Cable Neutral Corrosion
Selection and Evaluation of Semiconducting Thermoplastic Jacket Compounds for Concentric Neutral URD Primary Cables

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NOTICE

ABSTRACT

This report presents the results of a project pertaining to the selection and evaluation of semiconducting thermoplastic compounds for use as a corrosion protective overall jacket on concentric neutral URD primary cables. The work was performed as Phase I of EPRI Research Project RP 671, "Cable Neutral Corrosion".

Prior investigation indicated the likelihood that a semiconducting thermoplastic jacket would protect a concentric copper neutral conductor from corrosion in duct and in direct earth burial installations. If such a jacket possessed radial impedance comparable to that of the earth, and if the radial impedance remained essentially stable in service, such a jacketed cable should yield step-and-touch voltages under accidental dig-in conditions approaching those of a cable with an exposed neutral conductor.

The project consisted of compound screening and a six-month accelerated aging test program of full size 15kV cables. Eleven semiconducting thermoplastic compounds received from six compound manufacturers were subjected to the screening test program. Six compounds were accepted for further testing. Accelerated aging of full size 15kV cables, jacketed with each of the six approved compounds took place under the following conditions:

- Exposure in 100°C air oven
- Exposure in 75°C tap water
- Burial in three soils with and without ac test voltage applied between the copper concentric neutral conductor and ground.

Measurements of physical properties and radial resistance and capacitance of the semiconducting jacket compounds were performed initially and at regular intervals during the course of the test program.

Tests performed indicate that the ac current flowing radially through the semiconducting jacket in contact with the concentric tinned copper conductor has a small dc component.

The main conclusions drawn from the project are:

- Semiconducting thermoplastic compounds are commercially available that exhibit stable or declining radial resistance characteristics under conditions likely to be experienced in service.
- Semiconducting thermoplastic compounds do, however, cause rectification of ac current. The effect of rectification on corrosion of the concentric copper wires was negligible.
- Further investigation of the rectification phenomeno appears justified.

It is therefore recommended that this report be transmitted to Subcommittee 6 of Insulated Conductors Committee of IEEE with the recommendation that it serve as the basis for a performance type specification for a semiconducting thermoplastic jacket compound over the concentric neutral conductor of primary URD cable.

ACKNOWLEDGMENT

The investigators wish to acknowledge the contributions of Dennis Maybury in building the instrumentation, preparing samples for aging and performing numerous electrical measurements during this project.

This project was performed with the consultation of the following Members of ICC Subcommittee 6 Task Force 21:

Dr. G. Bahder -	General Cable Corporation
Mr. M. A. Martin -	Georgia Power Company
Mr. N. Piccione -	Long Island Lighting Company
Mr. J. B. Prime (Chairman) -	Florida Power & Light Company
Mr. D. A. Silver -	General Cable Corporation

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Section 1

INTRODUCTION & SUMMARY

INTRODUCTION

Corrosion of the bare copper concentric neutral conductor of primary underground residential distribution cable was first reported in the early 1960's. These incidences of corrosion were attributed to isolated and unique circumstances such as soil conditions and galvanic action. In recent years incidences of corrosion have increased and are widespread geographically. Corrosion of the bare copper wires is now attributed to soil conditions, galvanic action, concentration cells and stray currents. In a number of cases, the cause of corrosion has not been identified with any degree of certainty.

Starting in the mid 1960's, a cable employing a semiconducting jacket over the concentric neutral conductor was utilized in those cases where corrosion of the bare copper concentric neutral wires had been experienced. This practice increased over the years with some utilities employing an insulating jacket. However, jacketed URD cables have not been extensively employed due to (1) the higher cost as compared to bare neutral cables, (2) the higher cost of installation since jacketed URD cables are not presently permitted by the National Electrical Code for joint random installation with communication cable unless both parties agree and a separate bare conductor in contact with the earth and in close proximity to the cable is used and (3) the fact that the need for a jacketed cable has been difficult to assess.

