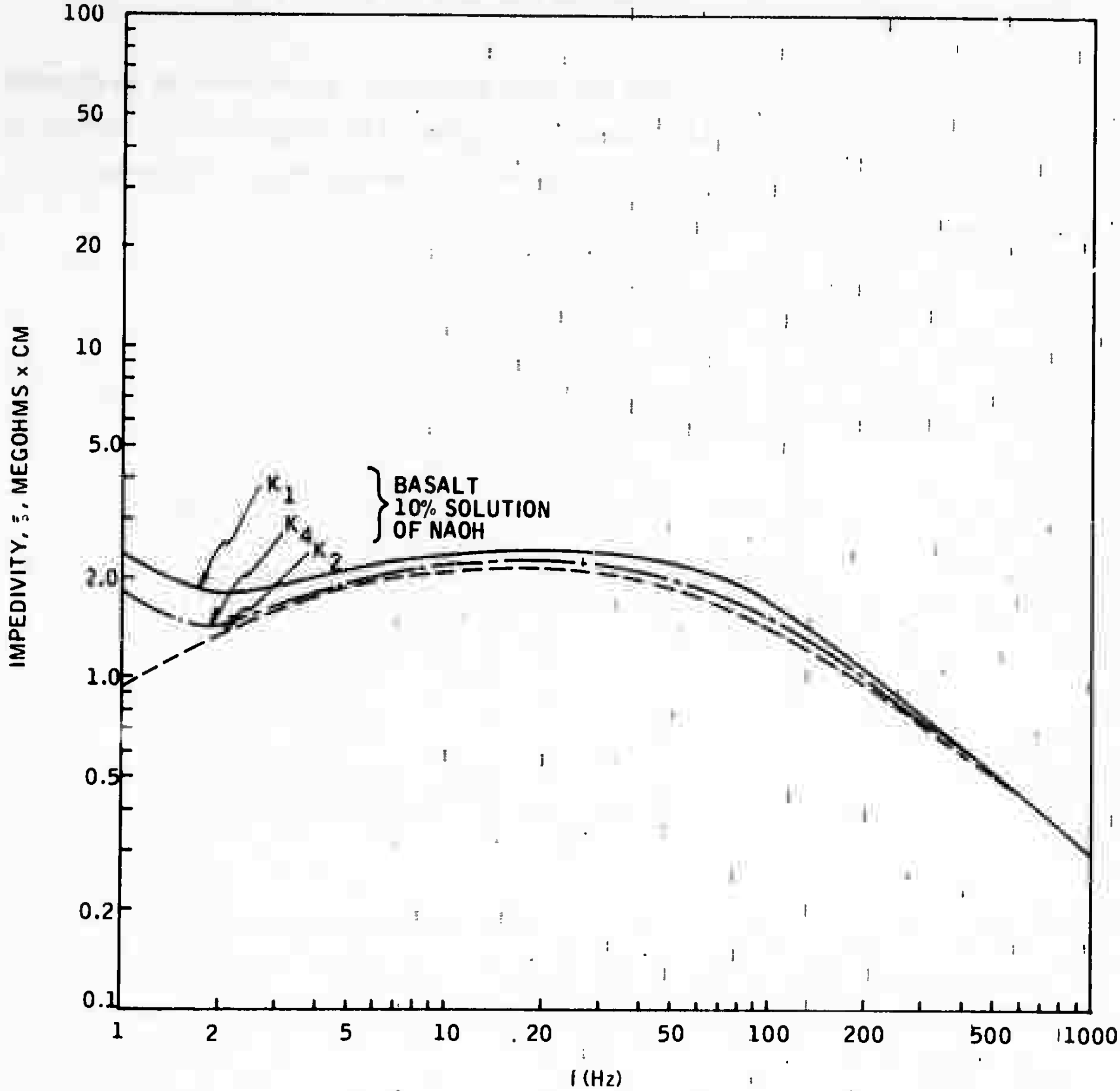


Figure 6-7. Variation of Impedivity with Frequency for Basalt Samples Following a 23-hour Pretreatment in 10% NaOH

The effect of sodium hydroxide concentration on the impeditivity at 1 Hz for the three basaltic rocks is shown by the data in Table 6-21.

The plot of impeditivity against the concentration, c, of sodium hydroxide in the pretreating solution is shown in Figure 6-8. Apparently, impeditivity decreases exponentially with the electrolyte concentration following an equation of the form

$$\xi = \xi_o e^{-\lambda c}$$

Table 6-21. Effect of Pretreatment in NaOH for 23 Hours

Conc. of NaOH	Impeditivity at 1 Hz, Megohm cm		
	K_1	K_2	K_4
0	11.0	19.0	27.0
1	7.0	9.0	16.5
5	7.4	5.0	3.5
10	2.4	0.9	1.8

The plots of log ξ against c for the three basalt cylindrical rocks are shown in Figure 6-9. The slopes of the lines in this figure allow a determination of the constant λ for each cylindrical rock. Table 6-22 gives these straight-line parameters.

It is interesting to note from these limited number of data points that the coefficient λ decreases linearly with increasing rock length, providing that the rocks are of the same cross sectional area. The variation of λ with d is shown in Figure 6-10 and indicates a significant dependence of the rock impeditivity decay constant due to electrolyte impregnation with the length of the rock samples.

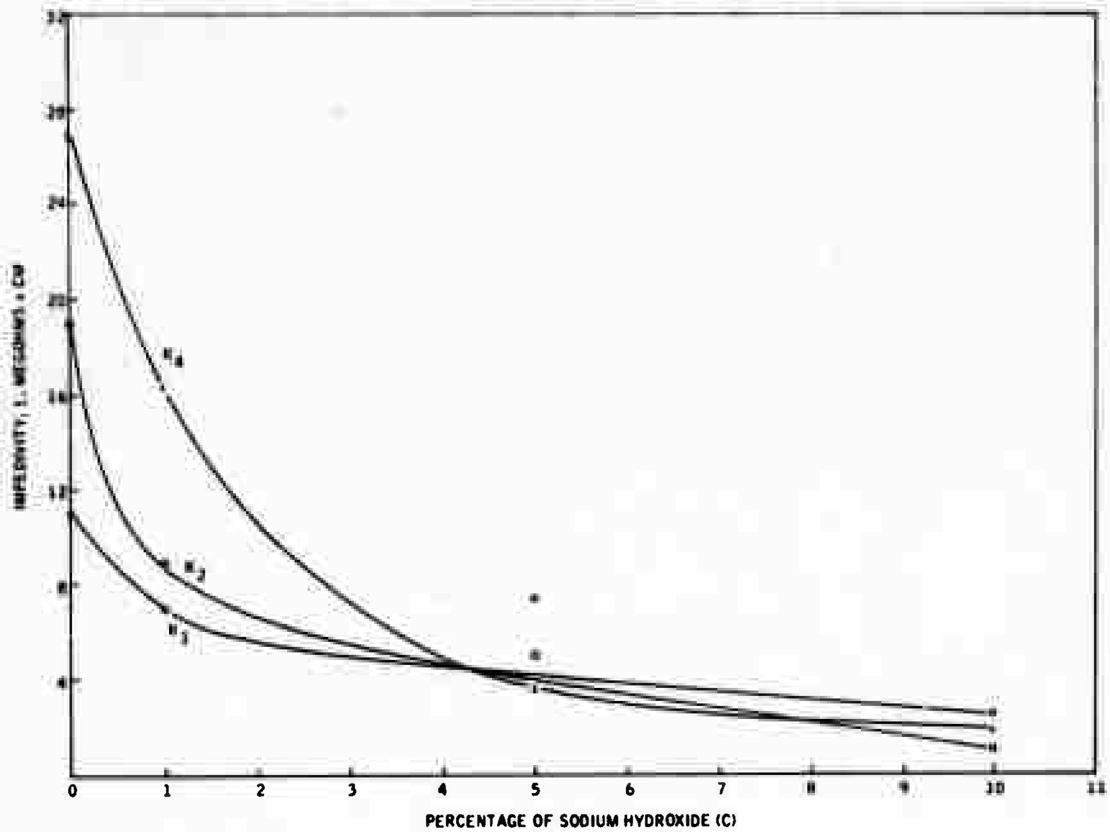


Figure 6-8. Variation of Impedivity with Sodium Hydroxide Concentration in the Pretreating Solution

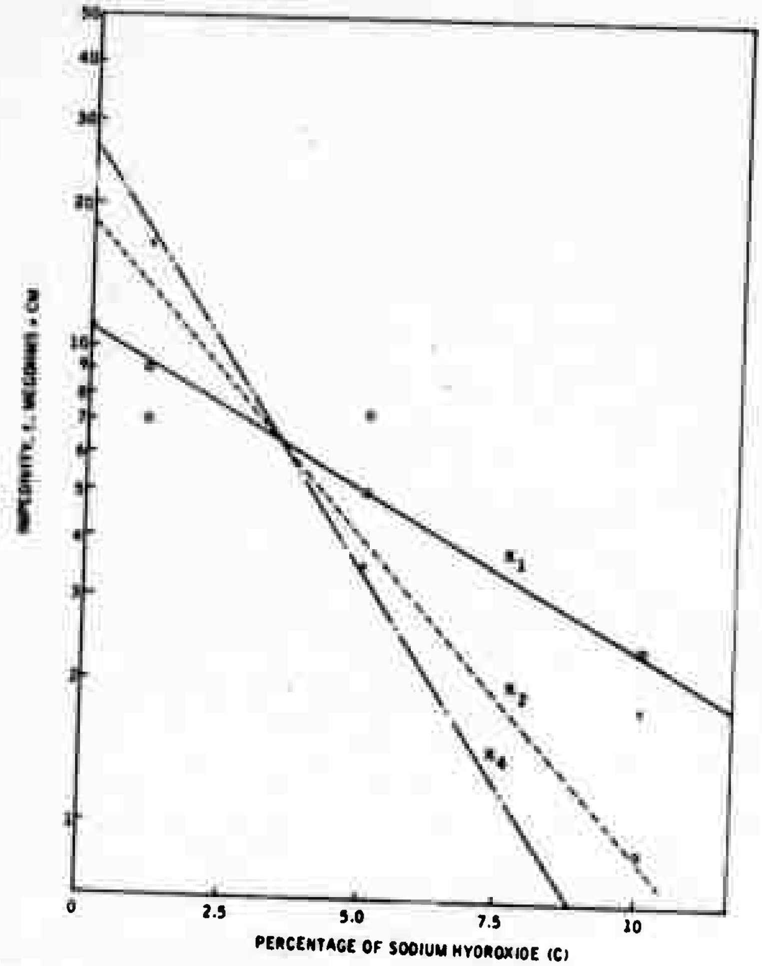


Figure 6-9. Semilogarithmic Plot of Basalt Impedivity with Concentration of Sodium Hydroxide in the Pretreating Solution

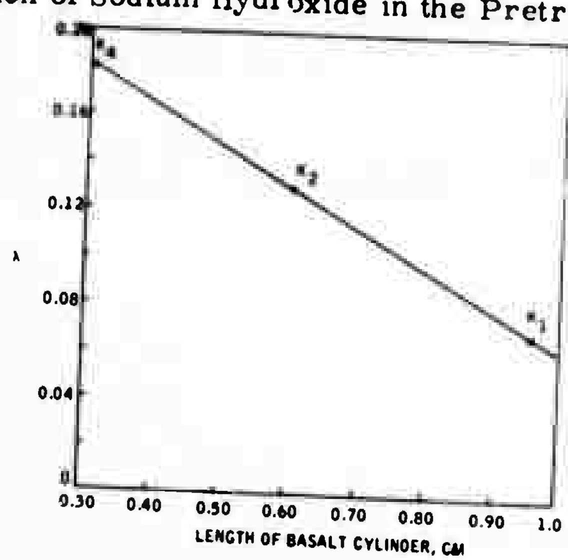


Figure 6-10. Variation of Parameter λ with Rock Thickness

Table 6-22. Exponential Decrease of Impeditivity with Electrolyte Concentration

Length of Rock Cylinder, d, cm	ξ_o(megohm)(cm)	λ(ml. gm^{-1})
0.956	11	0.07
0.605	19	0.13
0.304	27	0.18

EFFECT OF WATER SOAKING ON QUARTZ ELECTRIC PARAMETERS

Three quartz (II) disc samples were cut from one cylinder with lengths 0.31, 0.61, and 0.92 cm and are designated M1, M2, and M3, respectively. These samples had a cross sectional area over length (A/d) ratio of 0.122, 0.061, and 0.041 meter, respectively. The samples were pretreated in distilled water, once for 24 hours and another time for 75 hours. After each pretreatment, the rock was dried in an 80°C oven for two hours before the electrodes were applied and measurements were taken. Computer output data pertaining to the untreated and water-treated quartz are shown in Tables 6-23 to 6-31.

The variation of the untreated quartz impeditivity with frequency is shown in Figure 6-11. Following a 24-hour soak, the same quartz samples gave the impeditivity frequency relationships shown in Figure 6-12. When the soaking time was prolonged to 75 hours, the quartz impeditivity changed with frequency according to the curves of Figure 6-13.

Table 6-23. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_1

ENTER RS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
010.12219

M1 1/19/72 AOD= 0.12219 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZADD
9.990	140.7771	-1021.3215	18.1791	-124.7953	-81.7180	1032.1008	126.1124
20.050	153.0709	-559.1614	18.7770	-68.3239	-74.6386	579.8932	70.8571
40.064	63.9872	-326.9099	7.8186	-39.9451	-78.9311	333.1132	40.7031
80.000	22.3478	-177.5770	2.7307	-21.6981	-82.8332	178.9777	21.8693
99.900	7.4529	-141.1557	0.9107	-17.2478	-86.9841	141.3524	17.7718
200.535	5.6384	-70.8661	0.6890	-8.6591	-85.4572	71.0901	8.6865
400.641	4.1794	-34.7135	0.5107	-4.2416	-83.1410	34.9642	4.2723
805.009	3.9071	-16.9568	0.4774	-2.0720	-77.0304	17.4011	2.1262
1001.822	4.0005	-13.4710	0.4962	-1.6460	-73.2312	14.0697	1.7192

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 3426.6367 84.7719
RADIUS = 3413.4722
FIT = 0.9484

R0= 6839.0557 RINF= 14.2173

MODEL PARAMETERS - R1 =205878.000/FRQ
RP = 6824.8379

RMD = 0.83566E 11 OHM-CM

CP= 0.987824E-05

TAU= 67.43820MSEC E0=4306.42285 EINP= 9.11866

FRQ	EP	EPP
9.990	0.860028E 03	0.987557E 03
20.050	0.484019E 03	0.521772E 03
40.064	0.203072E 03	0.207748E 03
80.000	0.141485E 03	0.136149E 03
99.900	0.110126E 03	0.109483E 03
200.535	0.636786E 02	0.552051E 02
400.641	0.360991E 02	0.279481E 02
805.009	0.231424E 02	0.140663E 02
1001.822	0.204332E 02	0.113425E 02

DET. G,H FOR R1=G/F**H

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 3426.6367 84.7719
RADIUS = 3413.4722
FIT = 0.9484

R0= 6839.0557 RINF= 14.2173

MODEL PARAMETERS - R1 =205878.000/FRQ
RP = 6824.8379

```
        F            F-1/2         R1          XP         CP
     9.9960        0.3163-51493.0516 -1039.0498 -0.1532E-04
************ LOG  ************
```

Table 6-24. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_2

```
ENTER RS,AOD    PUT SSW1 UP FOR ELECTRODE CORRECTION
011.00154

      M2 1/19/72                    AOD=  0.06134    PHASE AND AMPLITUDE CORRECTED
```

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOO
9.976	154.5559	-1557.6934	9.4791	-83.2809	-83.5126	1366.4600	83.8186
20.096	230.1590	-740.5276	14.1167	-45.7797	-72.8676	781.0050	47.9068
40.161	87.0060	-452.8390	5.3569	-27.7771	-79.1299	461.1217	28.2852
100.000	52.5557	-194.3854	1.9846	-11.9236	-80.5562	197.0596	12.0876
202.705	6.4922	-95.7117	0.3982	-5.3710	-86.1259	95.9516	5.8844
402.570	4.9299	-47.0478	0.5024	-2.8859	-84.0243	47.5054	2.9017
805.572	5.0175	-22.7543	0.3078	-1.5945	-77.5605	25.2814	1.4281
1001.822	5.0558	-18.0180	0.5089	-1.1052	-74.3905	18.7085	1.1476

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 6167.8789  286.3789
                                  RADIUS = 6155.5809
                                  FIT    =     0.8996

R0= 12514.5918            RINF=    21.1660

MODEL PARAMETERS -    R1 =123120.562/FRQ
                      RP = 12293.4258

 RHO = 0.75558E 11 OHM-CM

CP= 0.69585OE-05

TAU=  65.63655MSEC             E0=7453.05516              EINF=  12.81009
```

FRQ	EP	EPP
9.976	0.123041E 04	0.137741E 04
20.096	0.683997E 05	0.725779E 05
40.161	0.371454E 05	0.574021E 05
100.000	0.105047E 03	0.155081E 05
202.703	0.905080E 02	0.782269E 02
402.576	0.528552E 02	0.402200E 02
805.572	0.535304E 02	0.205722E 02
1001.822	0.295871E 02	0.166103E 02

```
DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 6167.8789  286.3789
                                  RADIUS = 6153.3809
                                  FIT    =     0.8996

R0= 12314.5918            RINF=    21.1660

MODEL PARAMETERS -    R1 =123120.562/FRQ
                      RP = 12295.4258

        F          F-1/2          R1             XP          CP
      9.9761     0.3166104775.559 -1370.7942 -[illegible].1164E-04
*********** LOG  ***********
```

Table 6-25. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_3

```
ENTER RS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION
Ø12.Ø4Ø62

        M3 1/19/72                 AOD=  Ø.Ø4Ø62      PHASE AND AMPLITUDE CORRECTED

      FRQ        RS          XS           RAOD        XAOD        PHI          Z          ZAOD
    1Ø.Ø52    11Ø.315Ø  -1573.351Ø     4.431Ø    -63.9Ø95    -35.9956   1577.2148    64.Ø665
    2Ø.161    272.381Ø   -865.521Ø    11.Ø641    -35.1575    -72.5365    9Ø7.3689    36.8573
    4Ø.Ø96     89.1825   -54Ø.7Ø39     4.Ø288    -21.9634    -79.6115    549.7292.   22.3298
   1ØØ.ØØØ     29.1776   -233.1874     1.1852     -9.4721    -82.874Ø    235.ØØ58     9.5459
   2Ø1.613      4.585Ø   -112.897Ø     Ø.1862     -4.5859    -87.68Ø8    112.99Ø1     4.5897
   4Ø2.576      4.3589    -54.9416     Ø.1771     -2.2317    -85.47Ø2     55.1142     2.2387
   8Ø5.ØØ9      5.191Ø    -26.35Ø2     Ø.2189     -1.Ø7Ø3    -78.8613     26.8567     1.Ø9Ø9
  1ØØ1.822      5.37Ø7    -2Ø.7349     Ø.2184     -Ø.8422    -75.4686     21.42Ø6     Ø.87Ø1

RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 8785.55Ø8  299.9439
                                  RADIUS = 8764.8477
                                  FIT    =    Ø.8574

