A METHOD FOR DETERMINING THE MOISTURE GRADIENT IN A CONCRETE PAVEMENT SLAB

Thesis for the Degree of B. S.

MICHIGAN STATE COLLEGE

H. S. Wilson

1940

A Method For Determining The Moisture Gradient in a Concrete Pavement Slab

A Thesis Submitted to

The Faculty of

MICHIGAN STATE COLLEGE

of

AGRICULTURE AND APPLIED SCIENCE

by

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Candidate for the Degree of

Bachelor of Science

June 1940

INTRODUCTION:

Field control in curing concrete has been developed to a point where future research will be directed toward an attempt to determine the internal phenomena which occurs within the slab during the curing period. It is a well known fact that as concrete cures there is a definite loss of moisture within the concrete. The extent of this moisture loss and the variation of the moisture content throughout the mass has long been a subject for investigation. Many studies have been made of the moisture gradient in concrete slabs, but only a few of these studies have yielded conclusive results. As yet, all methods which render reliable results on this subject are not adapted to field use, and consequently are of little value for field control of concrete. The purpose of this project is to design an apparatus and develop a laboratory technique which will be practical in making field measurements of the moisture gradient in pavement slabs.

By "moisture gradient," is meant the variation in moisture content from one point to another in the pavement slab. We are primarily interested in the variation at the surface of the slab and the first three or four inches below the surface.

REVIEW OF RELATIVE RESEARCH:

A review of previous investigations of this problem may serve to clarify the objectives and results presented herein. As far as could be found through reference work, the first attempts to study moisture conditions within a large mass of concrete was done during the construction of Morris Dam in 1932. The tests run on this job were performed with a specially constructed hair hygrometer. Difficulty was experienced in keeping good contact with the concrete and the results were not considered valuable. Several devices which measured the thermal diffusity of the concrete were tried and seemed to render reasonable accurate data provided the concrete was not alternately wetted and dried. However, if the concrete was alternately wetted and dried the data could not be duplicated, the reason being attributed to a reduced bond between the embedded contacts and the concrete.

Electrical resistance measuring instruments have been used on soils,[1] and to determine the relative efficiency of curing materials for concrete. As yet, none of these devices have been adapted to field use. The principle of resistivity measurements is the most practical theory used to date

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1. Technical Bulletin 172, Michigan State College Experimental Station.

because readings can be taken at any point in the concrete, electrodes are inexpensive, their abandonment in the concrete is no material loss, and portable electrical equipment can be used which does not require an external source of power. The problem of calibrating an apparatus of this type is one of determining a moisture resistivity curve for every type of concrete tested.[2] Any variation in the type of cement, the presence of dissolved salts in quantities, leaching of soluble materials, variation in size of aggregate and long periods of time between measurements in the concrete will cause a change in the resistivity curve. This curve, however, will assume the same general shape regardless of the type of concrete tested, and if a standard mix is used, a moisture resistivity curve can be worked out that will always apply to that particular mix.

Several devices were experimented with in this problem. All were based on the Gish-Rooney Earth-resistivity Method. The reasons for adopting the principle worked out by Gish and Rooney are as follows:

(1) The effect of currents within the concrete may be neutralized

(2) The effect of natural currents due to electrolysis of bodies within the concrete can be eliminated

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2. American Concrete Institute, Y9:45-61, Sept.-Oct., 1937

(3) The effect of polarization or galvanic action on the electrodes can be stopped.[3]

All other schemes for measuring resistivities have failed in one or more of these three ways if an attempt was made to get contact between electrodes and the concrete. Gish and Rooney discovered that by reversing the current on the electrodes the above mentioned difficulties could be eliminated and there was no material effect on the results. For this reason the direct current circuit must be set up so that the direction of the current flow may be reversed at frequent intervals.

The theory upon which a multielectrode unit is based was worked out by Dr. L. V. King and is called Wenner's Formula. The proof is as follows:

Let V be the potential at any point due to the current flow. The electrodes C_1 and C_2 are current electrodes. P_1 and P_2 are potential electrodes. V must satisfy $\nabla^2 V=0$ at an infinite distance in a homogeneous medium.

At any point P at distances r_1 and r_2 from electrode C_1 and C_2 (the distance the electrodes penetrate the concrete being negligible) a solution of $\nabla^2 V=0$ is:

(1) $V= A/r_1+B/r_2$. A and B. are constants.

Then: If ρ is the specific resistance, $i=-1/\rho\ \partial V/\partial n$. Assuming the electrode has a spherical field, the outflow current from A is $I= 1/\rho\int \partial V/\partial n\ dS$.

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3. Applied Geophysics, p. 88

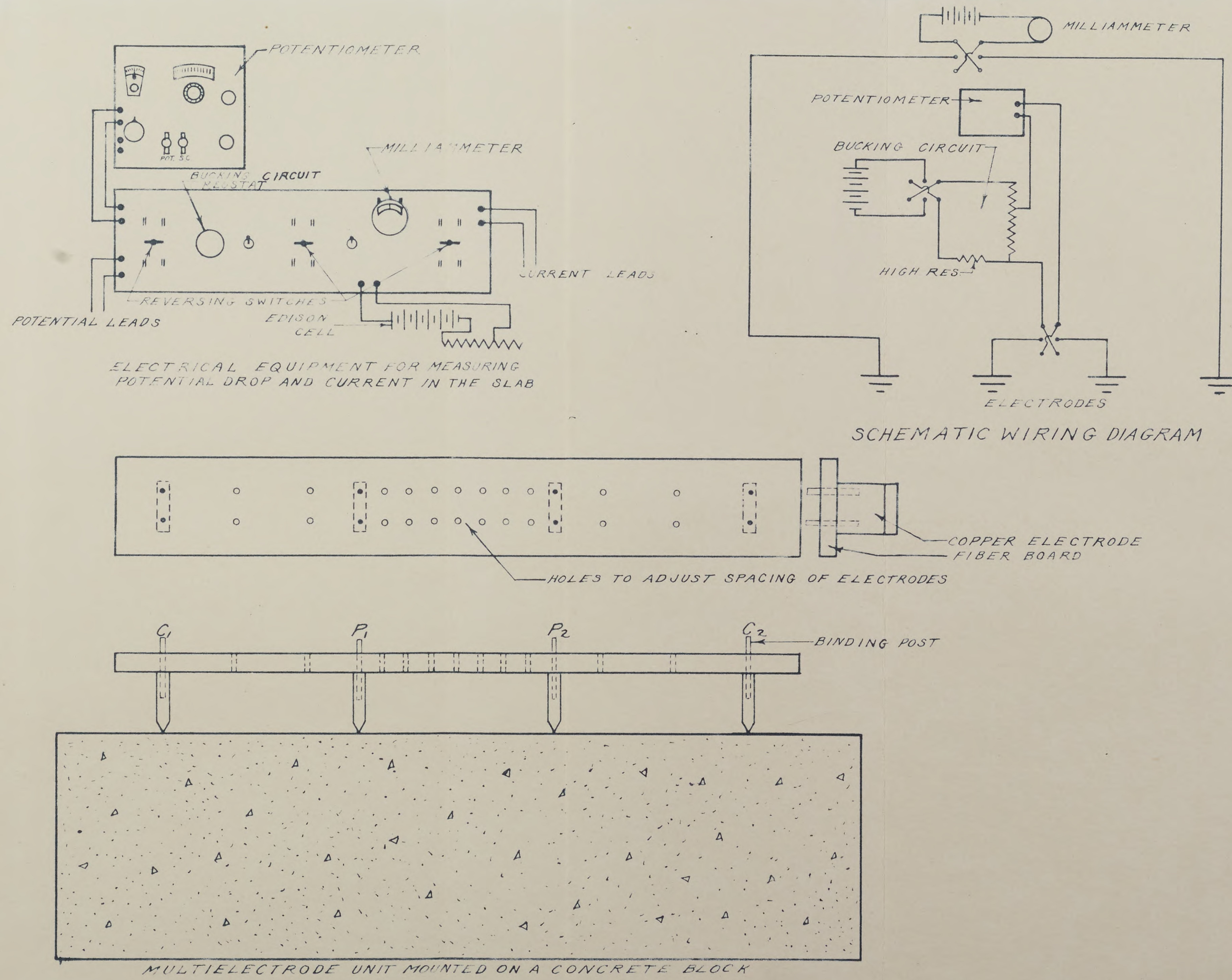
POTENTIOMETER
MILLIAMMETER
BUCKING CIRCUIT
RHEOSTAT
CURRENT LEADS
REVERSING SWITCHES
EDISON CELL
POTENTIAL LEADS
ELECTRICAL EQUIPMENT FOR MEASURING POTENTIAL DROP AND CURRENT IN THE SLAB
MILLIAMMETER
POTENTIOMETER
BUCKING CIRCUIT
HIGH RES
ELECTRODES
SCHEMATIC WIRING DIAGRAM
COPPER ELECTRODE
FIBER BOARD
HOLES TO ADJUST SPACING OF ELECTRODES
C1
P1
P2
C2
BINDING POST
MULTIELECTRODE UNIT MOUNTED ON A CONCRETE BLOCK

FIG ~ 1

Neglect B/r_2 and allow $ds = r^2 d\omega$, where ω is a solid angle in the sphere. Then:

(2) $I = -1/p \int \partial/\partial r (A/r)\ r^2 d\omega$ (from equation (1))

$I = A/\rho\ 2\pi$. $A = \rho I/2\pi$ and by symmetry $B = -\rho I/2\pi$.

$V = \rho I/2\pi (1/r, - 1/r_2)$. If the electrodes are on a straight line, $r_1 = r_2 = A$. $\therefore V_{p1} = \rho I/2\pi (1/A - 1/2A)$.

$V_{p2} = \rho I/2\pi (1/2A - 1/A)$. $\therefore V_{p1} - V_{p2} = \rho I/2\pi (1/A)$

$V = \rho I/2\pi\, 1/A$ and $\rho = 2A\pi E/I$. [3] ρ equals the specific resistance.

LABORATORY STUDY:

The first multielectrode unit used in an attempt to measure resistivities at different points in a concrete slab consisted of four copper electrodes mounted on a strip of fiber board. (Fig. 1.) The fiber board was so constructed that the electrodes could be spaced at intervals of from one to four inches. This theoretically facilitated the measurement of resistivities at any depth that the electrodes happened to be spaced. If good contact could have been obtained between the electrodes and the concrete, it would have been possible to read the resistivity of the concrete at points one to four

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3. Applied Geophysics, p. 241.

inches from the surface. Various methods of loading the unit and adjustment of the length of the electrodes to conform to the irregularities of the concrete were tried in order to bring the electrodes into intimate contact with the concrete. All of these alterations changed the nature of our readings to the extent that they could not be depended upon.