RØ= 17545.2617           RINF=   25.8379

MODEL PARAMETERS -   R1 =12Ø91Ø.218/FRQ
                     RP = 17519.4219

 RHO = Ø.71269E 11 OHM-CM

CP= Ø.574335E-Ø5

TAU= 1ØØ.6791ØMSEC           EØ=51Ø839.257              EINF=  15.96235

      FRQ         EP              EPP
    1Ø.Ø52   Ø.153822E Ø4   Ø.17Ø624E Ø4
    2Ø.161   Ø.8448Ø4E Ø3   Ø.885452E Ø3
    4Ø.Ø96   Ø.455Ø37E Ø3   Ø.455483E Ø3
   1ØØ.ØØØ   Ø.199963E Ø3   Ø.1869Ø2E Ø3
   2Ø1.613   Ø.1Ø9419E Ø3   Ø.942Ø73E Ø2
   4Ø2.576   Ø.636792E Ø2   Ø.47912ØE Ø2
   8Ø5.ØØ9   Ø.4Ø242ØE Ø2   Ø.243294E Ø2
  1ØØ1.822   Ø.355727E Ø2   Ø.196438E Ø2

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER = 8785.55Ø8  299.9439
                                  RADIUS = 8764.8477
                                  FIT    =    Ø.8574

RØ= 17545.2617          RINF=   35.8379

MODEL PARAMETERS -   R1 =12Ø91Ø.218/FRQ
                     RP = 17519.4219

        F           F-1/2        R1          XP         CP
    1Ø.Ø523     Ø.3154-4354Ø.ØØØØ -1577.8872 -Ø.1ØØ3E-Ø4
*********** LOG  ***********
```

Table 6-26. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_1 Following a 24-Hour Water Soak

ENTER RS,AOD PUT SS=1 UP FOR ELECTRODE CORRECTION
002.12219

M1 24HR AOD= 0.12219 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.002	1.6665	-0.1394	0.2036	-0.0170	-4.7631	1.6725	0.2043
2.010	1.6323	-0.0672	0.1995	-0.0106	-3.0614	1.6347	0.1997
4.033	1.5699	-0.1144	0.1937	-0.0139	-4.1303	1.5891	0.6946
8.052	1.5651	-0.1362	0.1912	-0.0166	-4.9730	1.5710	0.1920
10.034	1.5303	-0.1712	0.1870	-0.0209	-6.3820	1.3390	0.1601
20.113	1.5204	-0.1623	0.1863	-0.0198	-6.0616	1.5370	0.1676
40.017	1.4305	-0.2203	0.1748	-0.0269	-8.7344	1.4474	0.1769
80.120	1.3410	-0.2552	0.1640	-0.0311	-10.7700	1.3639	0.1669
100.200	1.2019	-0.3026	0.1566	-0.0369	-13.2030	1.3172	0.1609
201.013	1.1021	-0.3191	0.1390	-0.0389	-13.6131	1.1859	0.1449
403.220	0.9510	-0.3012	0.1102	-0.0441	-20.0007	1.0173	0.1263
807.899	0.7079	-0.2913	0.0865	-0.0336	-22.3050	0.7636	0.0935
1003.050	0.6105	-0.2456	0.0746	-0.0300	-21.9172	0.6581	0.0804
1515.151	0.6249	-0.2020	0.0763	-0.0246	-17.9144	0.6367	0.0802

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.0007 0.7206
RADIUS = 1.0412
FIT = 2.2641

R0= 1.7525 RINF= 0.2490

MODEL PARAMETERS - R1 = 393.0610/FRQ
RP = 1.5032

RHO = 0.2141E 02 OHM-CM

EP= 0.2450533E-03

TAU= 0.3113060SEC E0=1099.02012 EINF= 269.96960

FRQ	EP	EPP
1.002	0.1030106E 04	0.5745776E 02
2.010	0.1011035E 04	0.7973036E 02
4.033	0.1775216E 04	0.1006094E 03
8.052	0.1724135E 04	0.1450042E 03
10.034	0.1704112E 04	0.1592450E 03
20.113	0.1620493E 04	0.2000376E 03
40.017	0.1522358E 04	0.2500832E 03
80.120	0.1390035E 04	0.3024016E 03
100.200	0.1349135E 04	0.3152035E 03
201.013	0.1109350E 04	0.3425006E 03
403.220	0.1002193E 04	0.3450106E 03
807.899	0.0535794E 03	0.3241076E 03
1003.050	0.8122006E 03	0.3131436E 03
1515.151	0.7205736E 03	0.2001906E 03

DET. G,N FOR R1=G/FRQ^N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.0007 0.7206
RADIUS = 1.0412
FIT = 2.2641

R0= 1.7525 RINF= 0.2490

MODEL PARAMETERS - R1 = 393.0610/FRQ
RP = 1.5032

F	F-1/2	R1	XP	CP
1.0015	0.9992	7.8100	-14.5492	-0.1092E-01
2.0150	0.7044	6.6957	-22.0078	-0.3588E-02
4.0320	0.4980	5.7999	-15.7004	-0.2513E-02
8.0515	0.3524	5.5213	-12.8478	-0.1539E-02
10.0341	0.3157	5.0980	-9.7614	-0.1625E-02
20.1120	0.2230	5.0555	-10.2475	-0.7722E-03
40.0174	0.1509	4.0440	-6.5574	-0.5976E-03
80.1202	0.1117	3.5605	-4.9341	-0.4026E-03
100.2004	0.0999	3.4101	-3.0201	-0.4149E-03
201.0123	0.0704	2.3004	-2.8104	-0.2801E-03
403.2250	0.0498	1.7998	-1.7253	-0.2288E-03
807.0934	0.0351	1.0105	-1.0139	-0.1943E-03
1003.0497	0.0315	0.7505	-0.7777	-0.2039E-03
1515.1514	0.0250	0.6695	-0.9014	-0.1165E-03

G= 0.1040ZE 02 N= 0.32459E 00
########### STOP ###########

Table 6-27. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_2 Following a 24-Hour Water Soak

ENTER RS,AOD PUT 5041 UP FOR ELECTRODE CORRECTION
003.00134

M2 24HR AOD= 0.06134 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.000	2.9374	-0.2140	0.1802	-0.0131	-4.1664	2.9432	0.1807
2.012	2.8346	-0.2155	0.1739	-0.0132	-4.3478	2.8428	0.1744
4.041	2.7304	-0.2536	0.1675	-0.0136	-3.3487	2.7423	0.1682
8.021	2.6170	-0.2813	0.1603	-0.0172	-6.1363	2.6321	0.1613
10.016	2.6108	-0.2736	0.1603	-0.0167	-3.9729	2.6310	0.1614
20.004	2.5050	-0.3534	0.1337	-0.0218	-8.0733	2.3307	0.1332
40.193	2.3409	-0.4409	0.1440	-0.0273	-10.8291	2.3094	0.1466
100.100	2.0317	-0.6253	0.1246	-0.0383	-17.1076	2.1230	0.1304
201.013	1.6048	-0.7036	0.1033	-0.0431	-22.6697	1.8230	0.1120
403.220	1.2701	-0.6350	0.0704	-0.0402	-27.1361	1.4565	0.0801
603.333	0.9271	-0.5070	0.0368	-0.0311	-20.7007	1.0370	0.0648
1007.326	0.8090	-0.4377	0.0535	-0.0268	-26.7365	0.9731	0.0396
1515.152	0.6909	-0.3399	0.0427	-0.0288	-23.9998	0.7734	0.0473

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.6430 1.0705
RADIUS = 1.7203
FIT = 2.7057

R0= 2.9037 RINF= 0.2964

MODEL PARAMETERS - RI = 427.14577/FRQ
RP = 2.0932

RHO = 0.16559E 06 OHM-CM

CP= 0.18795E-03

TAU= 0.04006MSEC E0=4016.52441 EINF= 398.43040

FRQ	EP	EPP
1.000	0.38900/E 04	0.11492E 03
2.012	0.38413E 04	0.10690E 03
4.041	0.37573/E 04	0.23916E 03
8.021	0.3650/E 04	0.33402E 03
10.016	0.35900E 04	0.37021E 03
20.004	0.34029E 04	0.4987/E 03
40.193	0.31503E 04	0.64104E 03
100.100	0.27161E 04	0.60004E 03
201.013	0.23242E 04	0.60899E 03
403.220	0.19241/E 04	0.65220E 03
603.333	0.15500E 04	0.70322E 03
1007.326	0.14448E 04	0.72062E 03
1515.151	0.12044E 04	0.65996E 03

GET. G,R FOR RI=G/FRRM

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.6430 1.0703
RADIUS = 1.7203
FIT = 2.7037

R0= 2.9097 RINF= 0.2964

MODEL PARAMETERS - RI = 427.14577/FRQ
RP = 2.0932.

F	F-1/2	RI	XP	CP
1.0003	0.9999	23.9679	-32.0130	-0.4849E-02
2.0122	0.7050	17.0435	-30.1109	-0.2627E-02
4.0411	0.4975	13.9102	-23.4513	-0.1601E-02
8.0205	0.3531	11.0069	-19.4220	-0.1022E-02
10.0100	0.3159	11.0413	-19.9404	-0.7307E-03
20.0042	0.2232	9.3079	-14.0003	-0.3031E-03
40.1929	0.1577	7.0367	-9.0140	-0.4035E-03
100.1001	0.0993	5.0901	-5.4411	-0.2922E-03
201.0123	0.0704	4.1913	-3.4429	-0.2293E-03
403.2430	0.0490	2.7020	-2.1257	-0.1037E-03
603.3525	0.0351	1.9926	-1.2913	-0.1323E-03
1007.3262	0.0315	1.3025	-1.1000	-0.1331E-03
1515.1514	0.0250	0.6953	-0.0110	-0.1294E-03

G= 0.27042E 02 R= 0.41305E 00
********** STOP **********

Table 6-28. Computer Output for Electric and Dielectric Data of Untreated Quartz Sample M_3 Following a 24-Hour Water Soak

```
ENTER RS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION
005.04002

        M3 24 HR                         AOD= 0.04002      PHASE AND AMPLITUDE CORRECTED
```

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.002	105.2404	-14.6757	4.2732	-0.6042	-8.0434	106.2945	4.3177
1.999	101.0330	-21.2254	4.1040	-0.8022	-11.8635	103.2384	4.1955
4.031	95.3600	-31.5983	5.0239	-1.2734	-18.2243	100.4843	4.0784
8.017	81.5592	-44.3746	3.3040	-1.8186	-28.7193	92.7697	3.7685
10.022	74.2003	-48.3784	3.0173	-1.9733	-35.1867	88.7349	3.6032
20.008	47.3147	-40.9892	1.9300	-1.9867	-45.8319	68.1891	2.7698
40.225	25.4952	-37.3764	1.5356	-1.3182	-55.7034	43.2438	1.8378
80.000	12.0380	-25.0848	0.5134	-1.0189	-65.2652	28.0883	1.1410
99.000	9.6022	-21.5987	0.4000	-0.8691	-63.2389	23.3602	0.9370
200.535	3.2700	-12.5508	0.2141	-0.3181	-67.2345	13.6182	0.3332
402.575	3.3371	-7.1900	0.1304	-0.2921	-64.9763	7.9332	0.3223
802.139	2.2904	-5.9899	0.0932	-0.1621	-60.0812	4.6036	0.1870
1003.650	2.0900	-3.3372.	0.0831	-0.1356	-37.8726	5.9408	0.1601
1512.200	1.9251	-2.2994	0.0781	-0.0934	-50.0937	2.9976	0.1218

```
RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER =   53.7631     3.8338
                                  RADIUS =   33.2749
                                  FIT    =    2.2217

RO=   100.9017             RINF=     2.6265

MODEL PARAMETERS -   RI = 10550.0172/FRQ
                     RP =   100.2732

RHO = 0.44230E 09 OHM-CM

EP= 0.52100/E-04

TAU=   5.50009MSEC           EO=3004.92773             EINF= 142.04010
```

FRQ	EP	EPP
1.002	0.5600194E 04	0.2321410E 03
1.999	0.5405000E 04	0.4442800E 03
4.031	0.3119350E 04	0.8437760E 03
8.017	0.4571335E 04	0.1503890E 04
10.022	0.4343320E 04	0.1771000E 04
20.008	0.3494520E 04	0.2555400E 04
40.225	0.2550780E 04	0.2543350E 04
80.000	0.1707190E 04	0.1790230E 04
99.000	0.1470047E 04	0.1351410E 04
200.535	0.9160370E 03	0.8539440E 03
402.570	0.5670740E 03	0.4510310E 03
802.139	0.3700701E 03	0.2305350E 03
1003.650	0.3281480E 03	0.1911090E 03
1512.200	0.2092270E 03	0.1293010E 03

```
DET. G,N FOR RI=G/F**N
```

```
----RS,XS CIRCLE FIT RESULTS-  CIRCLE CENTER =   55.7631     3.8338 ----------
                                      RADIUS =   55.2749
                                      FIT    =    2.2217

RO=   100.9017             RINF=     2.6283

MODEL PARAMETERS -   RI = 10530.0172/FRQ
                     RP =   105.2732
```

F	F-1/2	RI	XP	CP
1.0021	0.9989	2705.0335	-722.7993	-0.2197E-03
1.9994	0.7072	1094.7400	-477.4441	-0.1667E-03
4.0300	0.4981	2035.1870	-305.3213	-0.1293E-03
8.0167	0.3532	2294.5500	-103.6342	-0.1881E-03
10.0220	0.3139	2639.7256	-134.2629	-0.1029E-03
20.0084	0.2231	997.1171	-90.1034	-0.8793E-04
40.2253	0.1377	566.3836	-51.3662	-0.7703E-04
80.0000	0.1118	220.2817	-29.0700	-0.6842E-04
99.0004	0.1001	200.1182	-23.0423	-0.6089E-04
200.5347	0.0706	145.6636	-13.1129	-0.6033E-04
402.5764	0.0430	209.7177	-7.2659	-0.3443E-04
802.1392	0.0333	-33.4476	-4.0173	-0.4939E-04
********** LOG **********				
********** LOG **********				
1003.6497	0.0315	-17.9181	-3.4222	-0.4634E-04
********** LOG **********				
********** LOG **********				
1512.2076	0.0237	-7.6265	-2.5157	-0.4183E-04
********** LOG **********				
********** LOG **********				

```
G= 0.1347dE 05 N= 0.11142E 01
********** STOP **********
```

Table 6-29. Computer Output for Electric and Dielectric Data of Quartz Sample M_1 Following a 75-Hour Water Soak

ENTER NS,AOD   PUT SSW1 UP FOR ELECTRODE CORRECTION
008.12219

M1 75 HR   AOD= 0.12219   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
0.999	5.3284	-0.4195	0.6311	-0.0312	-4.5015	5.3449	0.6511
2.015	5.1193	-0.4167	0.6253	-0.0509	-4.6541	[illegible]	[illegible]
4.020	4.9650	-0.4915	0.6067	-0.0600	-9.6519	[illegible]	[illegible]
8.015	4.7399	-0.6190	0.5792	-0.0756	-7.4405	[illegible]	[illegible]
20.064	4.4421	-0.8637	0.5428	-0.1035	-11.0033	[illegible]	[illegible]
40.096	4.0484	-1.0814	0.4947	-0.1321	-14.9368	[illegible]	[illegible]
80.128	3.4939	-1.5398	0.4272	-0.1637	-20.9707	[illegible]	[illegible]
99.900	5.5067	-1.5197	0.4040	-0.1615	-31.7592	[illegible]	[illegible]
201.072	2.5489	-1.3806	0.3114	-0.1687	-28.4448	[illegible]	[illegible]
401.929	1.8145	-1.2229	0.2217	-0.1494	-55.9806	[illegible]	[illegible]
803.372	1.2258	-0.8608	0.1493	-0.1032	-55.1240	[illegible]	[illegible]
1003.630	1.0959	-0.7933	0.1337	-0.0969	-53.9545	[illegible]	[illegible]
2025.783	0.7038	-0.4133	0.0862	-0.0307	-30.4845	[illegible]	[illegible]

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 2.8856 1.7549
RADIUS = 3.1103
FIT = 2.0303

R0= 5.4557   RINF= 0.5174

MODEL PARAMETERS - RI = 1103.9126/FRQ
RP = 5.1364

RHO = 0.66659E 08 OHM-CM

CP= 0.125530E-05

TAU= 0.78105MSEC   E0=2273.88325   EINF= 152.45570

FRQ	EP	EPP
0.999	0.221099E 04	0.632355E 02
2.013	0.217663E 04	0.955848E 02
4.020	0.212603E 04	0.141027E 03
8.013	0.203162E 04	0.204346E 03
20.064	0.190092E 04	0.318295E 03
40.096	0.175819E 04	0.418663E 03
80.128	0.153145E 04	0.509878E 03
99.900	0.143769E 04	0.552110E 03
201.072	0.120901E 04	0.363688E 05
401.929	0.962137E 05	0.553078E 05
803.372	0.741060E 03	0.434635E 03
1003.630	0.678381E 03	0.423201E 05
2025.783	0.311765E 05	0.321297E 05

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 2.8856 1.7549
RADIUS = 3.1103
FIT = 2.0303

R0= 5.4337   RINF= 0.3174

MODEL PARAMETERS - R1 = 1305.9126/FRQ
RP = 5.1364

F	F-1/2	R1	XP	CP
0.9983	1.0007	67.3181	-60.2831	-0.2644E-02
2.0132	0.7044	42.8714	-35.7525	-0.1417E-02
4.0196	0.4988	33.9869	-44.4586	-0.8906E-05
8.0128	0.3553	26.0536	-52.2178	-0.6165E-05
20.0642	0.2252	20.4321	-20.3652	-0.3858E-05
40.0962	0.1379	15.6325	-13.9543	-0.2845E-05
80.1282	0.1117	11.9333	-8.8807	-0.2237E-05
99.9001	0.1001	10.3320	-8.0908	-0.1969E-05
201.0724	0.0703	7.1063	-4.9874	-0.1587E-03
401.9293	0.0498	4.6026	-5.0359	-0.1296E-03
803.3713	0.0332	2.3207	-1.8134	-0.1091E-03
1003.6497	0.0315	2.2384	-1.3554	-0.1021E-03
2023.7827	0.0222	0.9829	-0.7787	-0.1009E-03

G= 0.78420E 02 N= 0.49970E 00
********** STOP **********

Table 6-30. Computer Output for Electric and Dielectric Data of Quartz Sample M_2 Following a 75-Hour Water Soak

ENTER RS,AOD PUT SSW1 UP FOR ELECTRODE CORRECTION
007.06154

M2 75 HR AOD= 0.06154 PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RAOD	XAOD	PHI	Z	ZAOD
1.010	2.7131	-0.1800	0.1664	-0.0115	-5.9645	2.7196	0.1668
2.006	2.6621	-0.2101	0.1655	-0.0133	-4.6835	2.6710	0.1638
4.004	2.6199	-0.2093	0.1607	-0.0128	-4.5669	2.6282	0.1612
8.009	2.5629	-0.2332	0.1572	-0.0145	-5.1985	2.5735	0.1579
10.018	2.5700	-0.2031	0.1576	-0.0124	-4.*198	2.57R0	0.1581
20.155	2.4924	-0.2578	0.1529	-0.0158	-5.9061	2.5057	0.1557
40.193	2.3876	-0.2868	0.1465	-0.0175	-6.8511	2.4048	0.1475
80.586	2.1853	-0.5557	0.1340	-0.0218	-9.2458	2.2141	0.1358
99.900	2.2115	-0.4407	0.1356	-0.0270	-11.2750	2.2548	0.1383
200.267	1.9041	-0.5553	0.1168	-0.0340	-16.2589	1.9834	0.1217
403.226	1.5804	-0.5655	0.0969	-0.0546	-19.6894	1.6786	0.1030
805.009	1.2250	-0.5282	0.0750	-0.0524	-23.5616	1.3322	0.0817
1003.650	1.1547	-0.4719	0.0700	-0.0289	-22.2297	1.2474	0.0765
2029.520	0.8855	-0.2879	0.0543	-0.0176	-18.0124	0.9312	0.0571

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.6467 0.9936
RADIUS = 1.5552
FIT = 2.6115

R0= 2.8171 RINF= 0.4764

MODEL PARAMETERS - R1 = 601.5010/FRQ
RP = 2.3407

RHO = 0.17280E 08 OHM-CM

CP= 0.158600E-05

TAU= 0.42557MSEC E0=1645.55640 EINF= 278.28558

FRQ	EP	EPP
1.010	0.160606E 04	0.579263E 02
2.004	0.158815E 04	0.541229E 02
4.004	0.156214E 04	0.766130E 02
8.009	0.152476E 04	0.106842E 03
10.018	0.150962E 04	0.118415E 03
20.153	0.145034E 04	0.160193E 05
40.193	0.137051E 04	0.200030E 05
80.386	0.124405E 04	0.256813E 03
98.900	0.122028E 04	0.270789E 05
200.247	0.109380E 04	0.505256E 03
405.226	0.945810E 03	0.316200E 03
805.009	0.801149E 03	0.209859E 05
1003.650	0.757611E 03	0.209630E 03
2029.570	0.652455E 03	0.246356E 05

DET. G,N FOR R1=G/F**N

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 1.6467 0.9956
RADIUS = 1.5552
FIT = 2.6115

R0= 2.8171 RINF= 0.4764

MODEL PARAMETERS - R1 = 601.5010/FRQ
RP = 2.5407

F	F-1/2	R1	XP	CP
1.0101	0.9950	11.2386	-26.7974	-0.5880E-02
2.0059	0.7061	10.2003	-22.1241	-0.5586E-02
4.0042	0.4997	9.3327	-22.1660	-0.1793E-02
8.0090	0.3554	8.4480	-18.9055	-0.1051E-02
10.0180	0.5159	8.4580	-21.7794	-0.7295E-03
20.1532	0.2228	7.5149	-16.0225	-0.4929E-03
40.1929	0.1577	6.5804	-15.0200	-0.5041E-03
80.3859	0.1115	4.8569	-8.5656	-0.2311E-03
99.9001	0.1001	5.3429	-7.2700	-0.2191E-03
200.2670	0.0706	3.9460	-4.2261	-0.1881E-03
403.2258	0.0498	2.7584	-2.7209	-0.1451E-03
805.0096	0.0352	1.8600	-1.5834	-0.1249E-03
1005.6497	0.0315	1.5661	-1.4468	-0.1096E-03
2029.5200	0.0221	0.7814	-0.8695	-0.9021E-04

G= 0.15917E 02 N= 0.31379E 00
********** STOP **********

Table 6-31. Computer Output for Electric and Dielectric Data of Quartz Sample M_3 Following a 75-Hour Water Soak

ENTER NS,AOD P:T SSW1 UP FOR ELECTRODE CORRECTION
009.04062

M3 75 HR   AOD= 0.04062   PHASE AND AMPLITUDE CORRECTED

FRQ	RS	XS	RADD	XADD	PHI	Z	ZADD
1.010	109.0204	-17.7542	4.4284	-0.7212	-9.2502	110.4566	4.4867
2.015	102.0855	-25.7605	4.1467	-0.9651	-15.1053	104.8140	4.2575
6.066	77.0051	-36.0534	3.1604	-1.4637	-24.8518	85.7440	3.4829
8.013	74.5559	-38.4600	5.0277	-1.5622	-27.2954	83.8756	3.4069
10.618	67.9982	-40.3577	2.7621	-1.6593	-30.6919	79.0727	5.2119
20.086	45.8807	-40.0585	1.8657	-1.6272	-41.1275	60.9075	2.4741
40.126	27.6611	-53.2904	1.0992	-1.5525	-50.8968	42.9017	1.7427
80.128	14.4824	-25.4754	0.5885	-0.9555	-58.5510	27.5815	1.1204
99.602	12.1089	-20.5269	0.4919	-0.8358	-59.4679	23.8323	0.9681
201.072	6.8541	-12.6178	0.2784	-0.5125	-61.4932	14.5592	0.5853
402.576	4.1916	-7.5679	0.1703	-0.2995	-60.3675	8.4769	0.344.
865.572	2.8873	-4.1555	0.1173	-0.1679	-55.0696	5.0421	0.2048
1003.650	2.5816	-5.5936	0.1049	-0.1578	-52.7426	4.2640	0.1752
2029.520	2.6192	-1.6606	0.0820	-0.0674	-59.4378	2.6143	0.1062

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 59.1587 21.5426
RADIU6 = 62.2774
FIT = 1.3099

R0= 117.6448   RINF= 0.6526

MODEL PARAMETER6 - R1 = 7954.4258/FRQ
RP = 117.0122

RHO = 0.47767E 09 OHM-CM

CP= 0.386524E-04

TAU= 4.61454MSEC   E0=521170.226   EINF= 113.83640

FRQ	EP	EPP
1.010	0.199245E 05	0.125135E 04
2.015	0.191155E 05	0.206094E 04
6.066	0.168492E 05	0.421877E 04
8.015	0.160400E 05	0.491230E 04
10.010	0.153222E 05	0.547709E 04
20.066	0.127159E 05	0.697200E 04
40.128	0.982605E 04	0.750457E 04
80.128	0.705955E 04	0.622448E 04
99.602	0.627615E 04	0.570648E 04
201.072	0.414557E 04	0.395633E 04
402.576	0.264655E 04	0.253345E 04
865.572	0.166300E 04	0.155599E 04
1005.650	0.143086E 04	0.132290E 04
2029.520	0.695603E 03	0.782851E 03

UET. 6,H FUR R1=6/F**H

RS,XS CIRCLE FIT RESULTS- CIRCLE CENTER = 59.1587 21.3426
RADIU6 = 62.2774
FIT = 1.3099

R0= 117.6446   RINF= 0.6326

MODEL PARAMETER6 - R1 = 7954.4258/FRQ
RP = 117.0122

F	F-1/2	R1	XP	CP
1.0057	0.9952	2062.5286	-679.4500	-0.2320E-03
2.0151	0.7045	1184.6790	-456.9467	-0.1729E-05
6.0665	0.4060	467.6264	-201.3152	-0.1305E-03
8.0128	0.5555	465.6825	-180.4699	-0.1101E-05
10.0100	0.3161	412.6055	-152.8055	-0.1041E-03
20.0864	0.2231	257.1005	-91.1684	-0.8690E-04
40.1264	0.1579	165.1920	-54.2714	-0.7300E-04
80.1262	0.1117	98.5751	-51.6451	-0.6277E-04
99.6016	0.1002	81.6500	-26.9432	-0.5931E-04
201.0724	0.0705	45.6016	-15.6855	-0.5046E-04
462.5764	0.0498	22.5917	-9.0872	-0.4351E-04
805.5715	0.0552	10.7294	-5.3634	-0.5695E-04
1005.6497	0.0315	8.4204	-4.5150	-0.5514E-04
2029.5266	0.6221	5.4751	-2.8184	-0.2785E-04

G= 0.24966E 04 N= 0.80274E 00
*********** STUP ***********

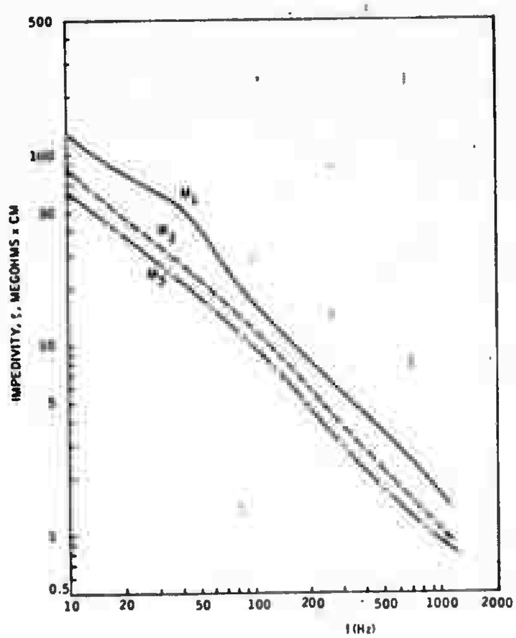


Figure 6-11. Variation of Impedivity with Frequency for the Untreated Quartz Samples

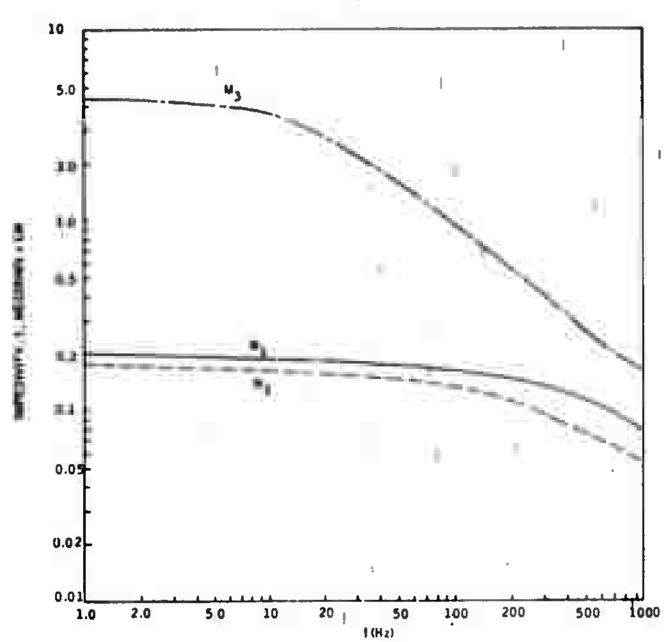


Figure 6-12. Variation of Impedivity with Frequency for the Quartz Following 24-hour Soak

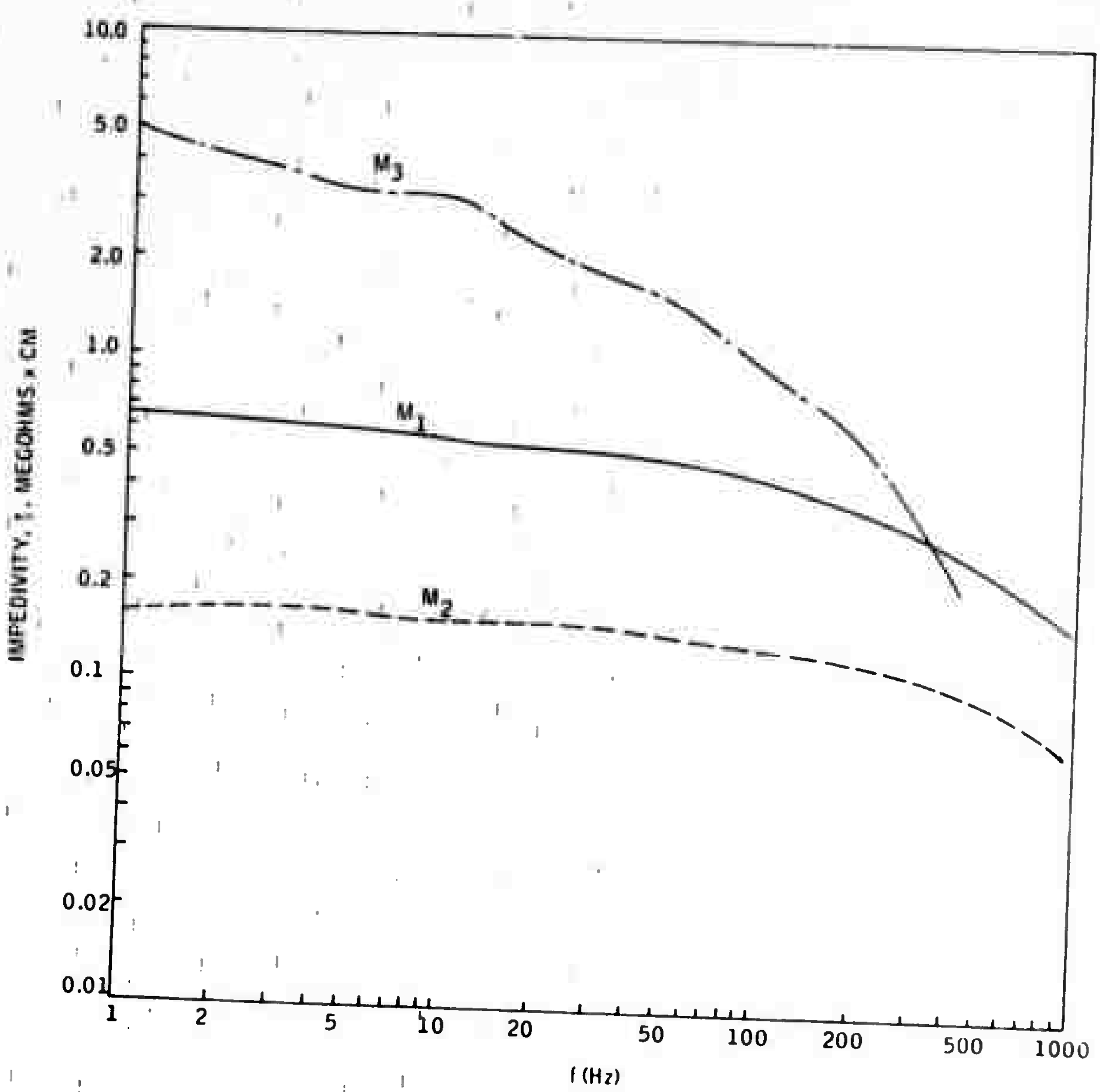


Figure 6-13. Variation of Impedivity with Frequency for the Quartz (II) Following 75-Hour Soak

The electric and dielectric parameters that exhibit the most significant change with water treatment are chosen and given in Table 6-32. It is noted that the resistivity at zero frequency (dc resistivity), ρ_o, decreases by about three orders of magnitude by mere soaking in water. This explains the frequent difficulties experienced in working with quartz where the output was often very unstable and exhibited considerable d-c drift, apparently due to slight changes in environmental humidity. The decrease in quartz resistivity with duration of soaking time is illustrated by the curves in Figure 6-14. The d-c resistivity of dry quartz was 8.36×10^{10}, 7.55×10^{10}, and 7.13×10^{10} ohm·cm for the three samples, with an average of 7.68×10^{10} ohm·cm. The water-treated samples exhibited larger variability in resistivity. In addition, prolongation of water treatment beyond 24 hours produced little variation in ρ_o, except for the thinnest sample M1 where a slight increase in ρ_o occurred at larger soaking times. This is suggestive of the leaching out of the conductive ions by prolonged soaking, a phenomena which should occur more readily with thinner rock samples.

Figure 6-15 shows the variation of the dielectric constant at the limit of zero frequency, K_o, with soaking time. For quartz the decrease in dielectric constant with soaking time is much smaller than the decrease in resistivity. The decrease was nearly linear except for the thinner sample M1, where K_o appeared to increase with increased soaking time after reaching a minimum at about 40 hours.

The foregoing experiments were planned to illustrate the effects of rock water content and alkali (mobile) ion content on the rock electric and dielectric properties. The experiments suggest a choice of certain electric or dielectric parameters that respond the most by change in water or alkali content. Further experiment should be done with shorter pretreatment times to show whether the chosen parameters can indeed be used to measure the quantity of water retained in the rock. The experiments described in this section are, therefore, illustrative in nature and by no means quantitative. Developments

Table 6-32. Effect of Water Pretreatment on Some Impedance and Dielectric Parameters of Quartz (II)

Quartz Sample → / Parameter ↓	M1, d = 0.31 cm			M2, d = 0.61 cm			M3, d = 0.92 cm		
	Blank (no pretreatment)	24 hr	75 hr	Blank (no pretreatment)	24 hr	75 hr	Blank (no pretreatment)	24 hr	75 hr
R_0 (ohm-cm)	[illegible] x 10^{10}	2.14 x 10^7	[illegible] x 10^7	7.55 x 10^{10}	[illegible] x 10^7	[illegible] x 10^7	7.12 x 10^{10}	4.42 x 10^8	4.78 x 10^8
C_p (microfarad)	[illegible]	288	126	[illegible]	188	126	3.76	52.2	38.6
τ (millisecond)	82.4	0.51	0.78	85.4	0.65	0.43	166.7	5.6	4.8
ε_0	[illegible]	1900	2276	7853	4018	1646	16823	5885	21170
ε_∞	[illegible]	270	132	12.01	398	278	15.96	142	114

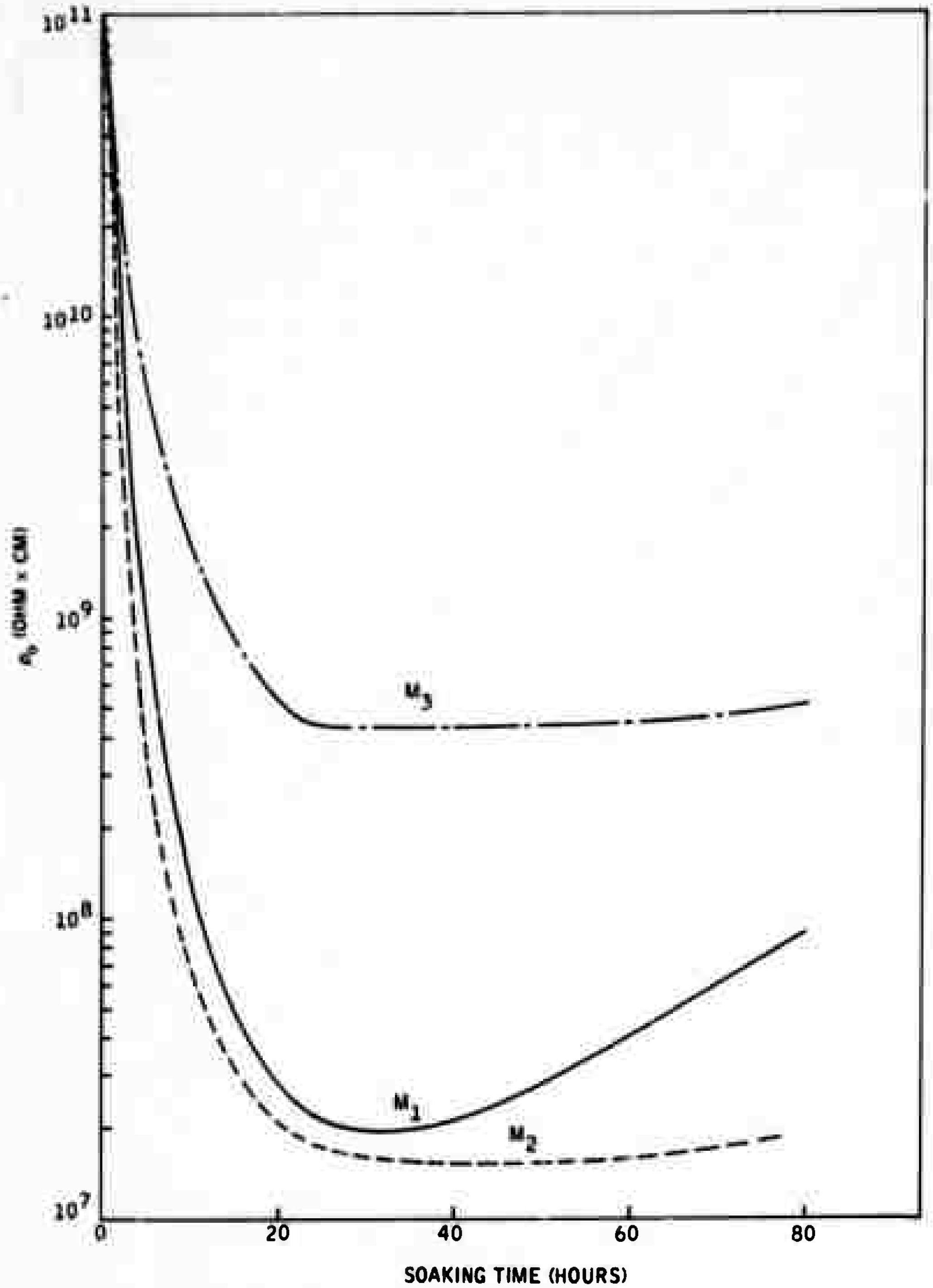


Figure 6-11. Variation of Quartz Resistivity with the Duration of Soaking Time in Water

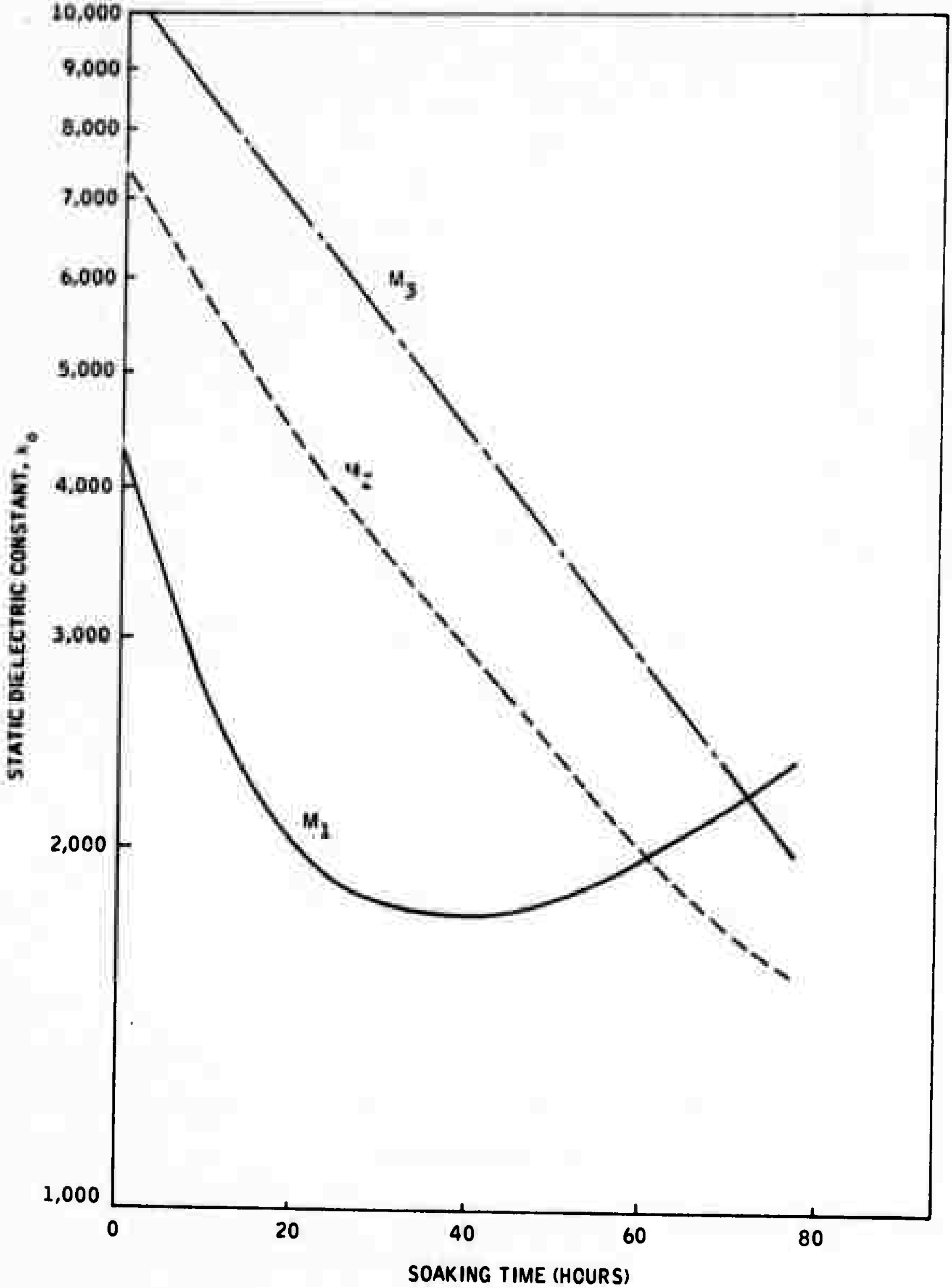


Figure 6-15. Variation of Quartz Dielectric Constant (K_o) with Its Soaking Time in Water

of procedures to measure the water content in rocks, while not the intent of this research, can nevertheless be improved by choice of the optimum electric or dielectric parameter; i.e., the one that exhibits the highest sensitivity to the presence of water or sodium ions. This research shows beyond doubt that the zero-frequency parameters (dc or those extrapolated from measurements at low frequencies) are the most sensitive ones, while the high-frequency parameters show little or no variation by presence of water or mobile sodium ions.

SECTION VII
MODELS TO SIMULATE THE ELECTRIC AND DIELECTRIC ROCK BEHAVIOR

This section is concerned with the mathematical description of physical models selected to describe the experimentally obtained electric and dielectric data on rocks.

Conventional models, such as the one by Debye (Ref. 18) and K.W. Wagner et al (Ref. 19), have been able to explain many fundamental characteristics of molecular behavior. They do, however, fail to explain the dielectric characteristics of complex systems such as rocks. For the interpretation of data obtained during this study, a mathematical model will be introduced that is able to explain many of the rock impedance characteristics. A method of converting the impedance data into the complex permittivity data is also treated in detail.

In principle, it is always possible to simulate the impedance and dielectric behavior of many real systems, rocks included, by circuits composed of frequency-independent parameter components. An impedance whose frequency dependence is given by

$$Z = r_2 + \sum_i \frac{R_{p(i)}}{1 + j(\omega\tau_i)^{1-\alpha}} \tag{7-1}$$

establishes a circular arc in the complex impedance plane (Argand diagram). In this equation, r_2 is the impedance at infinite frequency (equal to the resistance then, since any capacitive reactance will vanish and the presence of inductive reactance is not anticipated), $R_{p(i)}$ is the i^{th} component representing a difference between the zero and infinite frequency resistances, τ_i is a constant with the dimensions of time (relaxation time for the i^{th} component or subprocess), and α is a constant between 0 and 1, but less than 1.

The impedance circular arc subtends an angle, 2φ at the center, such that $\varphi = \frac{\pi}{2}(1-\alpha)$. For a rock system, the angle φ is called the rock phase angle.

From Equations (7-1) and (4-1), and with the assumption of an α of zero, we can separate the real and imaginary parts of the impedance to:

$$R_s = r_2 + \sum_i \frac{R_{pi}}{1 + (\omega\tau_i)^2}, \quad X_s = \sum_i \frac{\omega\tau_i R_{pi}}{1 + (\omega\tau_i)^2} \qquad (7\text{-}2)$$

The relationship between X_s and R_s can be shown to describe a semicircle.

These equations can also be represented by a plot of X versus log ω or log f. This representation is of particular value in determining the magnitude and frequency of the maximum value of X (turnover frequency). Equation (7-2) predicts that the maximum value of X is $R_p/2$, while the relaxation-time is found from the frequency of the maximum, ω_{max}, thus

$$\tau = \frac{1}{\omega_{max}} = \frac{1}{2\pi f_{max}} \qquad (7\text{-}3)$$

Impedance data for rocks have been found to describe a circular-arc plot when displayed in an Argand diagram with the series reactance as ordinate and the series resistance as abscissa. The display is never a full semi-circle, but is a part of a circle whose center does not lie on the real axis (resistance), and is substantially below it. The phase angle is defined as half of the angle, subtended by the circular-arc at the center of the circle, i.e., between the two radii of the circle defining the two points of intersection of the arc with the resistive axis.

An ideal dielectric dispersion model (Debye Model) is easily simulated by a parallel RC unit, and can be shown to give a full semicircular plot upon transformation to an isoimpedic series RC unit.

Sinbel (Khalafalla) (Ref. 20) derived various analytical proofs of the semicircular arc in an attempt to describe the relationship of the equivalent series reactance to the corresponding resistance. The derivations were based on a parallel-to-series transformation of electrical models with a single time-constant. In the simplest case, it was shown that the transformation from a parallel RC unit (with frequency independent components) to an adjustable series RC unit (with the same total impedance) results in a full arc plot in the Argand diagram. The locus of the series reactance, X_s, when plotted against the series resistance, R_s, follows the analytical equation of a circle of radius, $\frac{1}{2} R_p$, where R_p is the parallel resistance assumed to be a constant quantity characteristic of the system, thus

$$X_s^2 + [R_s - \frac{1}{2} R_p]^2 = \frac{1}{4} R_p^2 \quad (7\text{-}4)$$

The center of the semicircular plot should then have the coordinates $(0, \frac{1}{2} R_p)$ and hence is located on the real or resistive axis. This seems to represent a very idealized situation. In real systems the semicircular arc observed experimentally is usually translated vertically downwards so that its center has the coordinates (n and -m) and accordingly follows an equation of the form

$$[X_s + m]^2 + [R_s - n]^2 = a^2 \quad (7\text{-}5)$$

where m, n, and a are constants related to X_p and C_p.

An electrical model with a single time constant will be developed to account for the experimentally observed electrical data of rocks. The model will also permit a determination of the dielectric data of rocks. In addition, the introduced model allows one to select the parameters that are strongly influenced by rock conditions, such as the inclusion of water, mobile ions, entrapped gases, pores, and cracks; etc.

ELECTRICAL ANALOG WITH ONE FREQUENCY DEPENDENT RESISTANCE

An electrical model, Figure 7-1, in which a frequency dependent resistance, r_1, is shunted across the condenser, C_p, is capable of describing a circular arc in the series domain with a vertically displaced center (Figure 7-2). A condition to be imposed on the resistor, r_1, is that its value changes inversely with the frequency such that $r_1 = \frac{g}{f}$, where g is a constant and f is the frequency. The total impedance of this model is given by

$$Z_p = \frac{R_p \dfrac{jr_1X_p}{r_1 + jX_p}}{\dfrac{jr_1X_p}{R_p + r_1 + jX_p}} + r_2$$

$$= \frac{r_1R_pX_p^2(r_1 + R_p)}{r_1^2R_p^2 + X_p^2(r_1 + R_p)^2} + j\frac{r_1^2R_p^2X_p}{r_1^2R_p^2 + X_p^2(r_1 + R_p)^2} + r_2 \qquad (7\text{-}6)$$

$$= R_s + jX_s.$$

From which one obtains

$$R_s = r_2 + \frac{r_1R_1X_p^2(r_1 + R_p)}{r_1^2R_p^2 + X_p^2(r_1 + R_p)^2} \qquad (7\text{-}7)$$

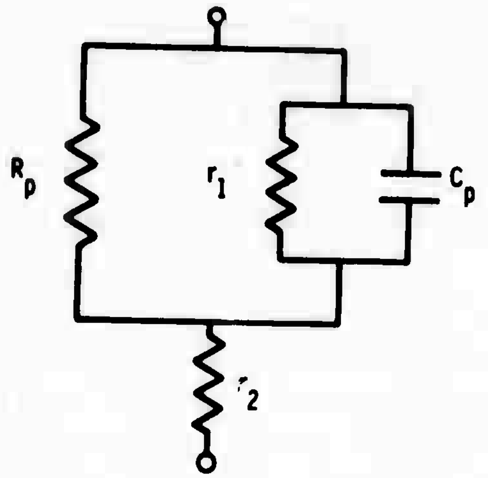


Figure 7-1. Electrical Model That Produces a Circular Arc Plot

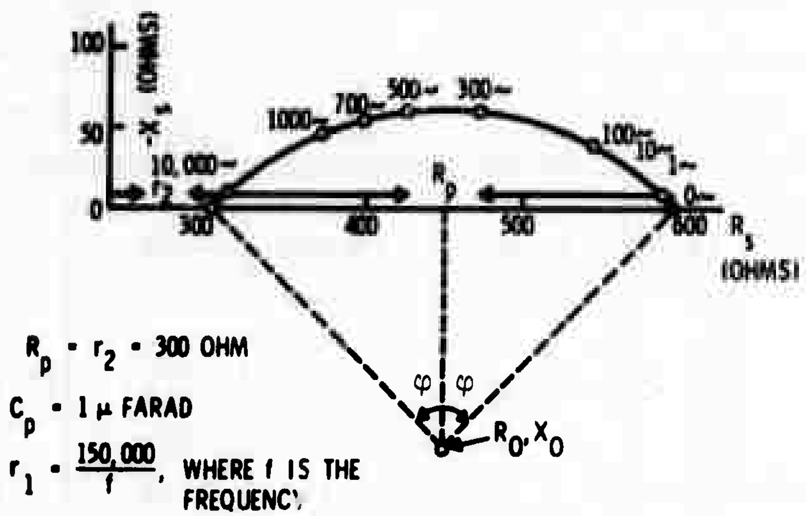


Figure 7-2. Circular Arc Plot Between Equivalent X_s and R_s of the Model

and

$$X_s = \frac{r_1^2 R_p^2 X_p}{r_1^2 R_p^2 + X_p^2 (r_1 + R_p)^2} \qquad (7\text{-}8)$$

Taking the following representative values for the electrical parameters,

$R_p = r_2 = 300$ ohm

$C_p = 1$ microfarad

g = 150,000 ohm per second, such that $r_1 = \frac{g}{f} = 300$ ohm at a frequency of 500 Hz, one is able to calculate values for R_s and X_s at various frequencies. These calculations are given in Table 7-1.

Table 7-1. Equivalent Series Resistance and Reactance for Electrical Model of Figure 7-1

f (Hz)	r_1 (ohm)	X_p (ohm)	R_s (ohm)	X_s (ohm)
0	150,000	159,000	599	0.6
10	15,000	15,924	594	5.4
100	1,500	1,592	544	38.3
300	500	531	467	58.9
500	300	318	423	57.8
700	214	227	396	52.8
1,000	150	159	372	45.1
10,000	15	16	308	7.1

The plot of X_s against R_s as shown in Figure 7-2 is found to describe a circular-arc with a depressed center and whose boundary values satisfy the limiting values required by the electrical model of the circuit in Figure 7-1. Thus, at infinite frequency, both r_1 and X_p become zero, and the total impedance of the network equals r_2; i. e., 300 ohm. The first intersection point of the circular-arc with the R_s axis is also found to be 300 ohm. At zero frequency, the limiting impedance of the network becomes $(R_p + r_2)$ = 600 ohm.

It appears, therefore, that the electrical model of Figure 7-1 gives a realistic analog to a system displaying a circular-arc plot in the Argand diagram. The limits of the rock impedance at zero frequency would be given by $(r_2 + R_p)$ and, at infinite frequency, by r_2. A direct estimation of r_2 and R_p is thus possible by extrapolating the circular-arc to intersect the real axis. The unusual resistor in this model is $r_1 = \frac{g}{f}$, where g is a constant given by

$$g = \frac{1}{2\pi K C_p} \qquad (7\text{-}9)$$

where K is a constant related to the phase-angle, and C_p is the frequency independent rock capacitance which can be taken as a constant.

The rock phase-angle, φ, would only be dependent on the values of C_p and r_1 and, since these two components are in parallel, then

$$\varphi = \tan^{-1}\left(\frac{r_1}{X_p}\right) = \tan^{-1}\left(\frac{1}{K\omega C_p} \bigg/ \frac{1}{\omega C_p}\right) = \tan^{-1}\left(\frac{1}{K}\right) \qquad (7\text{-}10)$$

and, hence,

$$K = \cot\varphi, \text{ or } \varphi = \cot^{-1} K. \qquad (7\text{-}11)$$

The angle, φ would also be identical with the experimentally measured phase-angle between the vertical through the semicircular-arc center and the line joining it to either of its intercepts with the real axis. Thus, experimentally determining the rock phase-angle, φ, in each individual case would enable a determination of the constant K required to calculate r_1.

To calculate the turnover-frequency, one can make use of the fact that it is the characteristic frequency which maximizes X_s. Upon differentiating Equation (7-8) for X_s with respect to ω, it is possible to derive (see Appendix B) that the turnover frequency is given by

$$f_{max} = \frac{1}{2\pi R_p C_p \sqrt{1 + K^2}} \tag{7-12}$$

Despite its unusualness for being "electrically unrealizable," the suggested model of Figure 7-1 provides a mechanism for explaining the observed results; i.e., a circular arc with a depressed center in the Argand diagram relating X_s to R_s. Previous literature on electrode polarization had often revealed many such unusual electrical components, similar to r_1, in the model. Warburg (Ref. 7) stated that the electrochemical polarization resistance is inversely proportional to the square root of frequency; thus

$$R_m = R + \frac{g}{\sqrt{f}} \tag{7-13}$$

where R_m is the measured resistance, R is the true electrolytic resistance, and g is the polarization resistance at a frequency, f, of 1 Hz. Fricke (Ref. 21) had also proposed a capacitance for cell membranes that changes as a power function of frequency.

CONVERSION OF IMPEDITIVITY DATA TO COMPLEX PERMITTIVITY IN A REAL SYSTEM

This subsection is concerned with a method of transforming the experimentally obtained electrical data (Argand diagram) into complex permittivity (Cole-Cole diagram). The technique used here invokes a single relaxation for both the circular arc plots in the Argand and Cole-Cole diagrams, and will be denoted as a "bracketing" technique. This method relates the boundary points for both the impedance and dielectric circular arcs with one characteristic relaxation time. Previous investigators (Refs. 19, 22, 23, and 24) used a distribution of relaxation times to account for dispersion in a real system. Unlike our electrical model, a mathematical distribution of time constants cannot provide a one-to-one correspondence between rock characteristics and their electrical parameters.

The relaxation time for a dielectric dispersion process following the Maxwell-Wagner mechanism is related to the volume resistivity by the following equation given in Vera Daniel's monograph (Ref. 25).

$$\tau = K \epsilon_r \rho \qquad (7\text{-}14)$$

where ρ is the volume resistivity defined by

$$R = \rho \left(\frac{d}{A}\right), \qquad \text{or } \rho = R\left(\frac{A}{d}\right) \qquad (7\text{-}15)$$

At the two boundary points of infinite and zero frequency, respectively, the application of Equation (7-14) with the provision that the value of ϵ decreases with increasing frequency, leads to

$$\tau = \epsilon_\infty \rho_o = \epsilon_\infty R_o \left(\frac{A}{d}\right) \qquad (7\text{-}16)$$

Also,

$$\tau = \epsilon_o \rho_\infty = \epsilon_o R_\infty \left(\frac{A}{d}\right) \qquad (7\text{-}17)$$

This is justified under the assumption of a single relaxation time.

The dielectric permittivity at infinite and zero frequency can therefore be calculated from

$$\epsilon_\infty = \left(\frac{\tau}{R_o}\right)\left(\frac{d}{A}\right) \qquad (7\text{-}18)$$

and

$$\epsilon_o = \left(\frac{\tau}{R_\infty}\right)\left(\frac{d}{A}\right) \qquad (7\text{-}19)$$

Both R_o and R_∞ can be determined from the experimental impedance circular arc as the points of furthest and nearest intersection with the real axis. The relaxation time, τ, can be determined from the experimental impedance data by the maximization of X_s with log f. The maximum reactance appears at a frequency, f_{max}, such that

$$\omega_{max}\tau = 1, \text{ or } \tau = \frac{1}{\omega_{max}} = \frac{1}{2\pi f_{max}} \qquad (7\text{-}3)$$

The relaxation time can also be estimated in terms of the model parameters. A detailed derivation (given in Appendix B) leads to

$$\tau = (R_o - R_\infty)\, C_p \sqrt{1 + \text{cotan}^2\, \varphi} \qquad (7\text{-}20)$$

where φ is the rock phase angle derived from the impedance diagram as follows:

$$\varphi = \sin^{-1}\left[\frac{R_o - R_\infty}{2r}\right] \tag{7-21}$$

where r is the radius of the circle whose arc represents the Argand diagram.

The Cole-Cole parameter (Ref. 24), α, is related to the phase angle, φ, as follows:

$$\varphi = \frac{\pi}{2}(1 - \alpha) \tag{7-22}$$

In the ideal case of a Debye dielectric, $\varphi = \frac{\pi}{2}$ and $\alpha = 0$. In general, α is a fraction, usually close to 0.5.

The capacitance, C_p, needed in Equation (7-20) for calculating the relaxation time can be obtained from the impedance data combining Equations (7-7) and (7-8) leads to the result:

$$C_p = \frac{-X_\omega}{\omega\left[(R_\omega - R_\infty)^2 + X_\omega^2\right]} \tag{7-23}$$

In practice, the plot of C_p as a function of frequency shows a sharp decrease between 0.01 and 100 Hz, which is followed by a plateau between 100 Hz to 2000 Hz. The average value of this plateau is considered to represent C_p.

The capacitance C_p can also be determined from Equation (7-20) by using the model-independent value of relaxation time, τ, from Equation (7-3), and R_o, R_∞, and ω from the experimental data. It was noted that τ determined by the maximization of X_s (7-3) was in close agreement with that determined from the model equations (7-20).

Using the phenomenological equations of the complex dielectric permittivity given by Cole and Cole (Ref. 22) and in V. Daniel monograph (Ref. 25) as

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_o - \epsilon_\infty}{1 + (J\omega\tau)^{1-\alpha}} = \epsilon' - J\epsilon'' \tag{7-24}$$

Equation (7-24) is separable into its real and imaginary parts using the identity:

$$j^\alpha = e^{\frac{j\pi}{2}\alpha} \tag{7-25}$$

to give

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_o - \epsilon_\infty}{2} \quad 1 - \left[\frac{\sinh(1-\alpha)\,s}{\cosh(1-\alpha)\;s + \cos\left(\frac{\alpha\pi}{2}\right)}\right] \tag{7-26}$$

and

$$\epsilon'' = \frac{\frac{1}{2}(\epsilon_o - \epsilon_\infty)\cos\left(\frac{\alpha\pi}{2}\right)}{\cosh(1-\alpha)\;s + \sin\left(\frac{\alpha\pi}{2}\right)} \tag{7-27}$$

where s is given by

$$s = \log_e(\omega\tau) \tag{7-28}$$

The plot of $\epsilon''(\omega)$(or $K'' = \epsilon''/\epsilon_r$) as a function of $\epsilon'(\omega)$ (or $K' = \epsilon'/\epsilon_r$) as calculated from Equations (7-26) and (7-27) gives the Cole-Cole diagram.

The necessary operational steps in accordance with the foregoing equations were, therefore, added to the computer algorithm to extract the dielectric permittivity data from the specific impedance parameters. Provision for correcting the measured impedance parameters for electrode effects was also included in the program. Note that the calculations of dielectric parameters according to this procedure can be made independently of any assumed model. All the needed quantities R_o, R_∞, φ, and τ are obtained experimentally. The proposed model in this section can, however, be used to calculate τ according to Equation (7-20).

EVALUATION OF THE MODEL PARAMETER, r_1, FOR BASALT

The model transformation equations from the parallel to the series domain were used to solve for r_1 of Figure 7-1 (with no condition imposed on its frequency dependence). At each frequency, r_1 was calculated from the measured values of X_s and R_s at that frequency.

Combining Equations (7-7) and (7-8), one obtains

$$\frac{R_s - r_2}{X_s} = \frac{X_p (r_1 + R_p)}{r_1 R_p} = \frac{X_p}{(r_1 // R_p)} \qquad (7\text{-}29)$$

$$X_s X_p = (R_s - r_2)(r_1 // R_p)$$

$$= \frac{(R_s - r_2)(r_1 R_p)}{(r_1 + R_p)} \qquad (7\text{-}30)$$

$$\text{and} \quad X_p = \frac{(R_s - r_2)(r_1 R_p)}{X_s (r_1 + R_p)}$$

Substituting the value of X_p from (7-30) into (7-8), one obtains

$$X_s = \frac{r_1 R_p X_s (R_s - r_2)}{(r_1 + R_p)\left[X_s^2 + (R_s - r_2)^2\right]} \qquad (7\text{-}31)$$

Hence,

$$r_1 R_p (R_s - r_2) = (r_1 + R_p) X_s^2 + (R_s - r_2)^2 \qquad (7\text{-}32)$$

Solving (7-32) for r_1, one obtains

$$r_1 = \frac{R_p\left[X_s^2 + (R_s - r_2)^2\right]}{R_p(R_s - r_2) - X_s^2 - (R_s - r_2)^2} \tag{7-33}$$

One can also calculate X_p at all frequencies by combining Equations (7-31) and (7-30), thus

$$X_p = \frac{X_s^2 + (R_s - r_2)^2}{X_s} = -\frac{1}{\omega C_p}$$

and hence

$$C_p = \frac{-X_s}{\omega\left[X_s^2 + (R_s - r_2)^2\right]} \tag{7-23}$$

Equations (7-23) and (7-33) were used to calculate r_1 and C_p for all the rocks studied in the pretreatment experiments of Section VI. An equation of the form

$$r_1 = g/f^n \tag{7-34}$$

was assumed for each of the basalt samples. At each frequency, f, the resistance r_1 was calculated from the X_s and R_s values measured at that frequency. A least-squares fit using Equation (7-34) was performed on these data points. Table 7-2 presents a summary of the values of g and n computed for each basalt sample in the dry state and after being subjected for various pretreatment conditions.

Table 7-2. Basalt Parameters of the Equation $r_1 = g/f^n$

Basalt Rock State ↓ / Sample →	K_1		K_2		K_4	
	g	n	g	n	g	n
Basalt (dry)	3626	0.474	2375	0.634	2048	0.704
Following 23 hour soak in water	5016	0.778	2331	0.554	2018	0.635
Following 77 hour soak in water	4775	0.782	2404	0.745	1517	0.741
Following treatment in 1% NaOH	4817	0.778	3333	0.772	2422	0.794
Following treatment in 5% NaOH	4022	0.735	2933	0.735	2159	0.779
Following treatment in 10% NaOH	3222	0.734	2344	0.670	1831	0.745
Average n		0.713		0.685		0.733
Standard deviation in n		0.109		0.075		0.052

Examination of the r_1 values in Equation (7-34) for the obtained data shows a systematic variation in the value of g with both the basaltic rock sample and its pretreatment history. Except for dry basalt, the constant n appears to be independent of the rock size or the presence of water or mobile sodium ions. For basalt, an average n value of (0.71 ±0.08) may be concluded from the present data.

Variation of the parameter g for basalt with the percentage of sodium hydroxide, c, in the pretreating solution is illustrated by the curves in Figure 7-3. The pretreatment time was 23 hours, and pretreatment in distilled water for the same period was taken to represent zero percent sodium hydroxide. In

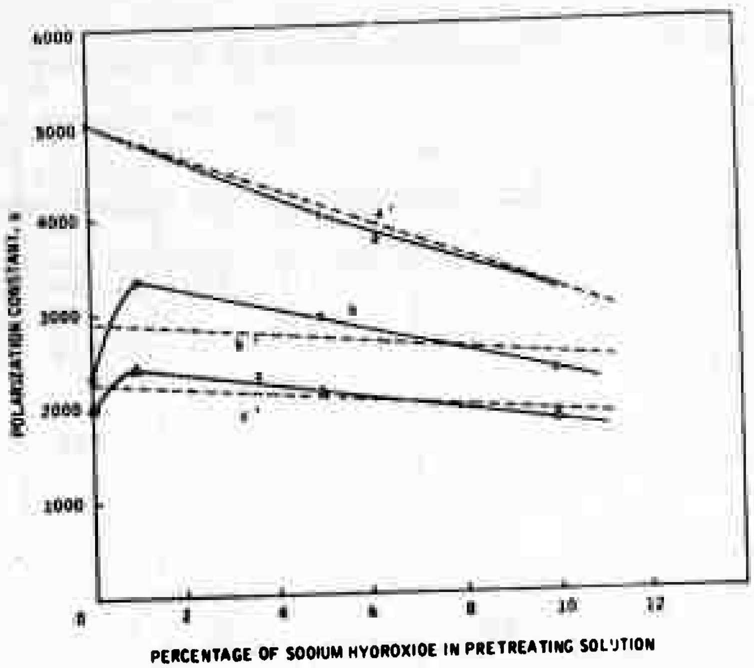


Figure 7-3. Variation of the Basalt Constant g with the Percentage of Sodium Hydroxide in the Pretreating Solution. Pretreatment Time = 23 Hours

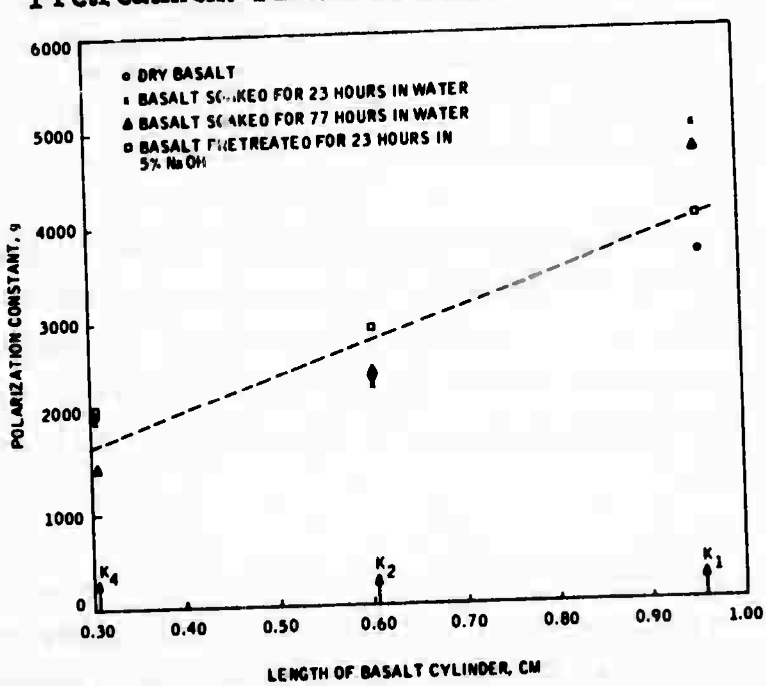


Figure 7-4. Effect of Length of Rock Cylinder on the Parameter g

general, g decreases linearly with increasing sodium content, except for the thinner rock samples K_2 and K_4 wnere a slight increase in g is observed between 0 and 1 percent sodium hydroxide. Linear least-square fitting of the data gives the following relationships:

For basalt sample K_1

$$g = 4989 - 180C \tag{7-35}$$

For basalt sample K_2

$$g = 2885 - 37.5C \tag{7-36}$$

For basalt sample K_4

$$g = 2249 - 35.4C \tag{7-37}$$

Systematic variations of the parameter g with the rock dimension are also evident from the data in Table 7-2. The variation of g with thickness of the basaltic rock cylinders is shown in Figure 7-4. The data indicate a systematic increase in g with increasing rock thickness.

CORRELATION OF IMPEDANCE POLARIZATION ARTIFACTS WITH THE MODEL

Electrode polarization effects have been found to constitute an integral part in impedance measurements. Polarization effects are simulated by the model resistor $r_1 = g/f^n$, which is parallel with the R_pC_p unit that represents the dielectric in Figure 7-1. The presence of r_1 in the model accounts for the observed deviation from the ideal or Debye dielectric behavior, and hence for the observance of a circular arc with a depressed center, rather than the Debye full semicircle in the Argand diagram.

When various basalt samples were pretreated in solutions of sodium hydroxide of various concentrations for a period of 23 hours, the polarization parameter, g, was found to decrease nearly linearly with increasing concentration of the sodium ion. It also decreases systematically with decreasing rock thickness. The exponent, n, on the other hand appears to be independent of the rock condition, dimension, or pretreatment history.

The foregoing findings suggest that most of the polarization effects reside in the electrical double layer at the rock/electrode interfacial contact. The mobile sodium ions are expected to influence the structure, and hence the relaxation properties of this double layer. Remembering that r_1 is in parallel with the dielectric model of Figure 7-1, it can be appreciated that polarization will be stronger at smaller values of r_1 (or g); i.e., in the presence of larger sodium ion contents.

CORRELATION OF r_1 WITH THE WARBURG POLARIZATION

The suggested model of Figure 7-1, with its unusual resistor r_1, provides a useful mechanism for explaining the observed results; i.e., the appearance of a circular arc with a depressed center in the Argand diagram relating the series reactance, X_s, to the series resistance, R_s (both measured at the same frequency). Electrochemical literature had often revealed many such unusual electrical components to account for electrode polarization effect. The Warburg electrochemical formula (Equation 7-13) suggests that the electrolytic polarization resistance is inversely proportional to the square root of frequency.

To explore the polarization significance of r_1, the data on dry basalt (Table 6-1) were examined in some detail. The variation of r_1 for dry basalt with $1/\sqrt{f}$ yielded a curvilinear plot, as shown in curve "a" of Figure 7-5. The points at frequencies larger than 100 Hz (the initial segments of curve "a" at $1/\sqrt{f}$ less than 0.1) appear to represent a straight line. This tangenial line (curve "b" of Figure 7-5) has a slope of 2509 and is taken to represent the Warburg resistance for dry basalt.

$$r_w = \frac{g_1}{\sqrt{f}} = \frac{2509}{\sqrt{f}} \tag{7-38}$$

The Warburg line (curve "b") was extrapolated to very low frequencies and subtracted point by point from curve "a". The resulting "difference curve" was concave as shown in curve "c" of Figure 7-5. When the data on curve "c" were plotted as a function of 1/f, straight line "d" in Figure 7-5 resulted. A new resistance, $r_k = g_2/f$, is therefore assumed to describe the polarization at very low frequencies. The slope of line "d" for the variation of this new resistance with 1/f gives a value of 4032 megohm Hz for g_2 of dry basalt.

The unusual resistor, r_1, appears to be analytically composed of two polarization terms, one of which is the Warburg resistance; thus,

$$\begin{aligned} r_1 &= r_w + r_k \\ &= \frac{g_1}{\sqrt{f}} + \frac{g_2}{f} = \frac{g}{f^n} \end{aligned} \tag{7-39}$$

For dry basalt

$$r_1 \text{ (megohms)} = \frac{2509}{\sqrt{f}} + \frac{4032}{f} = \frac{3626}{f^{0.71}} \tag{7-40}$$

Table 7-3 gives the parameters g_1 and g_2 for the rest of the basalt rock samples in the dry state as well as those following water soaking and pretreatment in sodium hydroxide. Except in a few instances, both g_1 and g_2 decrease

Table 7-3. Basalt Parameters of the Equation $r_1 = \frac{g_1}{\sqrt{f}} + \frac{g_2}{f}$

Basalt Rock State ↓ / Sample →	K_1		K_2		K_4	
	g_1	g_2	g_1	g_2	g_1	g_2
Basalt (dry)	2509	4032	881	1021	500	1000
Following 23 hour soak in water	2164	1625	1152	2187	1022	1302
Following 77 hour soak in water	1713	2256	1067	905	674	606
Following treatment in 1% NaOH	1796	2166	1389	1252	899	1035
Following treatment in 5% NaOH	2904	-382	1885	325	992	664
Following treatment in 10% NaOH	1414	1309	3607	-248	1102	233

with increasing sodium content in the pretreating solution as well as with decreasing rock thickness. Linear least-square fit of the data with the percentage, c, of sodium hydroxide gave the following relations:

- For rock sample K_1

$$g_1 = 2241 - 43C$$

and

$$g_2 = 1536 - 89C$$

- For rock sample K_2

$$g_1 = 1057 + 238C$$

and

$$g_2 = 1761 - 220C$$

- For rock sample K_4

$$g_1 = 951 + 13C$$

and

$$g_2 = 1212 - 101C$$

The increase in the Warburg coefficient g_1 for rock samples K2 and K4 with increasing sodium content is difficult to explain. Of the preceding six equations, two have a positive coefficient of g with c and the remaining have a negative coefficient. It may be suspected that the Warburg coefficient g_1 increases while the very low frequency polarization coefficient, g_2 decreases with increasing sodium content.

PHYSICAL SIGNIFICANCE OF r_1

The preceding data reveal the interesting finding that r_1 is indeed a polarization resistance. It, therefore, represents the term in which electrode polarization artifacts reside. An equally important conclusion is that electrode impedance is not in series with the sample impedance as has been universally accepted, but appears to be for the most part in parallel with it.

The inherent polarization represented by r_1, and which constitutes an integral part of the measurement, is evidently responsible for the deviation of the dielectric from the ideal or Debye behavior. The model has, therefore, permitted for the first time a clarification of the complex polarization term in rock impedance. R_p is directly determinable from the point of farthest intersection of the experimental circular arc with the R_s axis. If one corrects for the polarization effects, the time constant or relaxation time, τ, for the ideal system is given by the product R_pC_p. For the real system, the model Equation 7-12 gives a time constant of

$$\tau = R_pC_p\sqrt{1 + K^2} \qquad (7\text{-}20)$$

where $K = \cotan\varphi$ and φ is the rock phase angle. The relaxation time, τ, can be determined independently of the model assumptions by plotting $-X_s$ as a function of log f. The maximum in reactance will determine the turnover frequency, f_{max}, from which τ can be calculated as

$$\tau = \frac{1}{\omega_{max}} = \frac{1}{2\pi f_{max}} \qquad (7\text{-}3)$$

The capacitance of the condenser, C_p, can thus be calculated from experimental data by Equations (7-3) and (7-20). The model, therefore, permits complete analysis of the rock impedance parameters for estimating its complex dielectric constant, $\kappa^* = \kappa' - j\kappa''$. Here κ' will be related to the condenser C_p, and κ'' is related to the rock conductivity as given by the reciprocal of R_p.

SECTION VIII
TECHNICAL REPORT SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

TECHNICAL REPORT SUMMARY

This research program was initiated to determine the electric and dielectric properties of rocks with the objective of finding a correlation between these properties and the rock geophysical characteristics and structure. Low-frequency data will eventually be useful to determine the presence of underground water and entrapped oil and gases ahead of excavation, and for underground tunneling. Accurate knowledge of the rock impedance and dielectric properties enables us to determine the attenuation of electromagnetic fields and thus predict the range and frequency for underground communication systems.

For this study program a novel technique of determining the electrical properties of rocks has been used that allows us to directly display complex impedance as a function of frequency. Three characteristic rock samples have been investigated in the frequency range from 0.05 Hz to 2 kHz. The data obtained were displayed in an Argand diagram and could be fitted very closely by an arc of circle with a depressed center.

An equivalent circuit with an RC network was used to determine from the resistivity values at zero and infinite frequencies the dielectric constant at the corresponding frequencies. The method depends on "bracketting" the circular arc in both the Argand and the Cole-Cole plot and on the assumption that a single relaxation time must be the same for both the impedance and the dielectric dispersions. The computer algorithm has been extended to derive the dielectric loss, ϵ'', or imaginary part of the dielectric constant, κ'', and the real part of the dielectric constant, κ', at the frequencies at which the specific impedance parameters are measured. The conversion technique by rotating the impedance vector from the Argand plane and transforming it to the permittivity vector in the dielectric plane is novel and reported here for the first time. Application of this technique to the impedance data of basalt and quartzite gave dielectric constants that agree reasonably well with those reported in the literature.

The hypothetical electrical model used in this investigation consists of a resistor, which is frequency dependent, in parallel to a capacity. Both are shunted by a resistor. This model successfully describes the detailed experimental results. The polarization effect can be described by a resistor whose value is inversely proportional to frequency with a power between 0.5 and unity.

The electrode impedance effects have been determined from a series of measurements with slices of various thicknesses cut from the same cylindrical sample. The electrode effects are significant for thin rock samples where they may represent a substantial portion of the measured impedance. For long rock samples the electrode correction may be negligible. However, in this case the sample impedance may be comparable or larger than the amplifier impedance preventing a stable measurement.

RECOMMENDATIONS FOR FUTURE WORK

It is highly desirable to extend the capability of our on-line computer technique beyond the kilohertz range. Extention to the mega- and gigahertz range has been recommended in Honeywell proposal 1D-E-3, "Effect of Frequency and Temperature on Rock Dielectric Parameters." The effect of temperature on rock impedance is illustrated by the results of the following preliminary tests.

Experiments were performed on basalt (IV) to determine the effect of temperature on rock impedance. The basaltic sample (IV used in this experiment was a large circular disc 0.54 cm in thickness and 5.21 cm in diameter. It differed from the previous Dresser basalts (I), (II), and (III) used in previous experiment in both color and grain size. The new sample was darker in its greenish tint than the former samples. The change in texture may be attributed to a different phase of rock formation. Impedance was measured at both room temperature (22°C) and the melting point of ice (0°C). At the low frequency of 0.1 Hz, the impedance at the ice point is considerably higher than that at room temperature. As the frequency increases, the temperature effect becomes less pronounced. Table 8-1 gives the resistive and reactive impedance components at room temperature and at nominal frequencies ranging from 0.1 to 2000 Hz. The variation of the series reactance at room temperature, X_s, with log frequency is shown as curve A of Figure 8-1, while curve B shows the variation of the rock series resistance, R_s. Both curves indicate a turnover frequency, f_{max}, of 9.96 Hz, which corresponds to a room temperature relaxation time, τ, of

$$\tau = \frac{1}{\omega_{max}} = \frac{1}{2\pi f_{max}} = 15.9 \text{ milliseconds} \qquad (8\text{-}1)$$

When the previous experiment was repeated at the melting point of ice, the data in Table 8-2 were obtained. Variation of the impedance parameters, at room temperature with log frequency, is shown in Figure 8-2, where a turnover frequency, f'_{max}, of 2.00 Hz is determined. At 0°C, the relaxation time is given by

$$\tau' = \frac{1}{2\pi f'_{max}} = 79.5 \text{ milliseconds} \qquad (8\text{-}2)$$

Table 8-1. Impedance Data on Basalt (IV) at 22°C

LAST RECORD IS T4- 2 4/23/71
ZEEGO MOD I

B6-1 4/26/71

ENTER RCAL/UNITS
2Ø.
MEGS

FRQ	RES	RAEC	PHI
Ø.Ø9	32.6651	-3.5772	-6.25
Ø.5Ø	26.5789	-4.54Ø7	-9.7Ø
Ø.99	24.472Ø	-5.3178	-12.26
2.ØØ	21.8Ø83	-6.1671	-15.79
5.Ø2	17.6153	-7.Ø98Ø	-21.95
7.95	15.2352	-7.2887	-25.57
9.96	14.Ø585	-7.2972	-27.43
14.97	11.9454	-7.1662	-3Ø.96
2Ø.Ø2	1Ø.4838	-6.9575	-33.57
3Ø.Ø3	8.5419	-6.5137	-37.33
4Ø.16	7.2568	-6.11Ø3	-4Ø.1Ø
5Ø.1Ø	6.3452	-5.7679	-42.27
99.5Ø	4.Ø188	-4.5Ø73	-48.28
2ØØ.27	2.3545	-3.2393	-53.99
5Ø3.36	1.1232	-1.8585	-58.86
998.19	Ø.6598	-1.1528	-6Ø.22
2Ø22.Ø6	Ø.4Ø74	-Ø.654Ø	-58.Ø6

17 SAMPLES

CIRCLE CENTER = 16.9612 2Ø.4344
RADIUS = 27.6828
ERROR Ø.88188 REDUCED TO Ø.58838
IN 17 STEPS

Table 8-2. Impedance Data on Basalt (IV) at 0°C

CRT CALIBRATION

DATA TAPE ON UNIT 2 - PUSH START
************* PAUS *************
LAST RECORD IS B6-1 4/26/71
ZEEGO MOD I

B7-1 4/26/71

ENTER RCAL/UNITS
20.
MEGS

FRQ	RES	RAEC	PHI
0.09	160.3149	-26.5281	-9.40
0.50	110.5509	-36.2007	-18.16
0.99	92.3657	-39.2870	-23.04
2.00	72.3747	-39.8985	-28.87
5.00	47.1312	-36.0387	-37.41
7.96	35.9375	-32.2504	-41.91
9.95	31.1345	-30.1291	-44.06
20.02	19.0096	-22.9683	-50.39
30.08	13.8184	-18.9881	-53.96
40.23	10.8011	-16.3439	-56.54
50.05	8.8994	-14.4474	-58.37
99.50	4.7105	-9.4347	-63.47
200.27	2.3633	-5.7473	-67.65
504.20	0.9996	-2.7933	-70.32
998.19	0.5700	-1.5737	-70.10
2018.35	0.3682	-0.8424	-66.40

16 SAMPLES

CIRCLE CENTER = 91.5041 87.5214
RADIUS = 129.8529
ERROR 5.15521 REDUCED TO 2.35518
IN 11 STEPS

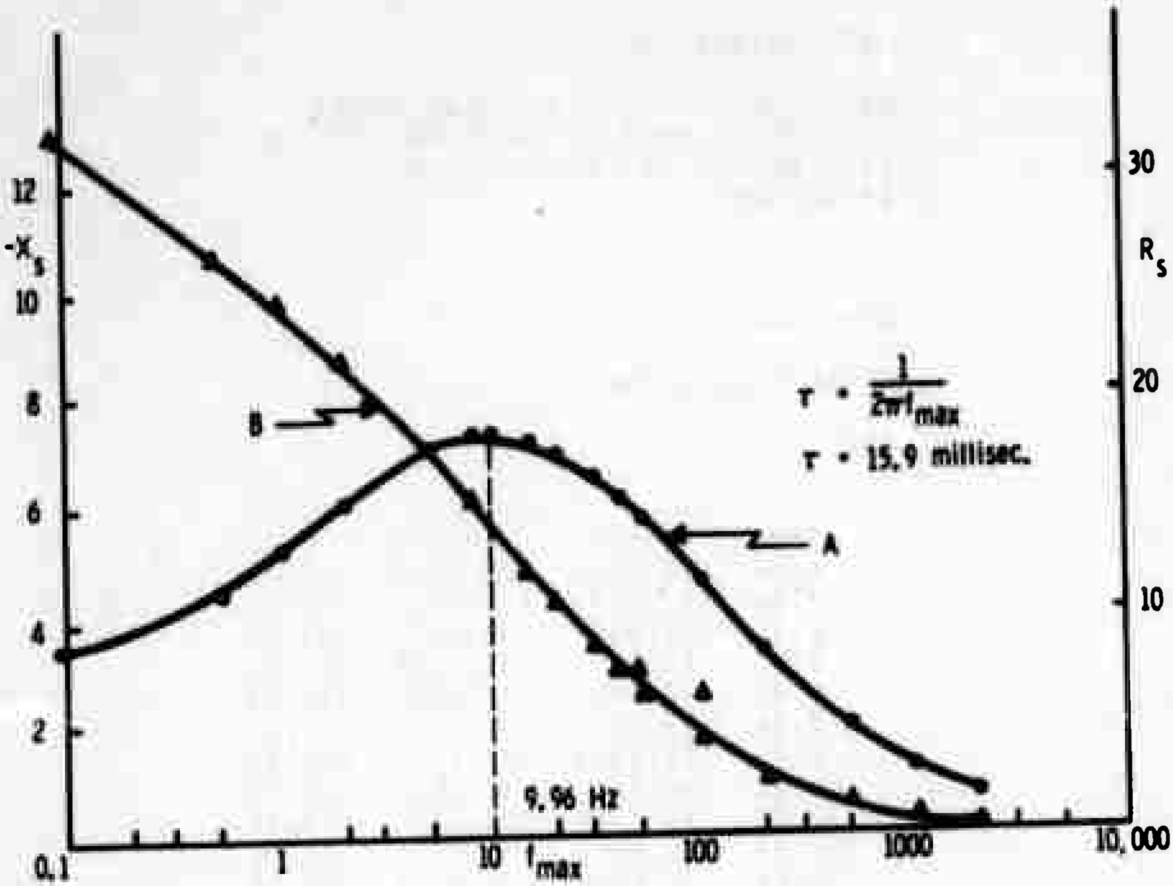


Figure 8-1. Variation of Impedance Parameters with Log Frequency for Dresser Basalt (IV) at Room Temperature, 22°C

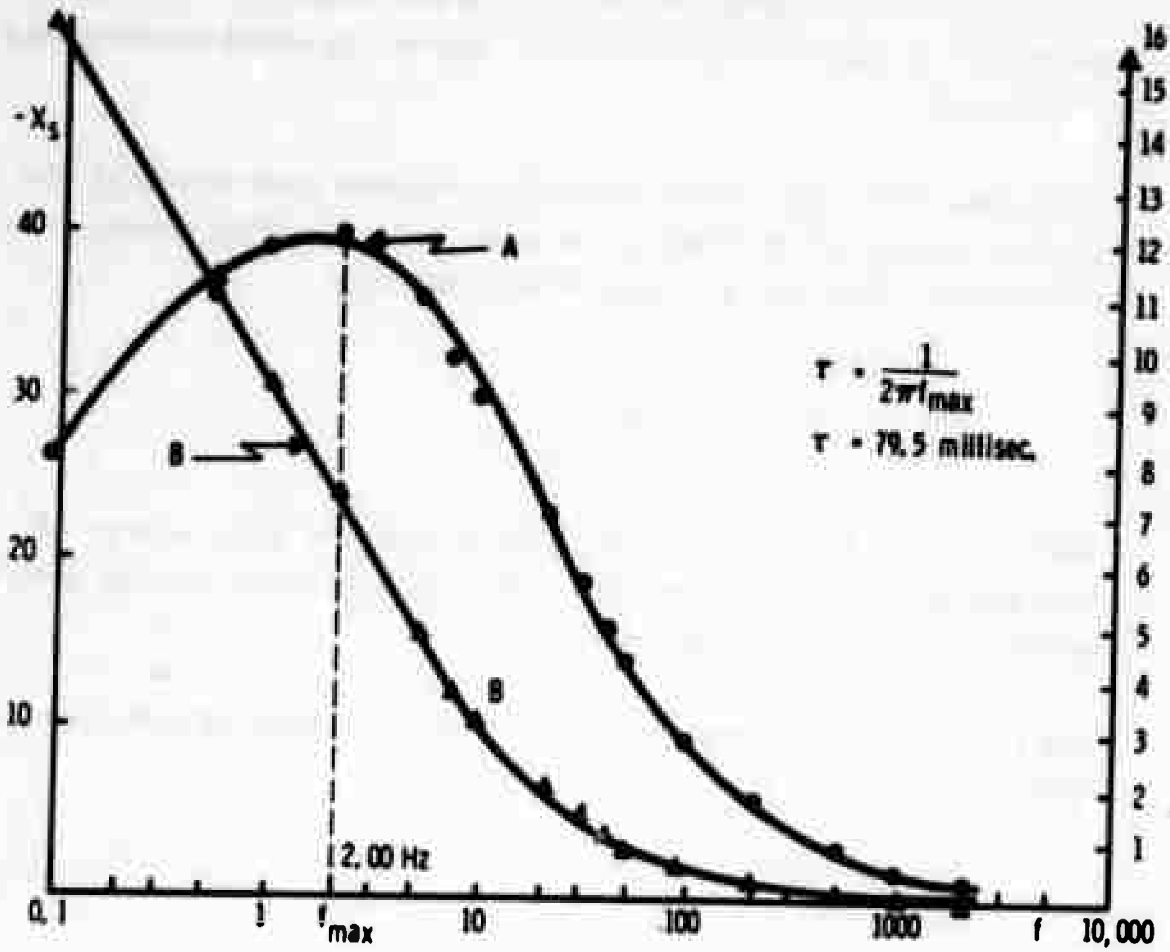


Figure 8-2. Variation of Impedance Parameters with Log Frequency for Dresser Basalt (IV) at 0°C

The rock d-c resistance, R_o, at 0°C is 191. 8 megohms, which should be compared to the room temperature value of 37. 3 megohm. Thus both rock d-c resistance and relaxation time decrease significantly with rise in temperature. At higher frequencies, the temperature effect becomes less pronounced.

According to Eyring's theory of absolute reaction rates (Ref. 26), the turnover or characteristic frequency is equal to the universal frequency (kT/h), modified by a free energy of activation term; thus

$$f_{max} = \left(\frac{kT}{h}\right) e^{-\Delta F^{\dagger}/RT} \qquad (8-3)$$

where k is Boltzmann's constant, T is the absolute temperature, $\Delta F^{\dagger}$ is the free energy of activation per mole of the relaxing unit within the rock matrix, and R is the molar gas constant.

The free energy of activation is related to the enthalpy of activation, ΔH, per mole of relaxing units by

$$\Delta F^{\dagger} = \Delta H^{\dagger} - T\Delta S^{\dagger} \qquad (8-4)$$

where $\Delta S^{\dagger}$ is the entropy of activation. Applying Equation (8-4) into (8-3), one obtains

$$f_{max} = \left(\frac{kT}{h}\right) e^{\Delta S^{\dagger}/R} \; e^{-\Delta H^{\dagger}/RT} \qquad (8-5)$$

or

$$\ln (f_{max}/T) = \ln \frac{k}{h} + \frac{\Delta S^\dagger}{R} - \frac{\Delta H^\dagger}{RT} \qquad (8\text{-}6)$$

Normally one determines f_{max} at a series of temperatures and establishes the validity of the foregoing equations by ascertaining that the plot of ln (f_{max}/T) against (1/T) is linear. From the slope of this linear plot one determines the enthalpy or heat of activation, $\Delta H^\dagger$; thus,

$$\text{Slope} = -\frac{\Delta H^\dagger}{R} \qquad (8\text{-}7)$$

and from the intercept of the linear plot with the ordinate, one can determine the entropy of activation, $\Delta S^\dagger$; thus,

$$\text{Intercept} = \ln\left(\frac{k}{h}\right) + \frac{\Delta S^\dagger}{R} \qquad (8\text{-}8)$$

Applying Equation (8-5) to the data obtained in this preliminary work, and remembering that T = 295°K for room temperature (22°C), and T = 273°K for the ice point, then

$$\frac{(f_{max}/T)}{(f'_{max}/T')} = e^{-\frac{\Delta H^\dagger}{R}\left(\frac{1}{T} - \frac{1}{T'}\right)}$$

or

$$\ln\left[\frac{f_{max}\,T'}{f'_{max}\,T}\right] = \frac{\Delta H^\dagger}{R}\left[\frac{1}{T'} - \frac{1}{T}\right] \qquad (8\text{-}9)$$

The enthalpy of activation, $\Delta H^{\dagger}$, is calculated from Equation (8-9); thus

$$\Delta H^{\dagger} = 2.303R \frac{TT'}{(T - T')} \log \left[\frac{f_{max} T'}{f'_{max} T}\right] = 10,700 \text{ calories}$$

For one mole of the relaxing unit within the rock (92 grams for the SiO_4 tetrahedron).

Hence, it is estimated that the activation energy for the relaxation process in basalt is about 11 Kcal per mole of relaxing units, or about 0.5 ev (1 ev = 23.05 Kcal/mole).

Future work in this area will further investigate the influence of temperature on the relaxation process and utilize it to compute both the enthalpy and entropy of activation. Further studies of the pressure effect should yield more information on the volume of activation and entropy of activation of aggregate interactions. This new set of data should yield deeper insights in rocks' ultimate structure and their petrogenesis.

The complex impedance of rock samples at a range of frequencies that brackets their turnover frequency would yield valuable information on the relaxation time(s) of the silica tetrahedra and other structural groups within the rock, and the presence or absence of conductive materials. In general, a Cole-Cole circular-arc plot would be obtained in the complex dielectric diagram. With complex structures, the resulting figure may be analyzed into a series of nearby semicircular arcs, each describing a given relaxation mechanism with some interaction coefficients among the various aggregates (Refs. 27 and 28). The same Cole-Cole plot can be obtained in a complex impedance diagram, sometimes called Argand diagram. Sinbel (Khalafalla) (Ref. 20) showed that the plot of the series reactance, X_s, against the series resistance, R_s (both determined at a given frequency), in a complex system should yield a semicircle arc. The intersection of this circular arc with the real (resistive) axis will define the d-c resistance, R_o (at the farthest right end). Any point on the arc will define the impedance radius vector with both its reactive and resistive components readily available.

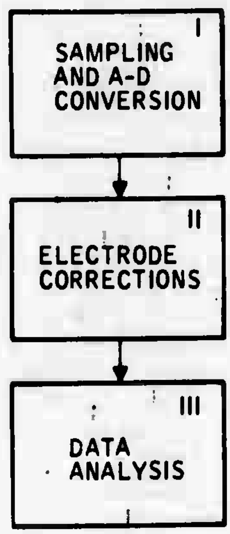
Structural relaxation times in rocks can also provide valuable information in rock elastic moduli. Debye (Ref. 18) related relaxation times to viscosity in liquid systems. Elasticity corresponds to mechanically recoverable energy and viscous flow or friction to the conversion of mechanical energy into heat. Because of the similarity between viscous resistance to flow and friction between solid surfaces, the resistance to flow of a fluid is the analogue to internal friction or shear within a solid. These areas of endeavor in rock dielectric relaxation constitute our long range research goals.

In his opening remarks for "tables of dielectric materials" Professor Arthur R. Von Hippel (Ref. 9), a leading authority who heads this country's clearing house for information about dielectrics since World War II, states "We are fully aware that these data should be expanded, especially towards higher temperatures and frequencies; that a real dielectric analysis of the materials should be undertaken, linking the dielectric response to composition and structure..." We believe the rock data in this research are a step toward achieving these goals.

SECTION IX
COMPUTER ALGORITHMS

DATA PROCESSING AND COMPUTER PROGRAMS

The system is composed of three main programs:



These three programs are described in further detail on the following pages. Program listings are included for programs II and III. Program I contains much machine language code; therefore, its listing was not included.

SAMPLING AND A-D CONVERSION

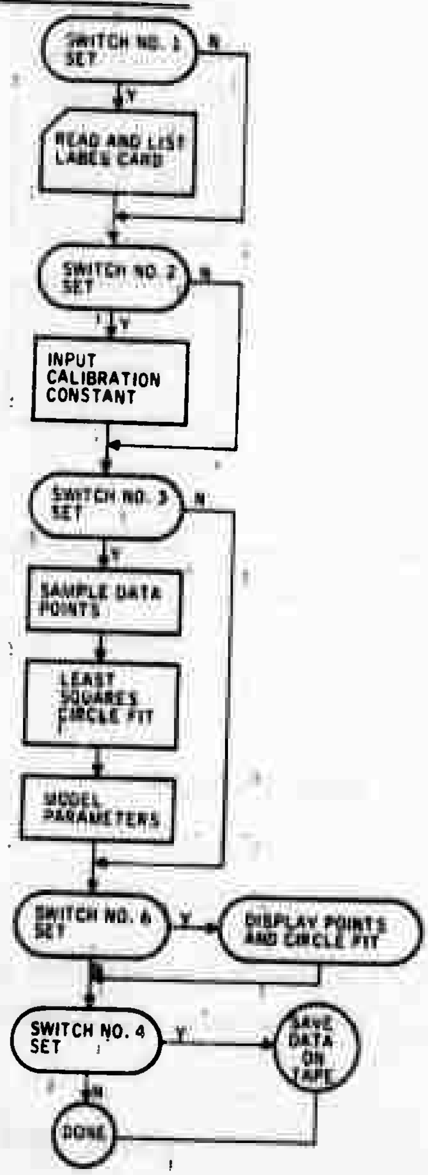
Description

The output of the rock amplifier is sampled and converted to digital form. Provision is made to enter a calibration constant for the circuit. At each frequency the series resistance R_s, series reactance X_s, series reactance X_s, and phase, angle are listed.

When all points have been sampled, a least-squares bit is made to the R_s, X_s data. This arc and the data points are optionally displayed on a CRT screen.

The data can also be stored on magnetic tape to be used by other programs in the system.

Flow Chart - Sampling and A-D Conversion



ELECTRODE CORRECTIONS

Description

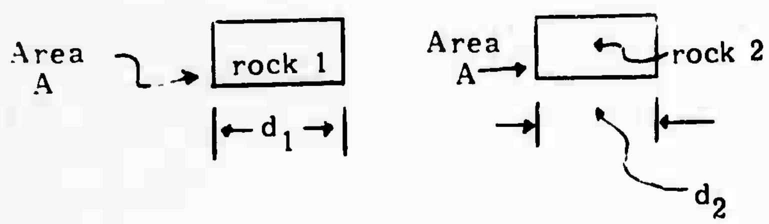
This program calculates the electrode corrections based on the R_s, R_s data fr from two samples. As a further refinement in the correction technique, all pairs of three racks taken two at a time are averaged to yield a better correction for each rack.

For example,

1) Compute correction for K1 and K2
2) Compute correction for K2 and K4

Average results of (1) and (2) yield correction for K2.

The correction formula is derived as follows: consider two samples of the same rock,



For rock alone,

$$Z_R \propto \frac{d}{A}$$

i.e., $R_R \propto \frac{d}{A}$, $X_R \propto \frac{d}{A}$

Thus for two rocks,

$$\frac{R_{R_1}}{R_{R_2}} = \frac{X_{R_1}}{X_{R_2}} = \frac{d_1}{d_2} = \frac{1}{\beta} \qquad (9\text{-}1)$$

We measure R_m, $\overline{X}_m$, which include electrode polarization effects.

Thus,

$$\left.\begin{aligned} R_{m_1} &= R_{R_1} + R_{e_1} \\ R_{m_2} &= R_{R_2} + R_{e_2} \end{aligned}\right\} \qquad (9\text{-}2)$$

from (9-1) one gets

$$\frac{R_{m_1} - R_{e_1}}{R_{m_2} - R_{e_2}} = \frac{1}{\beta} \qquad (9\text{-}3)$$

assuming

$$R_{e_1} = R_{e_2} = R_e$$

then R_e can be calculated as a correction to R_m; thus,

$$\frac{R_{m_1} - R_e}{R_{m_2} - R_e} = \frac{1}{\beta} \qquad (9\text{-}4)$$

yields

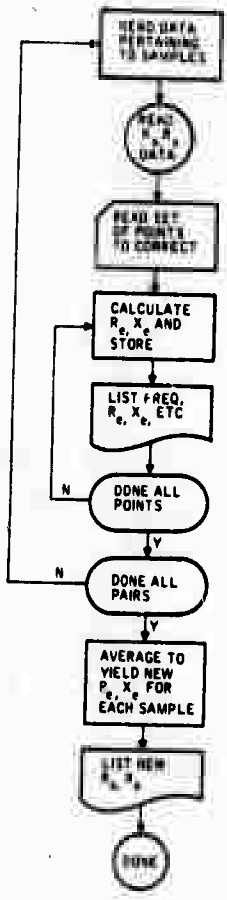
$$R_e = \frac{R_{m_2} - \beta R_{m_1}}{1 - \beta} \tag{9-5}$$

similarly

$$X_e = \frac{X_{m_2} - \beta X_{m_1}}{1 - \beta} \tag{9-6}$$

The electrode corrections R_e, X_e arrived at in this manner are listed on the console typewriter. Cards with these correction factors can then be punched to be used by the data analysis program.

Flow Chart -- Electrode Correction



The Data Analysis Program consists of the main program and 5 subroutines. In brief the program does the following:

- Recalls, from magnetic tape, data points resulting from a specified experimental run.
- Selects some or all of the data points for further analysis.
- Makes phase, amplitude, and, optionally, electrode corrections to the data points before further analysis.
- Fits a "best" circle to the data points
- Determines parameters of our model from this circle.
- Determines miscellaneous parameter from the data points.

Each of these is described in more detail in the following pages, with a general flow chart of the program and a program listing.

LOADING EXPERIMENTAL DATA

The data from each experiment consists of 5 physical records on magnetic tape. To locate required data, the appropriate number of records is skipped and the desired 5 data records are read. The following is a brief description of these records.

- Record 1, 8 words
- Words 1-4 - label describing experiment (e.g., K4 9/17/71 77 Hr)
- Words 5, 6 - unused

- Word 7 - N = number of data points
- Word 8 - unused.
- Record 2, 50 words (2 words/data point)

  Frequency:

  F(I) = I = 1, . . . N $N \leq 25$
- Record 3, 50 words (2 words/data point)

  R_s:

  X(I) I = 1, . . . N $N \leq 25$
- Record 4, 50 words, (2 words/data point)

  X_s:

  Y(I) I = 1, . . . N $N \leq 25$
- Record 5, 80 words (2 words/data point)

  Working array Q:

  Q(I) I = 1, . . . 40

This is an array where intermediate information is stored for communication between the main program and its subroutines. For example, Q(40) is the calibration constant used in the experiment.

DATA SELECTION

Selection of the data points is done by the following technique.

A card is read containing the number of points to delete from fruther analysis NDEL $0 \leq NDEL \leq N$. N is then decreased by this amount; N = N = NDEL.

Another card is then read specifying which points to select for this run. The points must be in ascending order and the total number of points must equal this revised N. The F, X, and Y arrays are then "compressed" (i.e., any points not selected are deleted) for ease of processing by the rest of program.

For example, assume original N = 7 and we wish to delete 2 points (2, 5):

- Card 1 contains Ø2
- Card 2 contains Ø1 Ø3 Ø4 Ø6 Ø7

CORRECTIONS TO DATA

Uncorrected phase angle PHIM is corrected to PHI. The following equation is used.

To correct for phase X frequency errors from the frequency generator used in the experiment.

$$R_s = \frac{X(I) \cos (PHI)}{\cos (PHIM)}$$

$$X_s = \frac{Y(I) \sin (PHI)}{\sin (PHIM)}$$

In addition, X_s, R_s are further corrected if the frequency F(I) is >1000 Hz.

Optional electrode corrections R_e, X_e are read in on cards.

$$R_s = R_s' - R_e$$

$$X_s = X_s' - X_e$$

$$Z = \sqrt{X_s^2 + R_s^2}$$

The corrected X_s, R_s are then stored back into X(I), Y(I); X_s, R_s, Z are all multiplied by A/d (AOD) for the given sample

The following are listed if desired on the console typewriter.

$$F(I),\ R_s,\ X_s\ R*\frac{A}{d},\ X*\frac{A}{d},\ PHI,\ Z,\ Z*\frac{A}{d}$$

FITTING CIRCLE TO DATA POINTS

Subroutine CENTER and EVAL are used together to fit a circle to X(I), Y(I) I = 1, . . . N.

Subroutine EVAL(CX, CY, R, RV, NSTEPS) does the following:

find

$$T_i = [CX - X(I)]^2 + [CY - Y(I)]^2$$

and

$$R = \sum_{i=1}^{N} T_i/N$$

$$RV = \left[\sum_{i=1}^{N} T_i^2/N - R^2\right]^{\frac{1}{2}} \qquad RV \geq 0$$

That is, it calculates the mean and standard deviation of the data points about a given center (CX, CY).

If the standard deviation is less than the previous standard deviation, the new center coordinates are stored along with the new mean and standard deviation. NSTEPS is increased by 1 and the subroutine is exited.

Subroutine CENTER utilizes subroutine EVAL as follows. A guess is made for the initial CX, CY and a counter Ns is set to zero. Call EVAL and store CX, CY, and standard deviation.

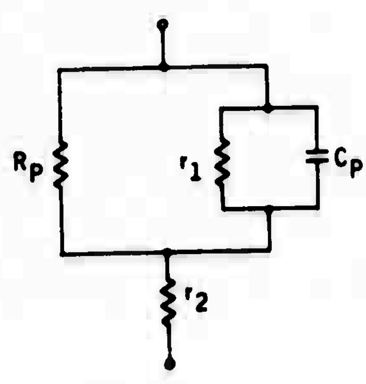
By successively modifying CX, CY and calling EVAL, a search is made for the CX, CY yielding the lowest standard deviation. These coordinate CX, CY, the radius, and

$$FIT = \frac{100 * \text{ standard deviation}}{R}$$

is printed and control returns to the main program

MODEL PARAMETERS

Having found the "best" circle fit to the data points, the following parameters are calculated and printed.



R_p, r_2, r_1 are determined from the circular arc.

In addition

$$C_p = \frac{\sum_{1=2}^{N} \frac{1}{2}(f_i - f_{i-1}) \times (C_i - C_{i-1})}{f_n - f_1}$$

where f_i is frequency at point i,

and

$$C_i = - \frac{X_{s_i}}{2\pi f_i \left[(R_{s_i} - R_2)^2 + X_s^2\right]}$$

$RHO = R_o\left(\frac{A}{d}\right)$ ohm-cm is also printed.

Also calculated and printed in subroutine EPSILN are the following:

$$\tau = (R_o - R_\infty)\, C_p \sqrt{1 + \cot an^2 \varpi}$$

where

$$\varpi = \sin^{-1}\left[\frac{R_o - R_\infty}{2r}\right] , \quad r = \text{radius of circle}$$

$$\epsilon_o = \frac{\tau}{\frac{A}{d} R_\infty} , \quad \epsilon_\infty = \frac{\tau}{\frac{A}{d} R_o}$$

also printed for each frequency f_i

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_o - \epsilon_\infty}{2}\left[1 - \frac{\sin h(1-\alpha)\, s}{\cos h(1-\alpha)\, s + \cos \frac{\alpha\pi}{2}}\right]$$

and

$$\epsilon'' = \frac{\frac{1}{2}(\epsilon_o - \epsilon_\infty)\cos\left(\frac{\alpha\pi}{2}\right)}{\cosh(1-\alpha)s + \sin\frac{\alpha\pi}{2}}$$

where $s = \log_e(\omega\tau)$ and Cole-Cole parameter α is related to the rock phase angle φ; thus

$$\varphi = \frac{\pi}{2}(1-\alpha)$$

MISCELLANEOUS PARAMETERS

For each of the samples K1, K2, K4 under various conditions, the following calculations were made.on the uncorrected data for each frequency

$$r_1 = \frac{R_o[X_s^2 + (R_s^2 - R_\infty)^2]}{R_o[R_s - R_\infty] - [X_s^2 + (R_s - R_\infty)^2]} \qquad (9\text{-}7)$$

An equation of the form

$$r_1 = \frac{g}{f^n}$$

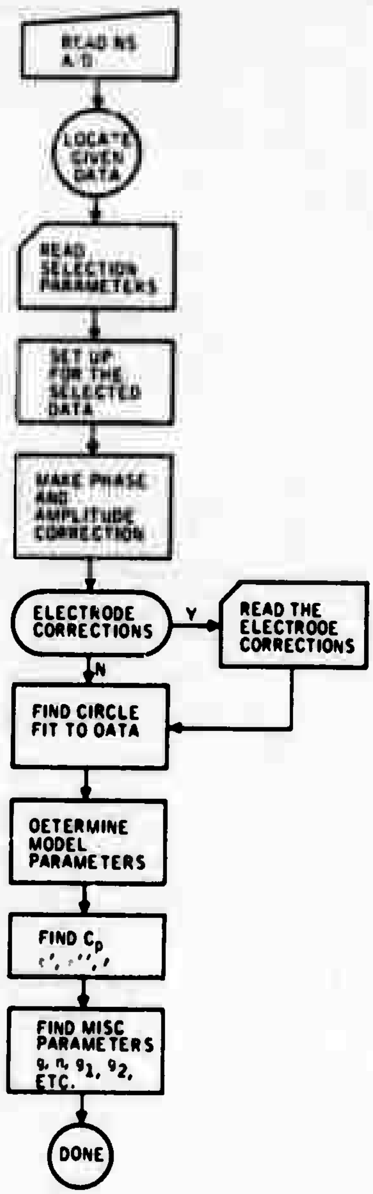
was assumed and a least-squares fit was done on the points calculated from (9-7).

An equation of form

$$r_1 = \frac{g_1}{\sqrt{f}} + \frac{g_2}{f} \qquad (9\text{-}9)$$

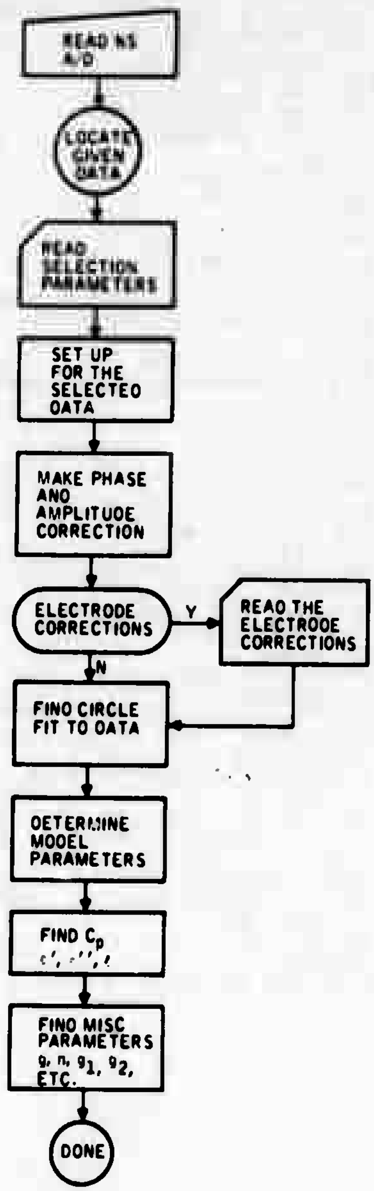
was also assumed and another least-squares fit wad done on points from (9-7).

DATA PROCESSING FLOW DIAGRAM PROGRAM LOGIC



was also assumed and another least-squares fit wad done on points from (9-7).

DATA PROCESSING FLOW DIAGRAM PROGRAM LOGIC