There were several important observations made while experimenting with this unit which influenced the design of the equipment used in later work. The first of these observations was that a constant and adequate contact had to be made between the electrode and concrete if the measured resistivities were to be relied upon. Second, the contact could be improved by weighting the unit but no definite limit for the weights could be reached because upon the slightest movement of the center of mass of the weights the potentiometer readings changed. The third observation was that a multielectrode unit must be placed on a slab of sufficient size to prevent the field set up around the electrodes from passing through any medium other than concrete. The block of concrete used for test readings on this first unit was not wide enough to allow the field set up around the electrodes, spaced at four inches, to remain totally inside the concrete. The result was that part of the field had to pass through a layer of air around the outside of the block and the measured resistivities were far out of proportion. It is known that air has a much higher resistance than wet concrete, and since the resistivities ran exceedingly high, the only thing that could have happened was that the field of the electrodes was passing outside the concrete block.

A second multielectrode set up was tried which operated on the same principles as the first and Wenner's formula was applied. Instead of using electrodes which had to be weighted for contact, we used four pieces of tool steel sharpened at the end and with large enough diameter to allow them to be driven into the concrete a short distance. By driving the points into the concrete excellent contact was obtained, and the readings on small spacings were nearly duplicated when several readings were taken at a time. However, the difficulty of the field passing outside the concrete when the electrode spacing exceeded two inches, was encountered again. The observations made with this apparatus were: (1) that it is possible to take resistivity measurements with a system of electrodes, and (2) that the results can be duplicated by taking several measurements in a small interval of time. Also it was observed that the readings were not affected by the pressure applied to the electrodes provided a good contact was secured when the electrodes were driven into the concrete. The principal fault in the use of the point electrode was that the concrete chipped out when

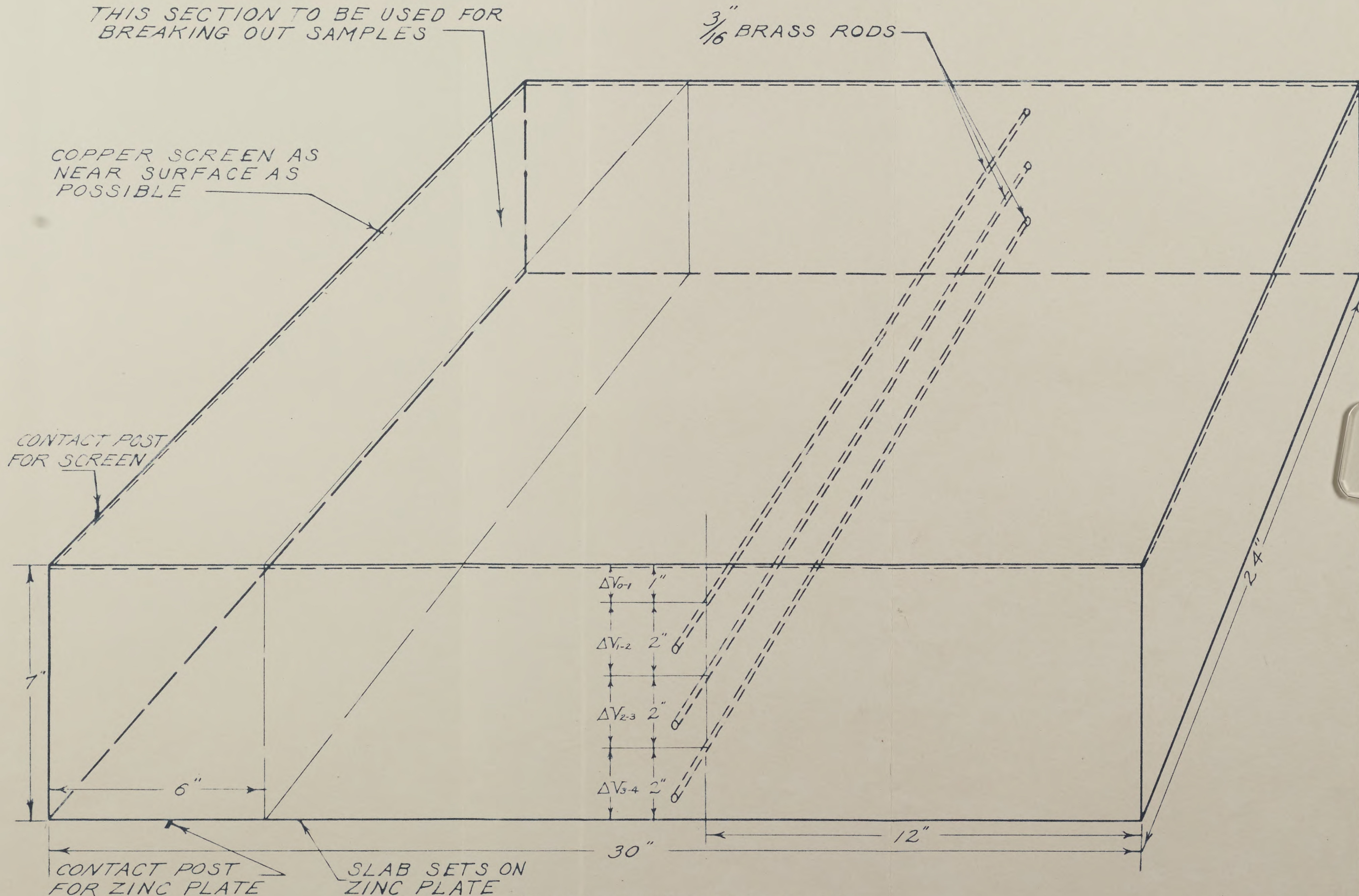


DIAGRAM OF TEST SLAB
FIG ~ 2

it became dry and the electrode could not be held in the concrete by driving it in.

The use of these two multielectrode units just described gave us sufficient preliminary data on design and technical difficulties to set up a test apparatus that would measure resistivities which did not need correction for mechanical errors. The apparatus was constructed in the following manner. (Fig. 2) A wooden form was built for the slab, which measured 30" x 24" x 7", and set on a zinc plate. In a plane twenty-four inches from one end of the box and perpendicular to the face of the slab, three 3/16" brass rods were installed to serve as electrodes. The rods were spaced 1", 3", and 5" from the face of the slab and fastened in place by running them through holes drilled in the side of the form. Before the top electrode could be placed, the form had to be filled with concrete. The concrete was a standard mix used by the Michigan State Highway Department for regular pavement work. The operation of pouring and puddling the concrete in the form was performed in nearly the same manner as that used in pouring pavement slabs. When the form was completely filled and troweled off, the top electrode was placed on the surface of the concrete. This electrode was a piece of copper screen 24" x 30", laid as near to the surface as possible. In order to secure a good contact, the screen was pushed down into the concrete as much as possible and then sprinkled with a thin layer of cement. The cement formed a mortar when it united with the water coming to the top of the concrete. Wires were fastened to the screen and zinc plate, and the brass rods were allowed to project far enough past the form to facilitate a connection for an electrical circuit. This arrangement of electrodes provided a means of passing current through the upper inch of the slab (between the screen and the first brass rod), through a section between one inch and three inches below the surface (between the first and second brass rods), through a section between three and five inches below the surface (between the second and third brass rods), and through a section between five inches below the surface and the bottom of the slab (between the third brass rod and the zinc plate.) (Fig. 2).

The electrical circuit, (Fig. 1.) consisted of a source of current from an edison cell, a potentiometer for measuring the voltage drop between electrodes, an ammeter for measuring the induced current, and a bucking circuit for neutralizing the effect of any self-induced potential in the concrete itself. The object of the bucking circuit was to "buck out" any self-induced potential in the slab due to polarization and electrolytic action of the wet concrete on the electrodes. This self-induced EMF presented a serious problem while the readings were being taken, and another piece of equipment was needed to correct the error. When the current passed through the electrodes in one direction, polarization took place in the same direction. When the current flowed in the opposite direction, the polarization was reversed. For this reason a reversing switch (Fig. 2.) was introduced into the circuit, and after each successive reading the current was reversed. By reversing the current in this manner, the polarization was kept neutralized, and we were not measuring the resistances of the gasses collecting on the electrodes along with the resistances of the concrete.

With this arrangement of electrodes, the resistance could easily be calculated from Ohms law $R = E/I$. The proof of this is as follows:

Assume that the bar electrode passes through a unit volume of concrete. Then integrating $i = \Delta V/\rho$, we have $I = V/R$ or $R = E/I$ which is Ohms law. The reciprocal of the resistance equals conductance (C), measured in Mhos. If the resistance is divided by the area of concrete, the result gives the resistance measured in inch ohms.

The following data was taken over a period of one hundred and twenty-three hours. During the first eighty-seven hours the concrete was allowed to cure in the open air at a temperature of approximately 75°F. After the first eighty-seven hours, the surface of the concrete was kept moist with wet burlap while the remainder of the readings were taken. The symbols used on the data sheets are as follows:

Vp equals the potentiometer reading before the current was turned on.

Vr equals the potentiometer reading while the current was turned on.

Vp - Vr equals the potential drop between the electrodes which were receiving current.

Vo-1 equals the potential drop between the screen and first brass rod.

V_1-2 equals the potential drop between the first and second brass rod.

V_2-3 equals the potential drop between the second and third brass rod.

V_3-4 equals the potential drop between the third brass rod and the zinc plate.

All V's are measured in millivolts.

C equals the conductance.

R equals the resistance

Δt equals the increment of time between readings.

The current is measured in milliamperes.