```
C      ELECRODE CORRECTION PROGRAM
       DIMENSION XE1(25),XE2(25),XE3(25)
       DIMENSION RE1(25),RE2(25),RE3(25)
       DIMENSION RM1(25),XM1(25),M1(25),M2(25)
       COMMON F(25),X(25),Y(25),N,Q(40)
       DIMENSION LABEL(4),U(25),V(25),M(8)
       EQUIVALENCE (M(1),LABEL(1)),(M(5),UNITS),(M(7),N)
       L=0
    90 L=L+1
       READ(3,103) NS1,NS2,D1,D2
   103 FORMAT(2I3,2F10.0)
       NSKIP=5*NS1
       IF(NS1.GT.0) CALL SKIPR(2,NSKIP)
     1 CALL TARO (2,M,8,4,IE)
       IF(IE.EQ.3) GO TO 10
       CALL TARO (2,F,50,4,IE)
       CALL TARC (2,X,50,4,IE)
       CALL TARC (2,Y,50,4,IE)
       CALL TARC (2,Q,80,4,IE)
       REWIND 6
       WRITE(1,104) LABEL
   104 FORMAT( /10X4A4)
       DO 3 I=1,N
       PHIM = ATAN2(Y(I),X(I))
       Z = SQRT(X(I)**2+Y(I)**2)
       G = Z/Q(40)
       PHI = PHIM + (7.0*ALOG10(G) + 15.0)*F(I)*0.00001
       RS = X(I)*COS(PHI)/COS(PHIM)
       XS= Y(I)*SIN(PHI)/SIN(PHIM)
       IF(F(I).LE.1000.) GO TO 4
     2 CF = *(1.9*EXP(ALOG10(G)) + 4.45)*(F(I)-1000.)*0.00001 + 1.
       RS=RS/CF
       XS=XS/CF
     4 RM1(I)=RS
     3 XM1(I)=XS
       NSKIP=5*NS2
       IF(NS2.GT.0) CALL SKIPR(2,NSKIP)
       CALL TARC (2,M,8,4,IE)
       IF(IE.EQ.3) GO TO 10
       CALL TARO (2,F,50,4,IE)
       CALL TARO (2,X,50,4,IE)
       CALL TARO (2,Y,50,4,IE)
       CALL TARO (2,Q,80,4,IE)
       REWIND 6
       WRITE(1,104) LABEL
       WRITE(1,110)
   110 FORMAT(//8X1HF,11X2HRE,8X2HXE,8X2HR1,9X2HX1,9X2HR2,9X2HX2)
       DO 8 I=1,N
       PHIM = ATAN2(Y(I),X(I))
       Z = SQRT(X(I)**2+Y(I)**2)
       G = Z/Q(40)
       PHI = PHIM + (7.0*ALOG10(G) + 15.0)*F(I)*0.00001
       X(I)=X(I)*COS(PHI)/COS(PHIM)
       Y(I)=Y(I)*SIN(PHI)/SIN(PHIM)
       IF(F(I).LE.1000.) GO TO 8
       CF = *(1.9*EXP(ALOG10(G)) + 4.45)*(F(I)-1000.)*0.00001 + 1.
       X(I)=X(I)/CF
       Y(I)=Y(I)/CF
     8 CONTINUE
C      RM2 AND XM2 ARE NOW IN X AND Y
```