DATA

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/13-5P.M.	.160			.517				.3090
" "	.150			.465				.3225
" "	.155			.432				.3587
" "							Av =	.3267
" "	.610	.177	1.035		.858			1.421
" "	.140	.185	.000		.185			1.513
" "	.600	.189	1.030		.841			1.420
" "	.150	.197	.000		.197			1.522
" "							Av =	1.469
" "	.595					.738		1.612
" "	.260					.335		1.552
" "	.600					.747		1.686
" "	.290					.370		1.567
" "							Av. =	1.604
" "	.120	.815	1.035				.220	1.090
" "	.340	.939	.333				.606	1.122
" "	.160	.815	1.100				.285	1.122
							Av =	1.111
5/14-9AM	.240	.041	.679	.638				.375
" "	.190	.050	.655	.605				.314
" "	.175			.500				.350
" "	.150			.565				.265
" "	.255			.930				.274
" "	.240			1.140				.210
" "							Av =	.298
" "	.360				1.020			.706
" "	.245				.700			.700
" "	.350				1.010			.693
" "	.260				.736			.706
" "							Av =	.7017
" "	.210					.415		1.012
" "	.390					.715		1.090
" "	.250					.525		.952
" "	.345					.705		.978

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/14-9AM							AV=	1.000
" "	.060	.564	.833				.269	.446
" "	.050	.610	.855				.245	.408
" "	.060	.570	.848				.278	.431
" "	.045	.666	.874				.208	.433
" "							AV:	.429
5/14-4PM.	.215			.524				.409
" "	.163			.396				.411
" "	.210			.535				.392
" "	.170			.383				.443
" "							AV=	.414
" "	.051				.189			.539
" "	.040				.145			.561
" "	.051				.189			.539
" "	.040				.146			.555
" "							AV=	.548
" "	.040					.096		.829
" "	.052					.128		.812
" "	.041					.100		.820
" "	.051					.127		.811
" "							AV:	.818
" "	.019	.400	.505				.105	.365
" "	.025	.615	.756				.141	.361
" "	.032	.519	.350				.169	.384
" "	.025	.491	.632				.141	.361
							AV=	.368
5/14-12PM	.0470			.1615				.2901
" "	.0382			.1105				.3457
" "	.0483			.1500				.3220
" "	.0384			.1103				.3481
" "							AV=	.3265

TIME	CURRENT	VP	VR	V0-1	V1-2	V2-3	V3-4	C
5/14-12P.M.	.0381				.1660			.4590
" "	.0486				.2121			.4584
" "	.0388				.1650			.4703
" "	.0466				.2059			.4526
" "							Av.=	.4601
" "	.0465					.1355		.6863
" "	.0388					.1063		.7300
" "	.0475					.1355		.7011
" "	.0386					.1057		.7303
" "							Av.=	.7119
" "	.0385	.4920	.711				.219	.3515
" "	.0493	.5010	.222				.279	.3534
" "	.0385	.4915	.693				.201	.3850
" "	.0470	.4950	.140			Not Used →	.355	.2647
" "							Av.=	.3633
5/15-7AM.	.0265			.0940				.2819
" "	.0342			.1385				.2469
" "	.0265			.1000				.2650
" "	.0341			.1280				.2664
" "							Av.=	.2650
" "	.0333				.1660			.4012
" "	.0268				.1345			.3985
" "	.0340				.1685			.4036
" "	.0269				.1340			.4015
" "							Av =	.4012
" "	.0265					.0807		.6567
" "	.0343					.1050		.6533
" "	.0268					.0815		.6576
" "	.0341					.1042		.6545
" "							Av=	.6555
" "	.0240	.5000	.2630				.2370	.2025
" "	.0195	.5000	.6475				.1475	.2644
" "	.0240	.5000	.2500				.2500	.1920
" "	.0198	.5000	.6575				.1575	.2514

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/15-7AM.							AV:	.2267
5/15-3PM.	.0290			.1648				.1760
" "	.0235			.1076				.2184
" "	.0293			.1587				.1846
" "	.0235			.1085				.2166
" "							AV=	.1989
" "	.0435				.2523			.3845
" "	.0545				.3245			.3359
" "	.0440				.2515			.3499
" "	.0543				.3150			.3448
" "							AV=	.3538
" "	.0375					.1301		.5765
" "	.0305					.0970		.6288
" "	.0385					.1295		.5946
" "	.0305					.1050		.5809
" "							AV=	.5952
" "	.0144	.4802	.6202				.1400	.2057
" "	.0180	.4965	.3130				.1835	.1962
" "	.0144	.4505	.5940				.1435	.2007
" "	.0183	.4950	.3110				.1840	.1989
							AV =	.2004
5/15-12PM	.0281			.2700				.1040
" "	.0232			.1779				.1304
" "	.0281			.2750				.1022
" "	.0230			.1749				.1315
" "							AV:	.1170
" "	.0310				.2130			.2911
" "	.0395				.2685			.2942
" "	.0311				.2120			.2933
" "	.0398				.2713			.2934
							AV =	.2930

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/15-12PM	.0378					.1517		.4983
" "	.0315					.1212		.5198
" "	.0390					.1500		.5200
" "	.0310					.1211		.5119
" "							Av=	.5125
" "	.0190	.4925	.6525				.1600	.2375
" "	.0239	.4960	.2280				.2680	.1784
" "	.0193	.4740	.6452				.1712	.2255
" "	.0238	.4950	.2301				.2649	.1797
" "							Av=	.2053
5/16-8AM	.0219			.5955				.0367
" "	.0180			.3020				.0596
" "	.0215			.5471				.0393
" "	.0182			.2855				.0637
" "							Av. =	.0498
" "	.0225				.1832			.2456
" "	.0290				.2417			.2399
" "	.0229				.1857			.2466
" "	.0295				.2467			.2392
" "							Av=	.2428
" "	.0275					.1288		.4270
" "	.0235					.1022		.4598
" "	.0278					.1328		.4187
" "	.0232					.1021		.4546
" "							Av=	.4400
" "	.0225						.2110	.2606
" "	.0280						.3633	.1541
" "	.0235						.2180	.2156
" "	.0270						.3481	.1551
" "							Av=	.1963

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/16-4PM	.0252			.8215				.0306
" "	.0210			.5989				.0350
" "	.0210			.5910				.0356
" "	.0230			.8065				.0285
" "							Av.=	.0324
" "	.0205				.2039			.2011
" "	.0266				.2591			.2053
" "	.0213				.2038			.2090
" "	.0248				.2400			.2066
" "							Av:	.2055
" "	.0242					.1261		.3838
" "	.0212					.1040		.4077
" "	.0235					.1249		.3763
" "	.0206					.1005		.4099
" "							Av.=	.3944
" "	.0200	.4765	.6802				.2037	.1963
" "	.0234	.4825	.1375				.3450	.1356
" "	.0202	.4600	.6800				.2200	.1836
" "	.0235	.4900	.1495				.3405	.1380
" "							Av:	.1634
5/17-8AM	.0121			1.0400				.0118
" "	.0101			.7101				.0142
" "	.0121			1.0895				.0111
" "	.0100			.7104				.0140
" "							Av=	.0127
" "	.0262				.3865			.1355
" "	.0350				.5509			.1270
" "	.0258				.3710			.1390
" "	.0340				.5352			.1270
" "							Av	.1321
" "	.0337					.2000		.3370
" "	.0271					.1779		.3046
" "	.0358					.2250		.3182
" "	.0280					.1776		.3153

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/17-8AM							Av=	.3188
" "	.0195	.4745	.6902				.2157	.1803
	.0259	.4850	.1000				.3850	.1345
	.0203	.4608	.7052				.2444	.1661
	.0249	.4829	.1007				.3822	.1302
							Av=	.1528
5/17-5PM	.0225			.2622				.0858
" "	.0182			.1601				.1136
" "	.0225			.1975				.1139
" "	.0185			.1335				.1385
" "	.						Av=	.1129
" "	.0181				.0447			.8098
" "	.0234				.0655			.7145
" "	.0186				.0570			.6526
" "	.0225				.0660			.6818
" "							Av=	.7147
" "	.0221					.0830		.5325
" "	.0189					.0685		.5518
" "	.0228					.0860		.5302
" "	.0190					.0708		.5367
" "							Av-	.5353
" "	.0182	.4609	.6563				.1954	.1862
" "	.0228	.4702	.1051				.5651	.0806
" "	.0183	.4400	.6539				.2139	.1711
" "	.0187	.4400	.6481				.2081	.1797
" "	.0221	.4750	.1345				.3405	.1298
" "							Av=	.1868
5/18-2AM	.0220			.2928				.0752
" "	.0184			.1402				.1312
" "	.0220			.2125				.1035
" "	.0183			.1461				.1251
" "							Av=	.1088

TIME	CURRENT	V_P	V_R	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}	C
5/18-2AM.	.0182				.0525			.6941
" "	.0230				.0659			.6985
" "	.0183				.0549			.6672
" "	.0221				.0662			.6671
" "							Av=	.6817
" "	.0217					.0758		.5717
" "	.0181					.0643		.5627
" "	.0223					.0812		.5496
" "	.0181					.0622		.5821
" "							Av=	.5665
" "	.0180	.4415	.6465				.2050	.1757
" "	.0223	.4721	.1461				.3260	.1369
" "	.0180	.4250	.6421				.2171	.1599
" "	.0217	.4700	.1190				.3510	.1238
" "							Av=	.1491
5/18-1PM.	.0208			.3461				.0601
" "	.0180			.1371				.1312
" "	.0222			.1715				.1295
" "	.0180			.1481				.1215
" "	.0225			.1555				.1448
" "							Av=	.1468
" "	.0220				.0685			.6521
" "	.0181				.0530			.6838
" "	.0226				.0671			.6735
" "	.0180				.0529			.6809
" "							Av=	.6726
" "	.0180					.0609		.5912
" "	.0229					.0619		.5825
" "	.0180					.0814		.5640
" "	.0180					.0599		.6005
" "							Av=	.5846

TIME	CURRENT	VP	VR	V0-1	V1-2	V2-3	V3-4	C
5/18-1PM.	.0179	.4380	.6422				.2042	.1752
" "	.0220	.4581	.1220				.3361	.1309
" "	.0181	.4150	.6387				.2237	.1620
" "	.0221	.4522	.1233				.3289	.1341
" "							Av.	.1506
5/18-8PM.	.0215			.2952				.0729
" "	.0179			.1479				.1211
" "	.0221			.2110				.1048
" "	.0180			.1339				.1347
" "							Av=	.1084
" "	.0179				.0534			.6710
" "	.0228				.0670			.6819
" "	.0183				.0551			.6744
" "	.0226				.0687			.6572
" "							Av=	.6711
" "	.0220					.0772		.5700
" "	.0183					.0623		.5875
" "	.0223					.0780		.5721
" "	.0182					.0625		.5823
" "							Av	.5780
" "	.0179	.4361	.6405				.2044	.1750
" "	.0217	.4350	.1000				.3350	.1294
" "	.0181	.4175	.6035				.1860	.1948
" "	.0217	.4525	.1008				.3517	.1235
							Av=	.1307

SUMMARY OF DATA

CONDUCTIVITIES IN MHOS

TIME	Δt	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}
0 HOURS	0 HOURS	.3267	1.4690	1.6040	1.1110
16 "	16 "	.2982	.7013	1.0080	.4296
23 "	7 "	.4143	.5487	.8180	.3684
31 "	8 "	.3265	.4601	.7119	.3633
38 "	7 "	.2650	.4012	.6555	.2267
46 "	8 "	.1989	.3538	.5952	.2004
55 "	9 "	.1170	.2930	.5125	.2053
63 "	8 "	.0498	.2428	.4400	.1963
71 "	8 "	.0324	.2055	.3944	.1634
87 "	16 "	.0127	.1321	.3188	.1528
96 "	9 "	.1129	.7147	.5353	.1868
105 "	9 "	.1088	.6817	.5665	.1491
116 "	11 "	.1468	.6726	.5846	.1506
123 "	7 "	.1084	.6711	.5780	.1307

RESISTIVITIES IN INCH OHMS

TIME	Δt	V_{0-1}	V_{1-2}	V_{2-3}	V_{3-4}
0 HOURS	0 HOURS	.004248	.000944	.0008653	.001249
16 "	16 "	.004554	.001979	.001376	.003230
23 "	7 "	.003350	.002529	.001696	.003767
31 "	8 "	.004251	.003016	.001949	.003820
38 "	7 "	.005237	.003459	.002117	.006122
46 "	8 "	.006978	.003923	.002331	.006926
55 "	9 "	.01186	.004737	.002708	.006920
63 "	8 "	.02784	.005716	.003154	.007070
71 "	8 "	.04278	.006754	.003519	.008494
87 "	16 "	.10920	.010500	.004353	.009083
96 "	9 "	.01129	.001942	.002592	.007430
105 "	9 "	.01275	.002036	.002450	.009309
116 "	11 "	.00945	.002063	.002374	.009216
123 "	7 "	.01280	.002068	.002401	.010611

COMPUTATIONS:

Let us use the readings taken at 4 P.M. on May 14.

V_3-4 = .505-.400 = .105 I = .0192

" = .756-.615 = .141 I = .0255

" = .519-.350 = .169 I = .0325

" = .632-.491 = .141 I = .0255

Since the spacing of all the electrodes, except Vo-1, was two inches, the distance the current had to travel in passing from one electrode to the other was two inches. In order to correct our readings for the one inch spacing of the top set of electrodes the current was multiplied by two for all readings except those for Vo-1.

C = Conductance = I/E

2x.0192/.105 = .3657

2x.0255/.141 = .3617

2x.0325/.169 = .3846

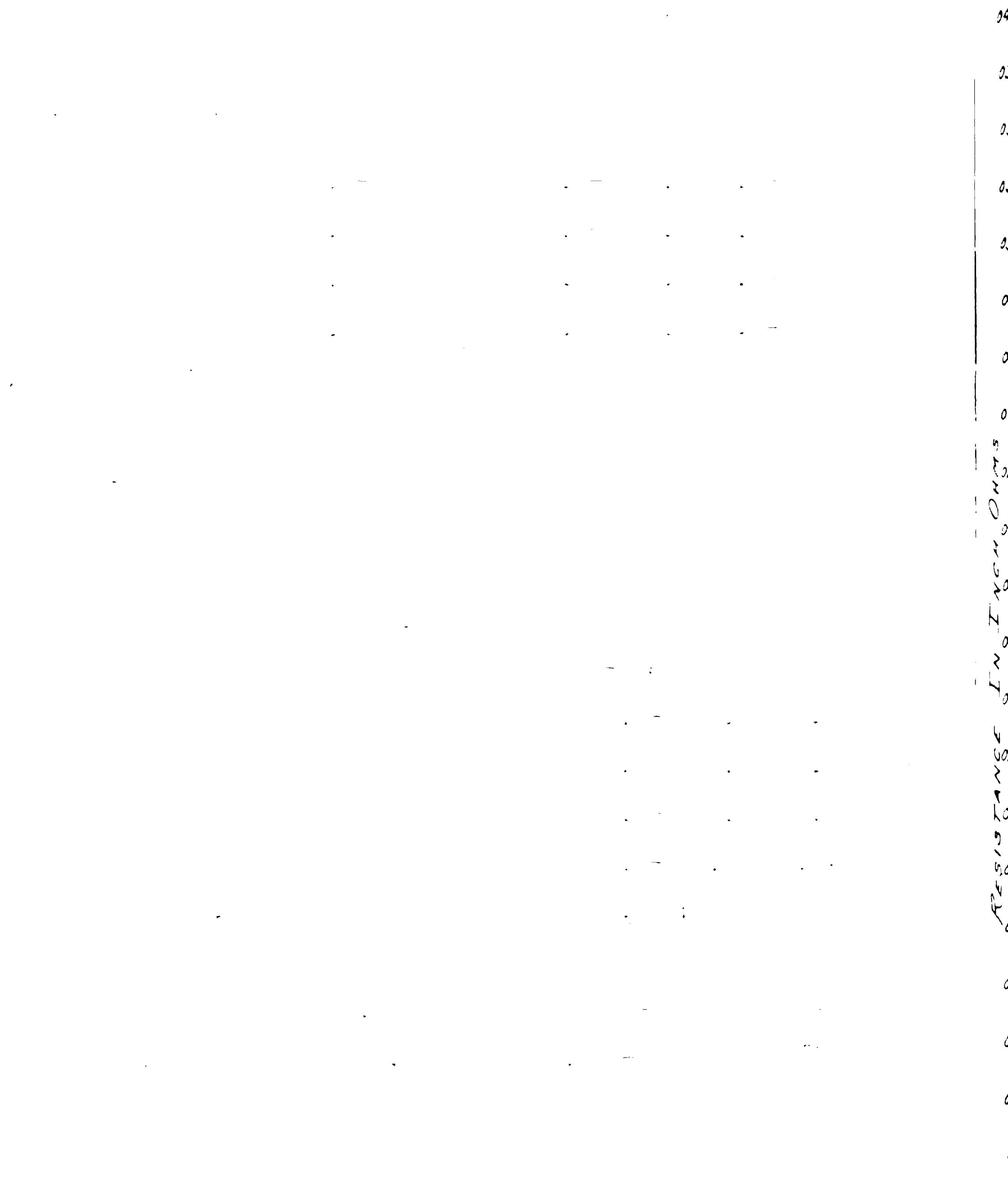
2x .0255/.141= .3617

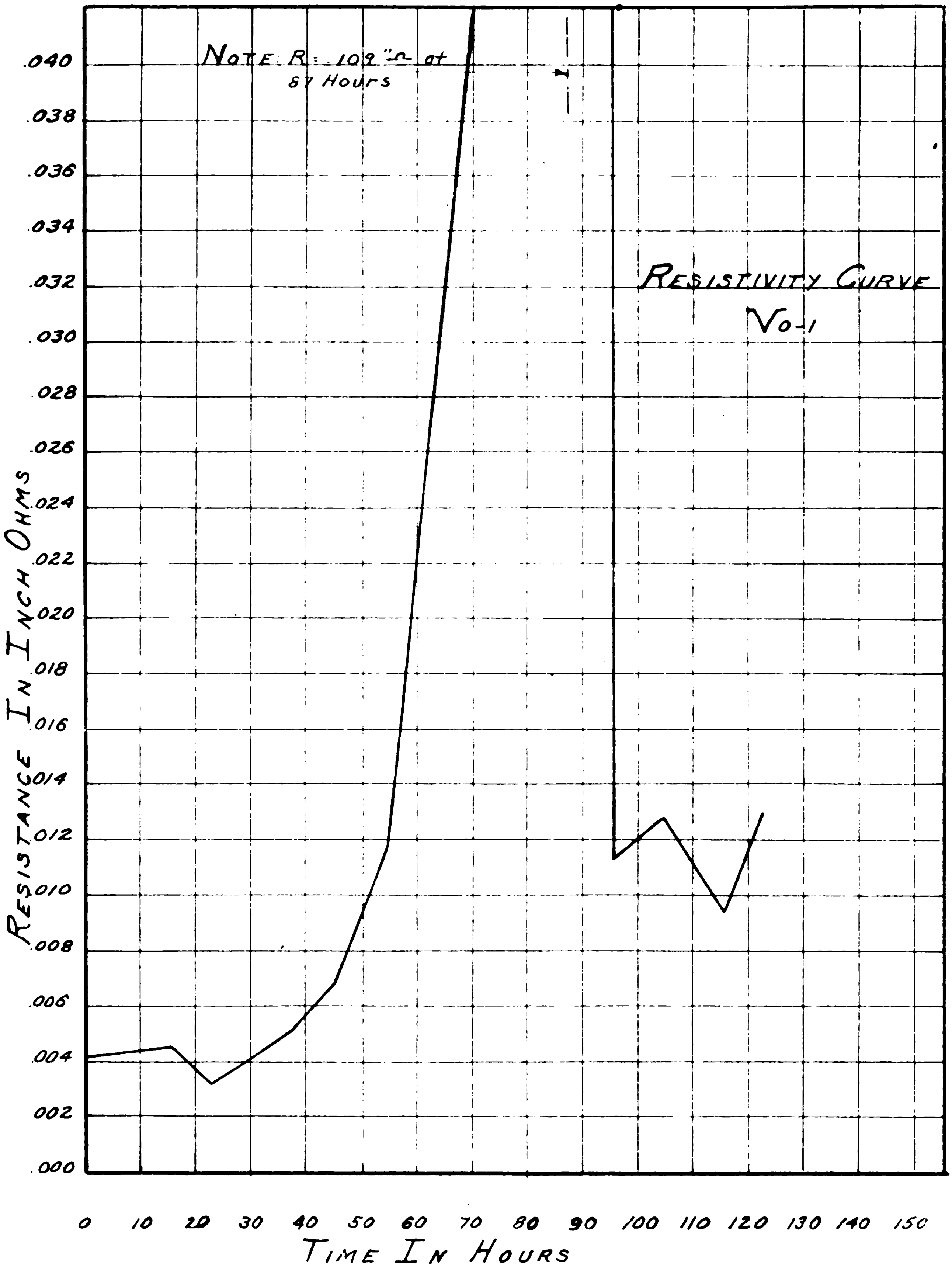
Average: .3684 = Conductance in mhos.