```
      READ(3,105) NN
  105 FORMAT(25I2)
      READ(3,105) (M1(J),J=1,25)
      READ(3,105) (M2(J),J=1,25)
      DO 5 I=1,NN
      J=M1(I)
      K=M2(I)
      XX=RM1(J)
      YY=X(K)
      DBD=D2/D1
      RE= (YY-DBD*XX)/(1.-DBD)
      XX=XM1(J)
      YY=Y(K)
      XE=(YY-DBD*XX)/(1.-DBD)
      RR1=RM1(J)-RE
      RR2=X(K)-RE
      XR1=XM1(J)-XE
      XR2=Y(K)-XE
      IF(L-2) 200,300,400
  200 RE1(I)=RE
      XE1(I)=XE
      GO TO 500
  300 RE2(I)=RE
      XE2(I)=XE
      GO TO 500
  400 RE3(I)=RE
      XE3(I)=XE
  500 CONTINUE
      WRITE(1,106) F(K),RE,XE,RR1,XR1,RR2,XR2
    5 CONTINUE
  106 FORMAT(3XF9.3,3X2F10.3,4F11.4)
      IF(L-2) 90,90,550
  550 CONTINUE
      DO 1000 L=1,3
      DO 1000 I=1,NN
      IF(L-2) 600,700,800
  600  RE=.5*(RE1(I)+RE2(I))
      XE=.5*(XE1(I)+XE2(I))
      GO TO 900
  700 RE=.5*(RE2(I)+RE3(I))
      XE=.5*(XE2(I)+XE3(I))
      GO TO 900
  800 RE=.5*(RE1(I)+RE3(I))
      XE=.5*(XE1(I)+XE3(I))
  900 CONTINUE
      WRITE(1,8000)RE,XE
 8000 FORMAT(2F11.5)
 1000 CONTINUE
   10 STOP
      END
```