R in inch ohms = I/CxA

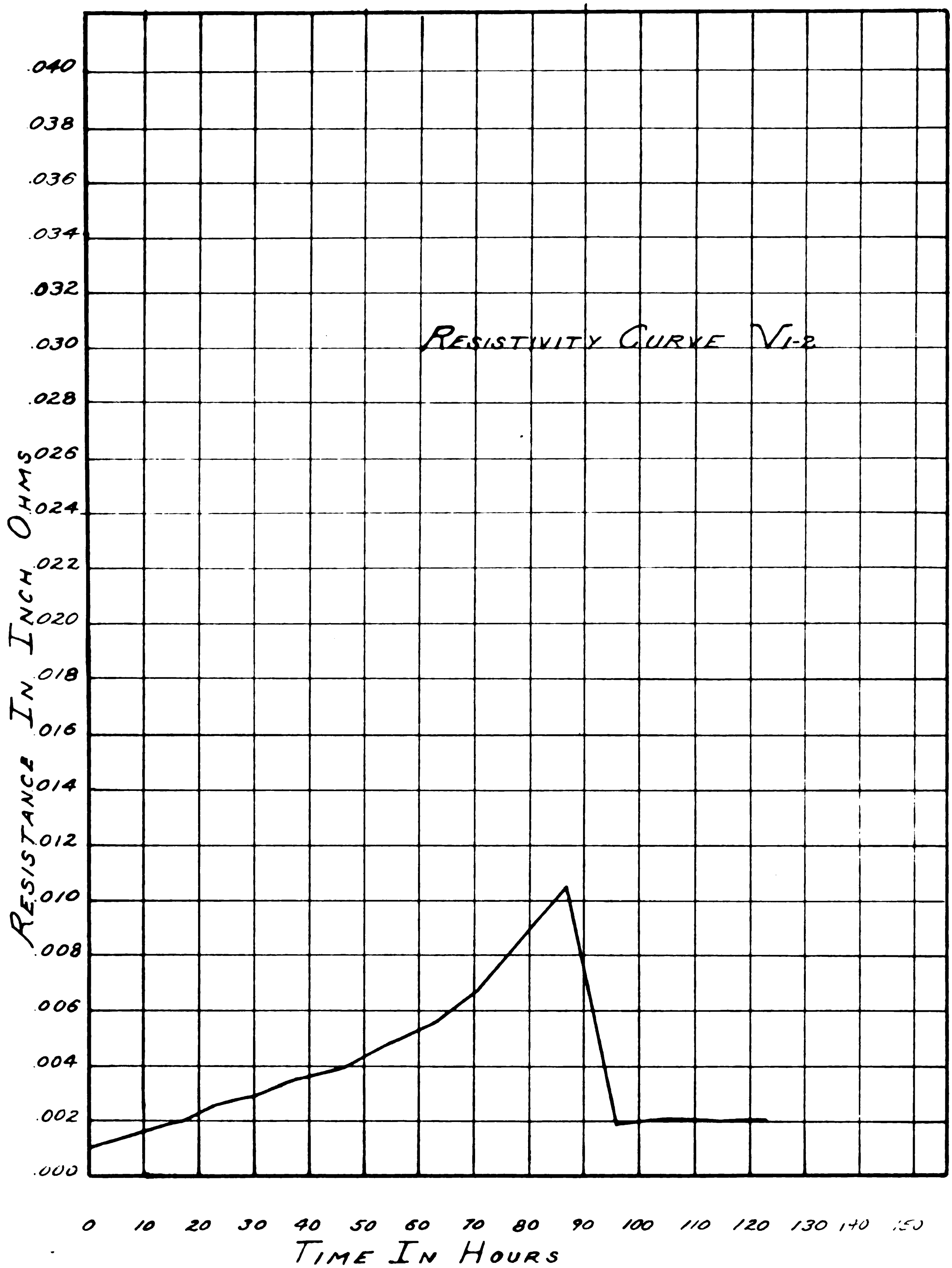
A = 24" x 30" = 720 square inches.

R in inch ohms = 1/.3684x720 = .003767 inch ohms.

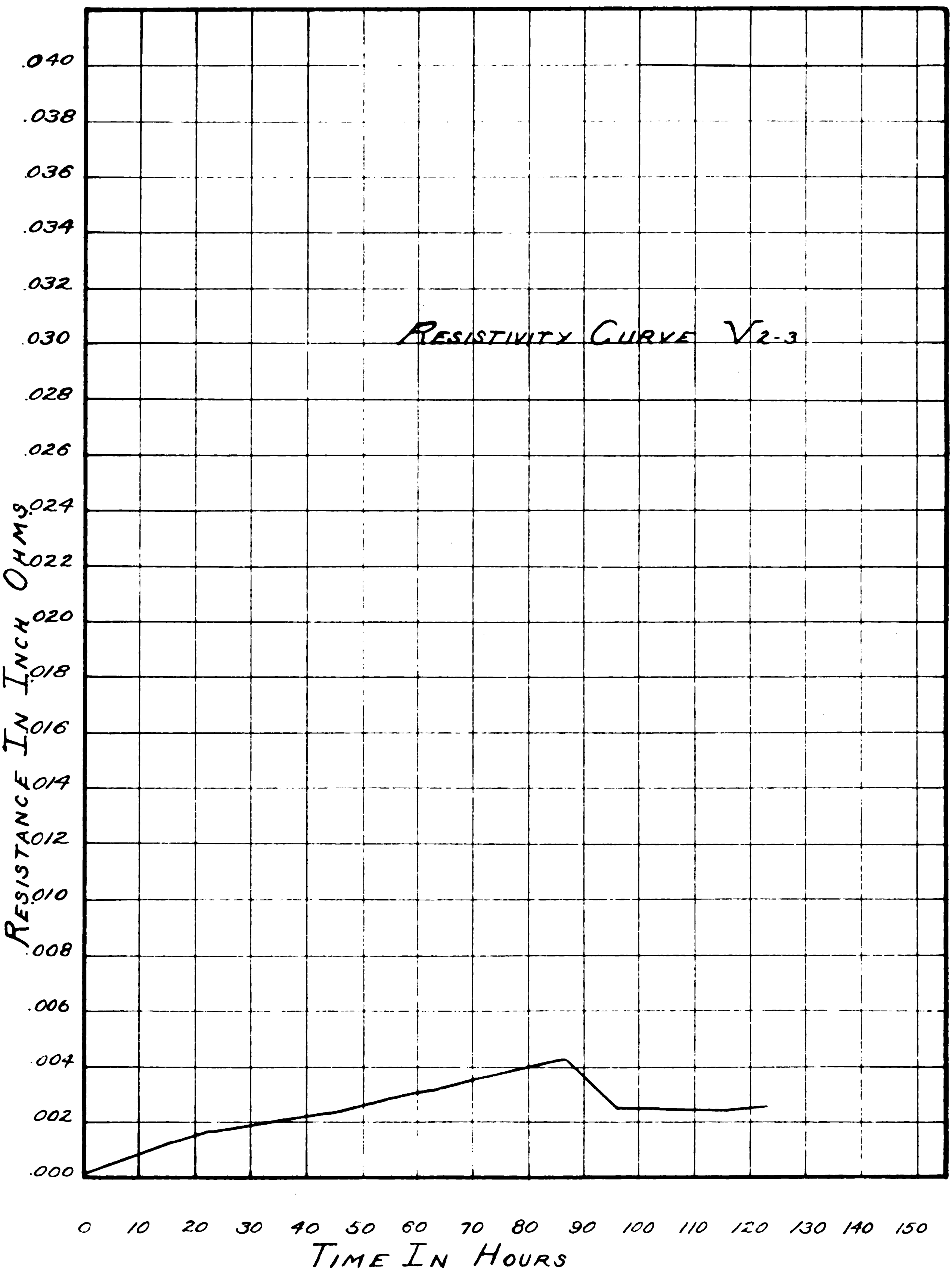

RESISTANCE IN INCH OHMS



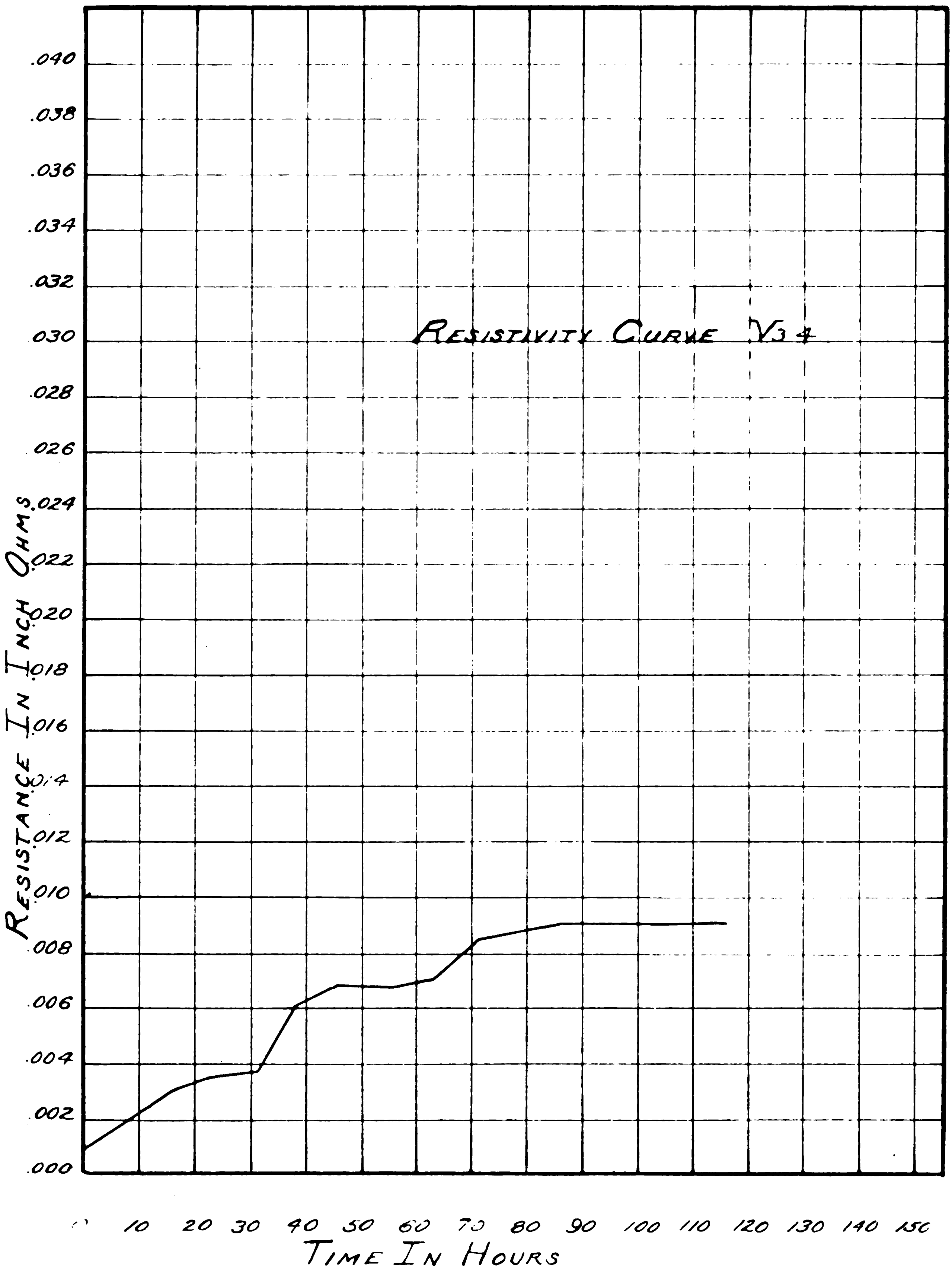
Note: R = .109"Ω at 87 Hours
Resistivity Curve
Vo-1
.040
.038
.036
.034
.032
.030
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
Resistance In Inch Ohms
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time In Hours



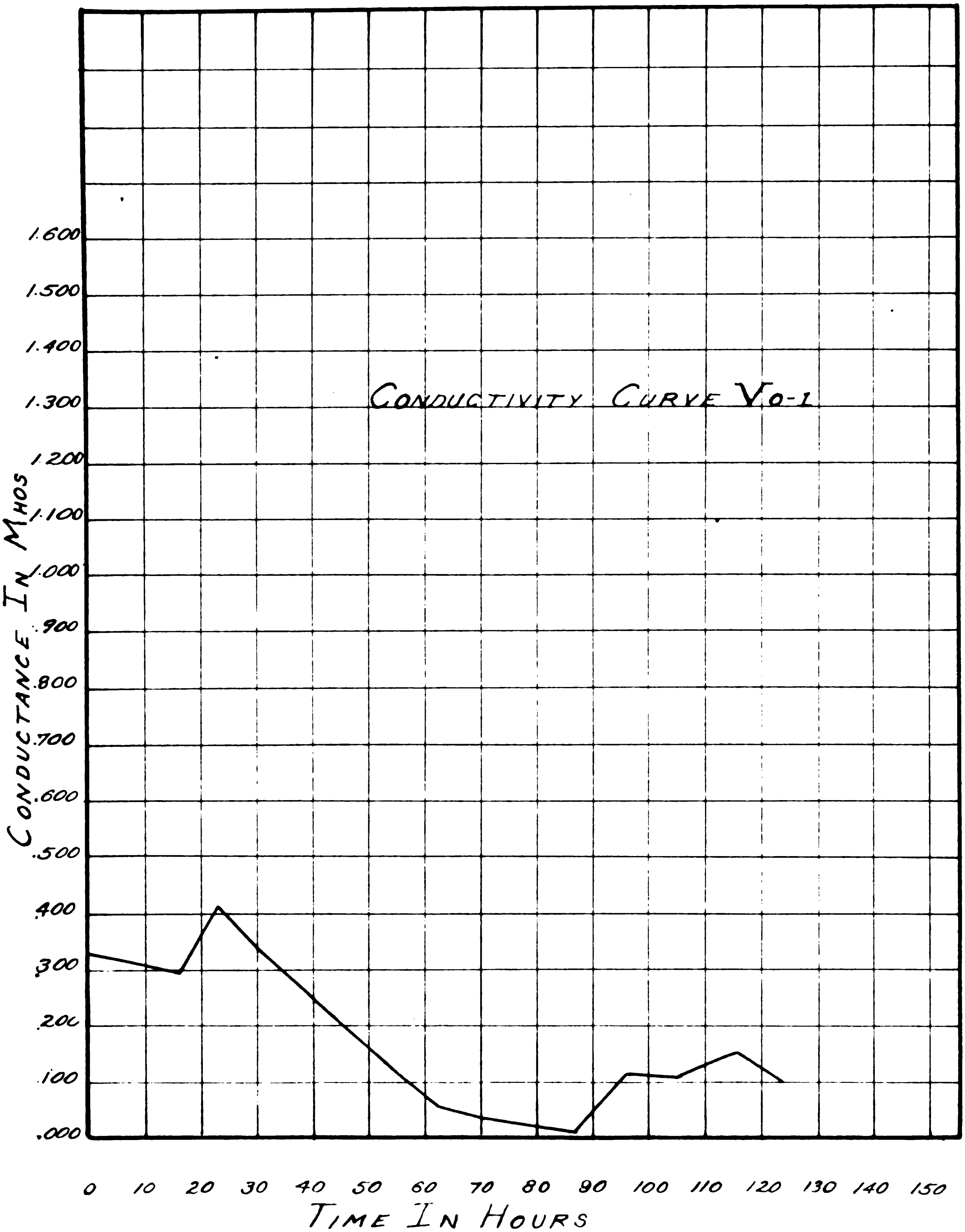
RESISTIVITY CURVE V1-2
RESISTANCE IN INCH OHMS
.040
.038
.036
.034
.032
.030
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
TIME IN HOURS



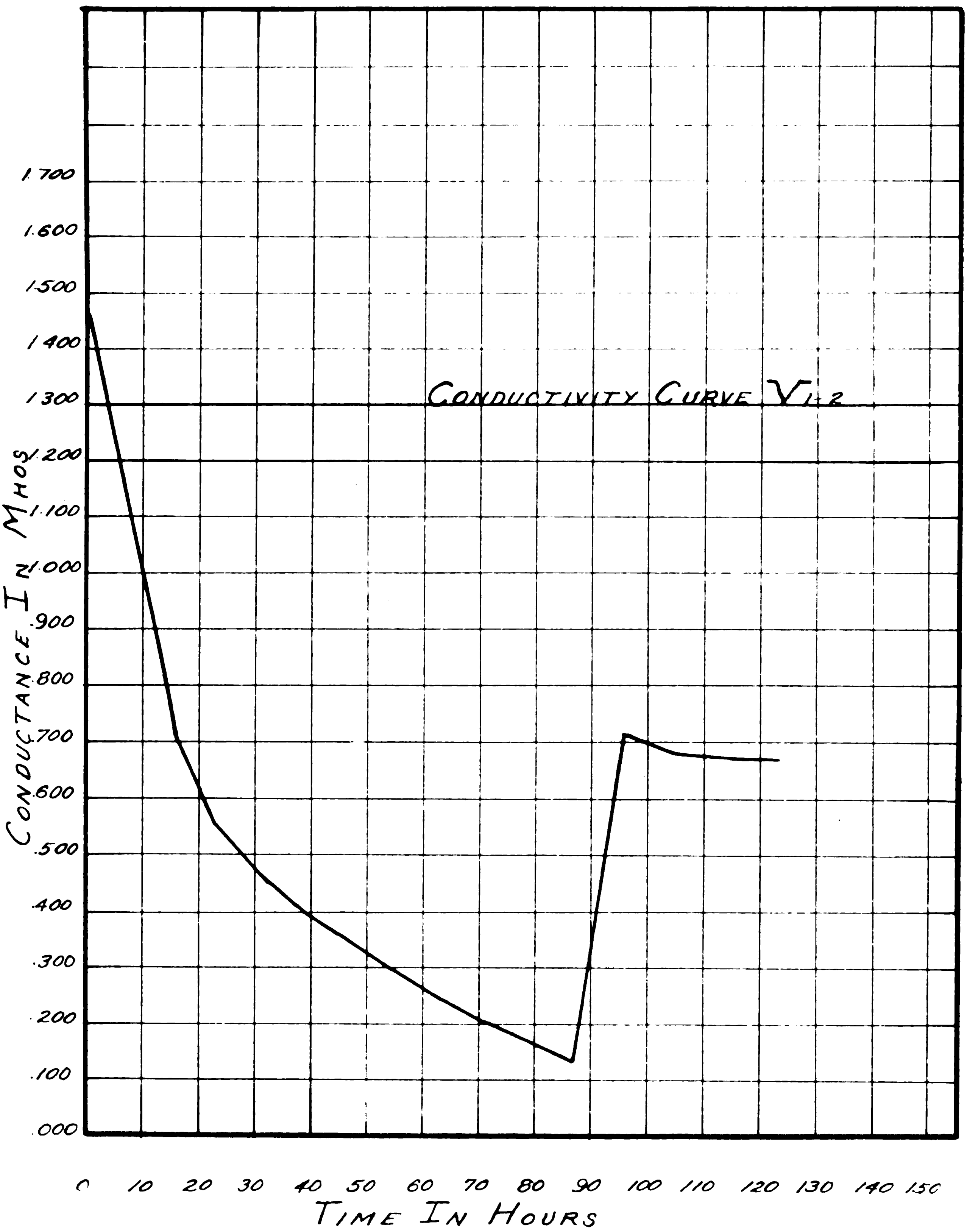
Resistivity Curve V2-3
Resistance In Inch Ohms
.040
.038
.036
.034
.032
.030
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Time In Hours