```
@FORTRAN LS
C      MAKES PHASE AND AMPLITUOE CORRECTIONS TO RAW DATA
C      MAKES ELECTROOE CORRECTIONS (SSW 1)
C      CIRCLE FITS CORRECTED OATA
C      CALCULATES PERMITIVITY AND LOSS FACTOR
        COMMON F(25),X(25),Y(25),N,Q(40),CP
        OIMENSION LABEL(4),U(25),V(25),M(8)
        EQUIVALENCE (M(1),LABEL(1)),(M(5),UNITS),(M(7),N)
        OIMENSION MAP(25)
        OIMENSION REV(25),XEV(25)
        WRITE(1,102)
  102 FORMAT(51HENTER NS,AOO   PUT SSW1 UP FOR ELECTRODE CORRECTION)
        READ(1,103) NS,AOO
  103 FORMAT(I3,F10.0)
        NSKIP=5*NS
        IF(NS.GT.0)CALL SKIPR(2,NSKIP)
    1 CALL TARO (2,M,8,4,IE)
        IF(IE.EQ.3) GO TO 10
        CALL TARO (2,F,50,4,IE)
        CALL TARO (2,X,50,4,IE)
        CALL TARD (2,Y,50,4,IE)
        CALL TARO (2,Q,80,4,IE)
        REWINO 6
        REAO(3,8000) NOEL
        N=N-NDEL
         READ(3,8000) MAP
 8000 FORMAT(25I2)
        OO 300 I=1,N
        J=MAP(I)
        IF(I-J) 290,300,290
  290 F(I)=F(J)
        X(I)=X(J)
        Y(I)=Y(J)
  300 CONTINUE
        WRITE(1,104) LABEL,AOO
  104 FORMAT(//10X4A4,10X4HAOO=F9.5,5X29HPHASE ANO AMPLITUOE CORRECTED/)
        CALL SSWTCH(5,I5)
        IF(I5.EQ.1) GO TO 50
        WRITE(1,101)
  101 FORMAT(/8X3HFRQ,8X2HRS,10X2HXS,9X4HRAOO,10X4HXAOD, 8X3HPHI,10X1HZ,
      18X,4HZAOO)
   50 CONTINUE
        OO 3 I=1,N
        PHIM = ATAN2(Y(I),X(I))
        Z = SQRT(X(I)**2+Y(I)**2)
        G = Z/Q(40)
        PHI = PHIM + (7.0*ALOG10(G) + 15.0)*F(I)*0.00001
        RS = X(I)*COS(PHI)/COS(PHIM)
        XS= Y(I)*SIN(PHI)/SIN(PHIM)
        IF(F(I).LE.1000.) GO TO 4
    2 CF = -(1.9*EXP(ALOG10(G)) + 4.45)*(F(I)-1000.)*0.00001 + 1.
        RS=RS/CF
        XS=XS/CF
        Z=Z/CF
    4 CALL SSWTCH(1,I1)
        REV(I)=0.
        XEV(I)=0.
        IF(I1.EQ.2) GO TO 6
        READ(3,106) RE,XE
  106 FORMAT(2F10.0)
```