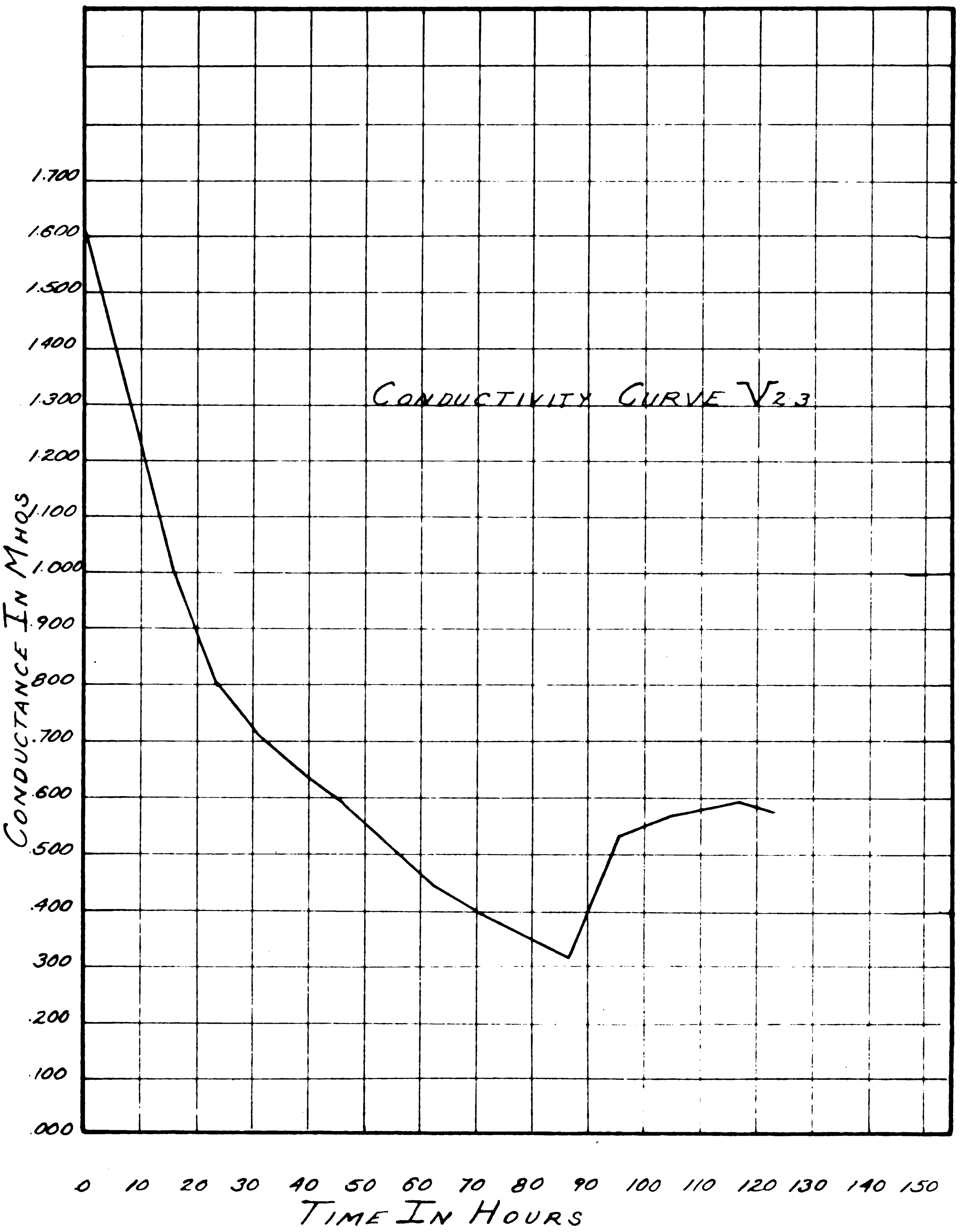
RESISTIVITY CURVE V34
.040
.038
.036
.034
.032
.030
.028
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
RESISTANCE IN INCH OHMS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
TIME IN HOURS



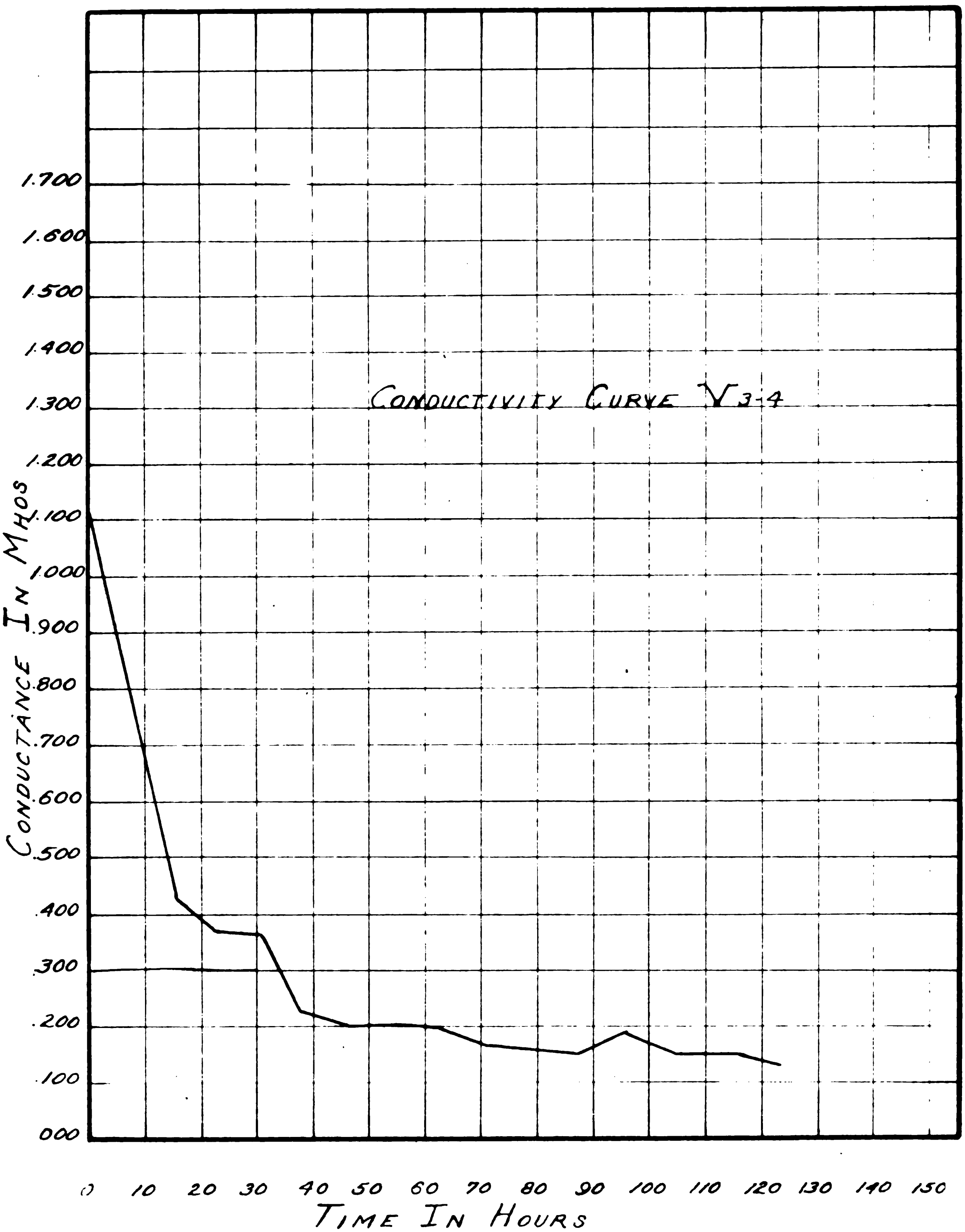
Conductivity Curve Vo-1
Conductance In Mhos
1.600
1.500
1.400
1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time In Hours



Conductivity Curve V1-2
Conductance In Mhos
1.700
1.600
1.500
1.400
1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time In Hours



CONDUCTIVITY CURVE V2.3
CONDUCTANCE IN MHOS
1.700
1.600
1.500
1400
1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
300
.200
.100
.000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
TIME IN HOURS



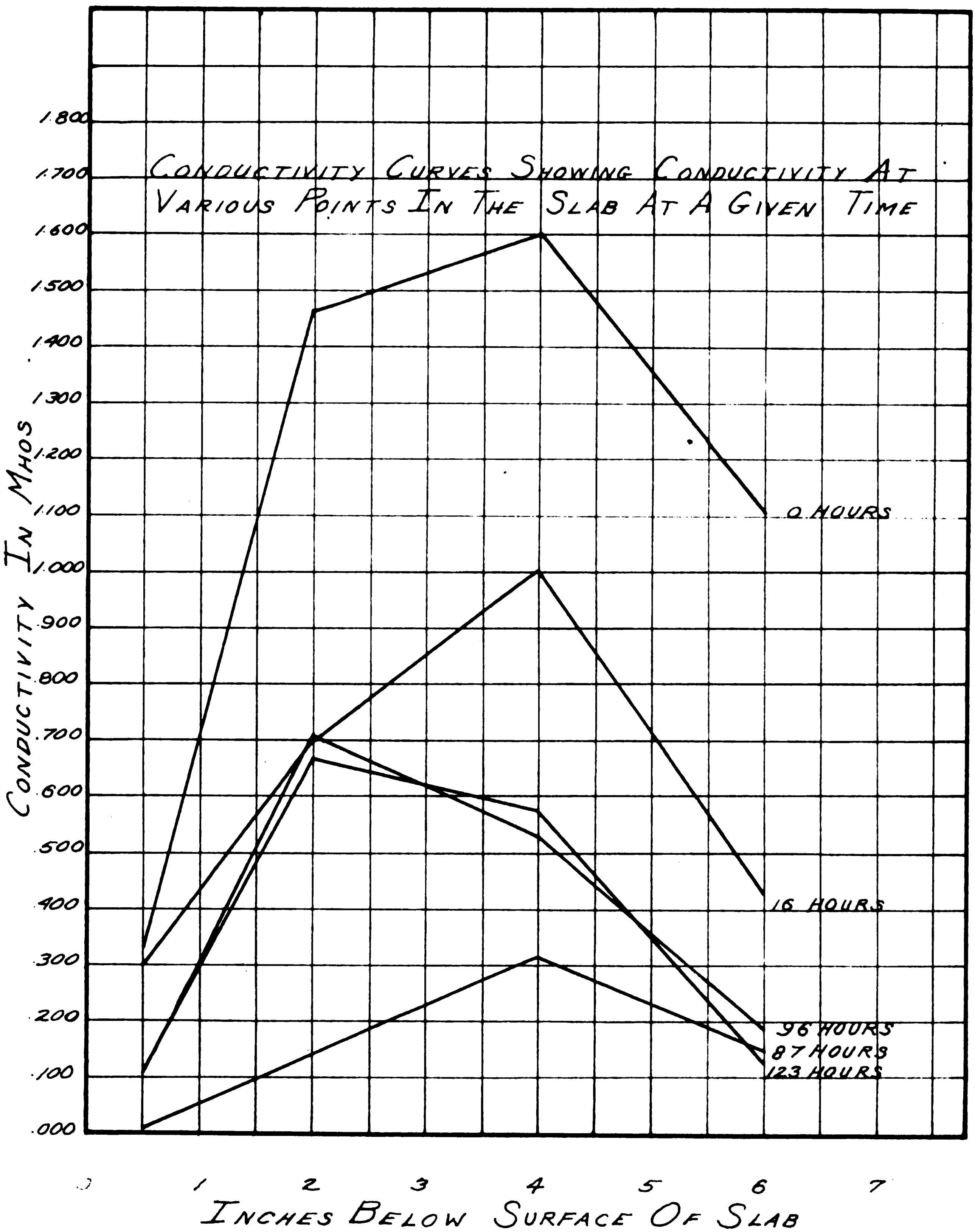
CONDUCTIVITY CURVE V 3-4
CONDUCTANCE IN MHOS
1.700
1.600
1.500
1.400
1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
TIME IN HOURS

The above data was plotted as curves for each set of electrodes and presents a graphical representation of what happened as the moisture gradient of the concrete varied. A study of these curves allows us to predict how the moisture content of the slab varies at different sections during the curing period, and how adapted this apparatus is to determining the moisture gradient in a concrete slab.

Both the conductivity and resistivity curves interpret the moisture variation in the slab, but since the resistivity curves are in smaller units (inch ohms), any change in moisture content gives a more pronounced slope to the resistivity curve. This fact makes it easier for us to draw our conclusions about the success of this test from the resistivity curves.

Examining the resistivity curve for the upper inch of the slab we find that as the slab cured and lost moisture, the resistance increased progressively. There is one discrepancy in this curve at the twenty-three hour reading which is difficult to explain. During the first sixteen hours of curing the resistance increased, but at twenty-three hours the resistance had dropped off. From twenty-three hours on, the resistance increased until water was applied with wet burlap at eighty-seven hours. As soon as water was applied, the concrete absorbed some moisture and the resistance dropped down to about two hundred percent of the resistance it offered at the time it was poured. There is one possible explanation for this unusual drop at twenty-three hours. The fact that the top electrode was covered with a cement paste in order to secure bond may have caused a chemical reaction between the copper screen and cement which affected our readings. This possibility should be investigated in future research.

The resistivity curves for all points in the slab below one inch have the same general form, and show an increase in resistance as the slab cured without application of water. As soon as the wet burlap was applied to the surface, there is evidence that the moisture affected the resistivity throughout the slab. The curves, however, show that there was a decreasing influence on the resistance of the slab from the surface downward. In the upper inch of the slab, the resistance dropped about .09 inch ohms as compared to .002 inch ohms in the lower two inches of the slab when the wet burlap was applied. At the intermediate points there was a gradual decrease in resistance from the surface downward, and in the bottom two inches the resistance remained nearly constant as shown by resistivity curve V 3-4. Curves V 1-2 and V 2-3 show that the resistance dropped abruptly to some value and then remained nearly constant while the burlap was kept saturated. Curve V 0-1 also dropped abruptly but was eratic during the application of moisture. The reason this occurred is because the burlap was not kept saturated to its ultimate capacity at all



Conductivity Curves Showing Conductivity At Various Points In The Slab At A Given Time
1.800
1.700
1.600
1.500
1.400
1.300
1.200
1.100
1.000
.900
.800
.700
.600
.500
.400
.300
.200
.100
.000
Conductivity In Mhos
0 Hours
16 Hours
96 Hours
87 Hours
123 Hours
1
2
3
4
5
6
7
Inches Below Surface Of Slab

times, but was watered at about six hour intervals. The resistivity varied somewhat depending on how soon readings were taken after the burlap was wet down.

The conductivity curves showing the conductivity at various depths in the slab at a given time represents the variance in moisture content throughout the depth of the slab. From these curves it is shown that at the time the concrete was poured, a section about four inches below the surface had the highest conductivity. Examination of the data shows that this section continued to have the highest conductivity until the surface was covered with wet burlap. After the wet burlap was applied, a section about two inches below the surface gave the highest conductivity readings. This indicates that the moisture penetrated the slab and caused a change in the moisture gradient. It is also shown that the top and bottom of the slab dried out much faster than the middle section because both ends of the conductivity curves are below the intermediate points on the curves. At no time, however, did the conductivity of the bottom of the slab become lower than the top. This is explained by the fact that the bottom was covered by a zinc plate and was not subjected to the drying conditions the top had. The value of these curves is that by plotting curves for several successive sets of readings, we are able to determine how much the conductivity of the concrete changed during the time interval betwe n readings.

CONCLUSIONS:

(1) In general, it may be said that this experiment produced evidence of the practicability of resistivity measurement for determining the moisture gradient in concrete slabs.

(2) The resistivity curves indicate that the apparatus used was extremely sensitive to slight changes in moisture content of the slab, and that it may be developed to measure the resistivity at any point in the slab.

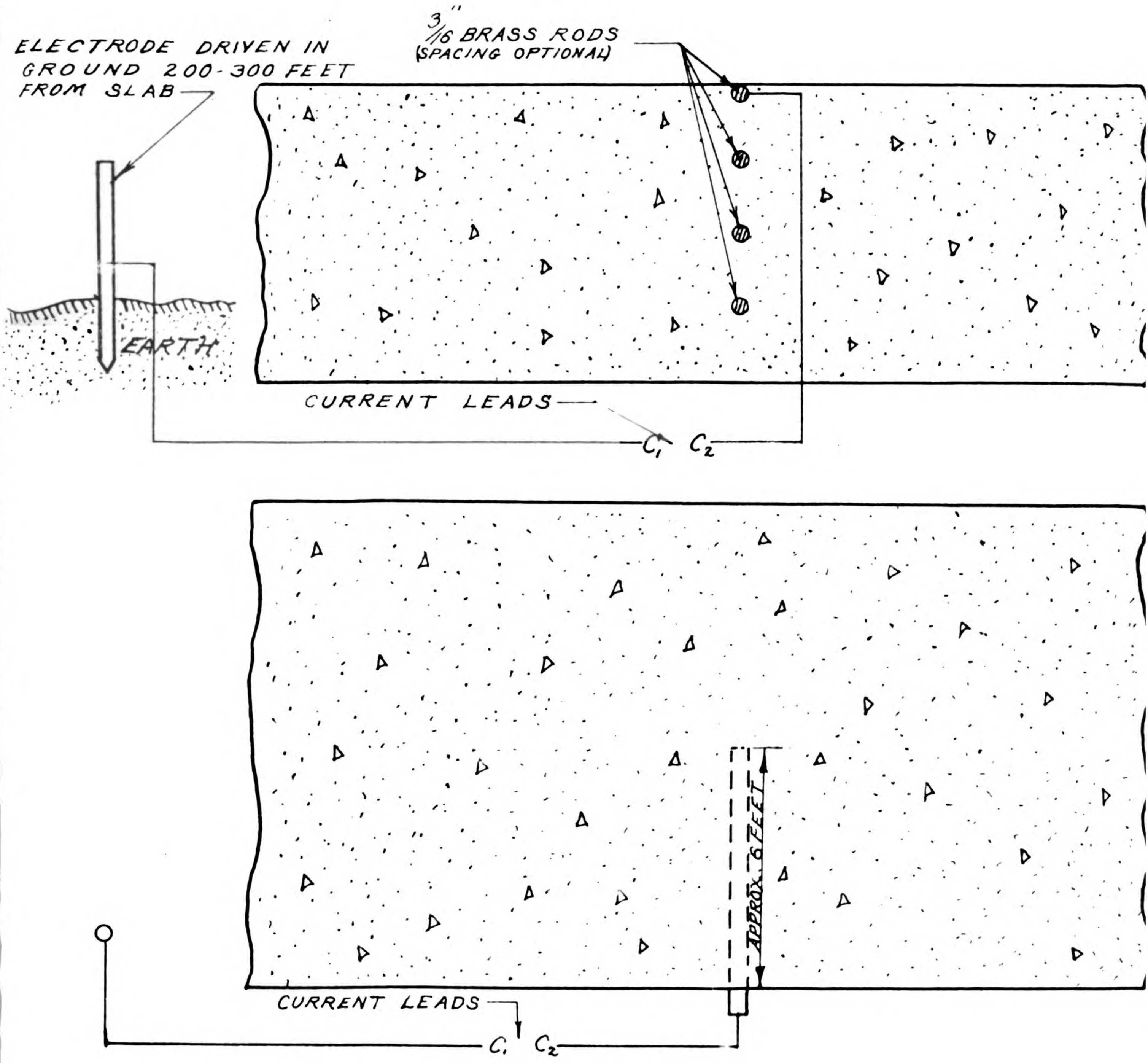
(3) The electrical difficulties heretofore encountered have been eliminated by the use of a bucking circuit and a reversing switch.

(4) Subsequent addition of water to the concrete after it has partially cured will be detected readily by this apparatus and the effect on any point in the slab may be determined regardless of the point of application of the water.

(5) The method of securing bond between the top electrode and the concrete must be in such a manner that all of the electrodes are embedded in a homogeneous material.

(6) This apparatus is portable and can be adapted for field use. The electrodes are inexpensive and easily cast in the concrete.

Due to the time limitations a numerical evaluation of the relationship between the resistivity and moisture gradient in



SECTION OF A PAVEMENT SLAB SHOWING A TENATIVE LAYOUT OF THE ELECTRODES AS THEY WILL BE USED IN MAKING RESISTIVITY MEASUREMENTS IN THE FIELD

FIG ~ 3

the slab was not possible. This correlation is very easily made by taking measurements on concrete samples of known moisture content and plotting a curve of resistivity against percent moisture. A separate curve will be necessary for any particular type of concrete and should not be made up until the mix is decided upon.

In setting up this apparatus in the field some changes will be necessary in arranging the electrodes. The top electrode can be a 3/16" brass rod laid flush with the surface of the slab. The other current electrode should be a brass rod driven in the ground two hundred to three hundred feet from the slab. The potential electrodes can be 3/16 inch brass rods spaced to give readings wherever they are desired. The length of the electrodes will have to be worked out experimentally and depends on what lengths give the best results. (Fig. 3.)

Ohms law will not apply when one of the electrodes is at infinity. However, the line electrode formula, based on Wenner's formula, can be worked out easily and applied to an apparatus using an electrode at infinity.

Aside from this change in electrode arrangement, the field procedure will be exactly like that carried out in the laboratory. The resistivities will be calculated by the line electrode formula and the results should be comparable to the laboratory results calculated by Ohms law.

ACKNOWLEDGMENTS:

The results of this investigation were made possible through the cooperation and interest shown by those who generously donated their services in the conduct of the tests. The writer gratefully acknowledges this, and his special indebtedness to E. A. Phinney for his advice and assistance in procuring equipment, and to W. G. Keck for aid in the design and construction of testing apparatus. Mr. Keck's technical advice in solving mechanical difficulties throughout the tests is also greatly appreciated.

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