```
      RS•NS•RE
      XS•XS•XE
      REV(I)•RE
      XEV(I)•XE
      PHI•ATAN2(XS,RS)
      Z•SQRT(XS••2•RS••2)
    6 PHI • PHI•57•3
      RABD • RS•ABD
      XABD • XS•ABD
      ZABD•Z•ABD
      X(I)•RS
      Y(I)•XS
      CALL SWTCH(5,IS)
      IF(IS•EQ•1) GO TO 3
      WRITE(1,105) F(I),RS,XS,RABD,XABD,PHI,Z,ZABD
  105 FORMAT(3XF9•3,2XF10•4,2XF10•4,2XF10•4,2XF10•4,2XF10•4,4XF10•4,2X,
     1F10•4)
    3 CONTINUE
      CALL CENTER
      CALL MODEL
      RHO•Q(5)•ABD•1•E•8
      WRITE(1,8030) RHO
 8030 FORMAT(/6H RHO •,E12•5,7H OHM•CM )
      CALL CAP
      CALL EPSILN(ABD)
      WRITE(1,8060)
 8060 FORMAT(/23H DET• G,N FOR R1•G/F••N,/)
C•••• UNCORRECT
      DO 150 I•1,N
      X(I)•X(I)•REV(I)
  150 Y(I)•Y(I)•XEV(I)
      CALL CENTER
      CALL MODEL
      SX•0•
      SY•0•
      SXY•0•
      SX2•0•
      WRITE(1,8040)
 8040 FORMAT(/7X,1HF,8X,6H F•1/2,7X,2HR1,9X,2HXP,6X,2HCP,/)
      DO 200 I•1,N
      TEMP•Y(I)••2•(X(I)•Q(6))••2
      R1•Q(5)•TEMP/(Q(5)•(X(I)•Q(6))•Y(I)••2•(X(I)•Q(6))••2)
      XP•TEMP/Y(I)
      CP•Y(I)/(6•283•F(I)•TEMP)
      SQF•1•/SQRT(F(I))
      WRITE(1,8010) F(I),SQF,R1,XP,CP
 8010 FORMAT(4F11•4,E12•4)
      SX•SX•ALOG(F(I))
      SY•SY•ALOG(R1)
      SX2•SX2• ALOG(F(I))••2
      SXY•SXY•ALOG(R1)•ALOG(F(I))
  200 CONTINUE
      XN•N
      BOT•SX••2•XN•SX2
      A•(SX•SXY•SY•SX2)/BOT
      A•EXP(A)
      B•(XN•SXY•SY•SX)/BOT
      WRITE(1,8020) A,B
 8020 FORMAT(/ 3H G•,E12•5,3H N•,E12•5)
C•••• CORRECT
      DO 250 I•1,N
      X(I)•X(I)•REV(I)
  250 Y(I)•Y(I)•XEV(I)
   10 STOP
      END
```

```
      SUBROUTINE EPSILN(AOD)
      COMMON F(25),X(25),Y(25),N,Q(40),CP
      DIMENSION EP(25),EPP(25)
      ARG=(Q(5)-Q(6))/2./Q(4)
      P=ATAN(ARG/SQRT(1.-ARG**2))
      AP=1.5708-P
      A= 1.-P/1.5708
      TAU=(Q(5)-Q(6))*CP*SQRT(1.+(COS(P)/SIN(P))**2)
      EA=8.85E-06*AOD
      EO=TAU/(EA*Q(6))
      EINF=TAU/(EA*Q(5))
      C=COS(AP)
      SN=SIN(AP)
      E=.5*(EO-EINF)
      T1=TAU*1.0E+03
      WRITE(1,202) T1,EO,EINF
  202 FORMAT(/ 4HTAU=F10.5,4HMSEC,10X3HEO=F10.5,10X5HEINF=F10.5)
      WRITE(1,201)
  201 FORMAT(/ 8X3HFRQ,8X2HEP,10X3HEPP,/)
      DO 10 I=1,N
      S=ALOG(6.283*F(I)*TAU)
      SH=.5*(EXP((1.-A)*S)-EXP(-(1.-A)*S))
      CH=.5*(EXP((1.-A)*S)+EXP(-(1.-A)*S))
      EP(I)=EINF+E*(1.-SH/(CH+C))
      EPP(I)=E*C/(CH+SN)
      WS=1./(6.28*F(I))**2
      WRITE(1,200) F(I),EP(I),EPP(I)
  200 FORMAT(3X,F9.3,3E15.6)
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CENTER
      COMMON F(25),X(25),Y(25),N,Q(40),CP
      NC=1+N/2
      X1=(X(1)+X(NC))/2.
      X2=(X(NC)+X(N))/2.
      Y1=(Y(1)+Y(NC))/2.
      Y2=(Y(NC)+Y(N))/2.
      S1=(X(1)-X(NC))/(Y(NC)-Y(1))
      S2=(X(NC)-X(N))/(Y(N)-Y(NC))
      CX=(Y1-Y2-S1*X1+S2*X2)/(S2-S1)
      CY=S1*(CX-X1)+Y1
      NS=0
      CALL EVAL(CX,CY,R,RVI,NS)
      Q(1)=CX
      Q(2)=CY
      Q(3)=RVI
      D=R
      DO 6 IG=1,10
      D=D/2.
      CX=Q(1)
      CY=Q(2)
      RV=Q(3)
      CXP=CX+D
      CXM=CX-D
      CYP=CY+D
      CYM=CY-D
      CALL EVAL(CXP,CY,XXX,RXP,NS)
      CALL EVAL(CXM,CY,XXX,RXM,NS)
      CALL EVAL(CX,CYP,XXX,RYP,NS)
      CALL EVAL(CX,CYM,XXX,RYM,NS)
      GX=RXP-RXM
      GY=RYP-RYM
      XM=SQRT(GX*GX+GY*GY)
      GX=GX*D
      GY=GY*D
      DO 4 I=1,60
      CXN=CX-GX
      CYN=CY-GY
      CALL EVAL(CXN,CYN,RNEW,RVNEW,NS)
      IF(RVNEW.GE.RV) GO TO 5
      CX=CXN
      CY=CYN
    4 RV=RVNEW
    5 CONTINUE
    6 CONTINUE
      FIT = 100.*Q(3)/Q(4)
      WRITE(1,210) Q(1),Q(2),Q(4),FIT
  210 FORMAT(//25HRS,XS CIRCLE FIT RESULTS=,2X15HCIRCLE CENTER =2F10.4/3
     14X8HRADIUS =F10.4/34X8HFIT    =F10.4)
      RETURN
      END
```

```
      SUBROUTINE MODEL
      COMMON F(25),X(25),Y(25),N,Q(40),CP
      CX=Q(1)
      CY=Q(2)
      R=Q(4)
      A=1.
      B=-2.*CX
      C=CX*CX+CY*CY-R*R
      DET=SQRT(B*B-4.*A*C)
      R2=(-B-DET)/(2.*A)
      RP=(-B+DET)/(2.*A) - R2
      M=1+N/2
      W=6.2832*F(M)
      RR=X(M)-R2
      XW=Y(M)
      SQ=RR*RR+XW*XW
      GP=(RP*RR-RR*RR-XW*XW)/(SQ*RP*W)
      R1=1./(6.2832*GP)
      Q(5)=RP+R2
      Q(6)=R2
      Q(8)=R1
      WRITE(1,220) Q(5),R2,R1,RP
  220 FORMAT(/3HRO=F11.4,10X5HRINF=F11.4//18HMODEL PARAMETERS -,3X4HR1 =
     1F11.4,4H/FRQ/21X4HRP =F11.4)
      RETURN
      END
```

SECTION X
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APPENDIX A

PARALLEL TO SERIES TRANSFORMATION OF ELECTRICAL MODELS WITH A SINGLE TIME CONSTANT AND FREQUENCY-INDEPENDENT COMPONENTS

This appendix presents an analytical proof of the semicircle equation relating X_s to R_s. It is easy to show that a transformation of a parallel R_pC_p unit with frequency-independent components to an isoimpedic R_s C_s unit with adjustable components will result in a circular plot between X_s and R_s.

The impedance of the parallel R_pC_p unit is given by

$$Z_p = \frac{jR_pX_p}{R_p + jX_p} = \frac{R_pX_p^2 + jR_p^2X_p}{R_p^2 + X_p^2}$$

$$= \frac{R_pX_p^2}{R_p^2 + X_p^2} + j\frac{R_p^2X_p}{R_p^2 + X_p^2} \qquad \text{(A1)}$$

Comparing this equation with the series parameters $Z_s = R_s + jX_s$, one obtains

$$R_s = R_p \Big/ \left[1 + \frac{R_p^2}{X_p^2}\right] \qquad \text{(A2)}$$

and

$$X_s = \left(\frac{R_p^2}{X_p}\right) \Big/ \left[1 + \frac{R_p^2}{X_p^2}\right] \qquad \text{(A3)}$$

From Equations (A2) and (A3), the following identity can be deduced

$$X_sX_p = R_sR_p = R_s^2 + X_s^2 \qquad \text{(A4)}$$

Let R_p represent a constant quantity characteristic of the rock system, call it 2a, then according to Equations (A2) and (A4) one has

$$R_p = 2a = R_s \left[1 + \frac{R_p^2}{X_p^2} \right] = R_s \left[1 + \frac{X_s^2}{R_s^2} \right] \qquad \text{(A5)}$$

Rearranging Equation (A5), one obtains

$$X_s^2 + R_s^2 = 2a\, R_s$$

or

$$X_s^2 + R_s^2 - 2a\, R_s + a^2 - a^2 = 0$$

hence,

$$(R_s - a)^2 + X_s^2 = a^2 \qquad \text{(A6)}$$

Equation (A6) is the analytical equation of a circle of radius $a = \frac{1}{2} R_p$, and whose center has the coordinates (0, a) in the X_s, R_s diagram, or the Argand diagram.

The transformation from the parallel to series combination describes a semicircle in the series domain for constant parallel circuit parameters. This condition represents an ideal situation in which the system has no polarization and in which the capacitance C_p is regarded as a perfect condenser, and hence the semicircle has its center on the real axis and will pass through the origin. In all rock systems studied thus far, one always obtained a circular arc; i.e., the semicircle was translated vertically downwards, so that its center has the coordinates (m and -n). This situation can be described as follows

$$(R_s - m)^2 + (X_s + n)^2 = a^2 \qquad \text{(A7)}$$

The phase angle, φ, of the rock system is defined such that

$$\cos\varphi = \frac{n}{a} \tag{A8}$$

Note that φ is not the same as the impedance phase angle, ϕ, defined by

$$\tan\phi = \frac{X_s}{R_s} = \frac{R_p}{X_p} \tag{A9}$$

The attachment of a "leak" resistance, r_2, in series with the parallel R_pC_p unit, as shown in Figure 4-1a of Section IV will also result in a semicircle with radius $\frac{1}{2} R_p$, and whose center has the coordinates $(\frac{1}{2} R_p + r_2)$ and 0. This is because the impedance of this system is given by

$$Z_p = r_2 + \frac{jX_pR_p}{R_p + jX_p}$$

$$= r_2 + \frac{R_p}{\left[1 + \frac{R_p^2}{X_p^2}\right]} + j\,\frac{R_p^2/X_p}{\left[1 + \frac{R_p^2}{X_p^2}\right]} \tag{A10}$$

Comparing Equation (A10) with the isoimpedic series parameters $Z_s = R_s + jX_s$, one obtains

$$R_s - r_2 = R_p \Bigg/ \left[1 + \frac{R_p^2}{X_p^2}\right] \tag{A11}$$

and

$$X_s = \frac{R_p^2}{X_p} \Bigg/ \left[1 + \frac{R_p^2}{X_p^2}\right] \tag{A12}$$

These relationships lead to

$$\frac{X_s X_p}{R_p} = R_s - r_2$$

or

$$\frac{R_p}{X_p} = \frac{X_s}{R_s - r_2} \qquad (A13)$$

Combining Equations (A11), (A12) and (A13) and letting $R_p = 2a$, one obtains

$$(R_s - r_2)\left[1 + \frac{X_s^2}{(R_s - r_2)^2}\right] = 2a$$

or

$$(R_s - r_2)^2 + X_s^2 = 2a\,(R_s - r_2)$$

hence

$$(R_s - r_2)^2 + X_s^2 - 2a\,(R_s - r_2) + a^2 = a^2$$

and

$$\left[R_s - (r_2 + a)\right]^2 + X_s^2 = a^2 \qquad (A14)$$

This equation represents a circle with radius $a = \frac{1}{2} R_p$, and center at $(a + r_2) = \left(\frac{R_p}{2} + r_2\right)$, located on the real axis.

APPENDIX B

RELAXATION TIME AND TURNOVER FREQUENCY OF A MODEL WITH A SINGLE TIME CONSTANT AND ONE FREQUENCY-DEPENDENT POLARIZATION RESISTANCE

Using the model in Figure 7-1, and starting with Equation (7-8) one has

$$X_s = \frac{r_1^2 R_p^2 X_p}{r_1^2 R_p^2 + X_p^2 (r_1 + R_p)^2}$$

The objective is to maximize X_s with respect to ω (or f). The various components are given by:

$$r_1 = \frac{g}{f}; \quad X_p = \frac{-1}{\omega C_p} = \frac{-1}{2\pi f C_p} \quad \text{: and } R_p \text{ is independent of f.}$$

$$\frac{1}{X_s} = \frac{1}{X_p} + X_p \frac{(r_1 + R_p)^2}{r_1^2 R_p^2}$$

$$= \frac{1}{X_p} + X_p \left[\frac{1}{R_p} + \frac{1}{R_1}\right]^2$$

$$= \frac{1}{X_p} + \frac{X_p}{R_p^2} + \frac{X_p}{r_1^2} + \frac{2X_p}{r_1 R_p} \qquad \text{(B1)}$$

Substituting the values of r, and X_p in Equation (B1), one obtains

$$-\frac{1}{X_s} = 2\pi f C_p + \frac{1}{2\pi f C_p R_p^2} + \frac{f}{2\pi g^2 C_p} + \frac{2}{2\pi g R_p C_p} \qquad \text{(B2)}$$

$$-\frac{d\left[\frac{1}{X_s}\right]}{df} = 2\pi C_p + \frac{1}{2\pi g^2 C_p} + \frac{1}{2\pi C_p R_p^2 f^2} \qquad \text{(B3)}$$

X_s will be a maximum when $\frac{1}{X_s}$ is a minimum. This happens at the turn-over frequency, f_{max}, which is given by

$$\frac{1}{2\pi C_p R_p^2 f_{max}^2} = \frac{4\pi^2 g^2 C_p^2 + 1}{2\pi g^2 C_p}$$

or

$$\frac{g^2}{R_p^2 f_{max}^2} = 1 + 4\pi^2 g^2 C_p^2 \qquad \text{(B4)}$$

Equation (7-9) defines g as $\frac{1}{2\pi K C_p}$ and Equation (7-11) equates K to cotan φ. Using these relations in Equation (B4), one obtains

$$\frac{1}{4\pi^2 R_p^2 C_p^2 f_{max}^2} = 1 + K^2$$

or

$$\frac{1}{4\pi^2 f_{max}^2} = R_p^2 C_p^2 \ (1 + K^2)$$

$$= R_p^2 C_p^2 \ (1 + \cot^2 \varphi) \qquad \text{(B5)}$$

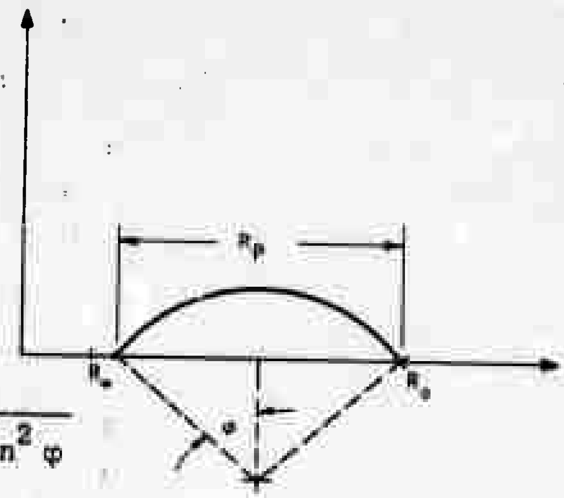
The relaxation time $\tau = \frac{1}{\omega_{max}} = \frac{1}{2\pi f_{max}}$.

hence; $\tau^2 = R_p^2 C_p^2 \ (1 + \cot^2 \varphi)$

and $\tau = R_p C_p \sqrt{1 + \cot^2 \varphi}$ (B6)

One chooses the positive root because τ is always greater than zero.

From the experimental data, one measures R_o, R_∞ and φ.



$$R_p = (R_o - R_\infty)$$

Hence τ can be calculated as

$$\tau = (R_o - R_\infty)\, C_p \sqrt{1 + \cot an^2 \varphi}$$