Severe deterioration of the concentric neutral conductor as a result of corrosion presents a problem of serious concern to power and communication companies as well as to other utilities using direct buried metallic facilities. Loss of, or discontinuity in the power cable neutral can cause (1) improper operation of protective devices, (2) unbalanced line-to-neutral voltages and (3) improper operation and possible damage to buried communication facilities. It can also create safety problems.

In recognition of the complexity and potentially serious nature of the situation, Task Force 21 of Subcommittee 6 of the Insulated Conductor Committee (ICC) of IEEE reacted by defining a research program to develop corrosion mitigating methods. The program, forwarded to EPRI for funding consideration, consisted of the following projects:

- Study of the Mechanism(s) of Corrosion of Copper Concentric Neutral Cable and Determination of Test Procedures for Early Detection and Mitigation of Corrosion on Installed Cable
- Evaluation of Commercially Available Semiconducting Thermoplastic Jacket Compounds
- Outdoor High Voltage and High Current Short-Circuit Tests on Single Phase Extruded Dielectric Primary Distribution Cables

The EPRI Distribution Advisory Task Force reviewed this research program and recommended funding. EPRI agreed to fund the evaluation of commercially available semiconducting thermoplastic compounds (RP 671 Phase I) and the outdoor high voltage high current short-circuit tests on single phase extruded dielectric primary distribution cables (RP 671 Phase II). General Cable was awarded a Research Contract for both phases of the project. Under the terms of the Contract for Phase II, Georgia Power, Long Island Lighting and McGraw Edison acted as sub-contractors to General Cable. The McGraw Edison Laboratory at Franksville, Wisconsin was used to perform the simulated fault tests. The General Cable Research Laboratories at Union, New Jersey performed all tests under Phase I of the Contract.

Phase I was predicated on theoretical considerations and limited service experience indicating the likelihood that a semiconducting thermoplastic jacket would protect a concentric copper neutral conductor from corrosion in duct and direct earth burial installations. Furthermore, it was postulated that if such a jacket possessed radial impedance comparable to that of the earth and if the radial impedance remained essentially stable in service, the resultant cable would yield step and touch voltages, under accidental dig-in conditions, approaching those of a cable with an exposed concentric neutral conductor. The purpose of the project was therefore to evaluate commercially available semiconducting thermoplastic compounds to define their initial physical and electrical properties and to determine their stability under long time accelerated aging tests simulating field conditions. This project was not concerned with an evaluation of the various compounds from a commercial point of view. The objective was to identify the critical characteristics by short term and/or qualification type tests that should be included in a cable specification to insure that a compliant cable jacket would maintain long term stability in physical and electrical characteristics under typical field installation and operating conditions. The work performed in Phase 1 was divided into four tasks:

- Selection of Semiconducting Thermoplastic Compounds and Manufacture of Full Size Cable Samples
- Re-design and Re-building of the General Cable Impedance Bridge and Development of a Procedure for Semiconducting Jacket Radial Impedance Measurement
- Measurement of Semiconducting Compound Characteristics
- Investigation of Rectification Effects of Semiconducting Compounds in Galvanic Contact with Concentric Copper Wire

SUMMARY

Manufacturers of semiconducting thermoplastic compounds were contacted and compounds were solicited for the performance of selected physical and electrical screening tests on slabs and model cables. The screening test program was of two fold purpose. The first was the selection of a suitable semiconducting jacket compound for the cables to be subjected to the high voltage short-circuit tests in Phase II. The second purpose was to eliminate those compounds deficient in one or more important properties and thus narrow the list of compounds for in-depth investigation of the stability of their physical and electrical characteristics under accelerated aging and environmental exposure conditions to be performed on full size cables.

A total of eleven semiconducting compounds were tested. Four compounds were rejected due to poor performance on the screening tests and one compound was rejected due to severe gassing during extrusion with resultant porosity. Subsequently, six 300 foot lengths of single conductor 2AWG aluminum XLP insulated 15kV concentric neutral cables were manufactured employing each of the six selected compounds as the overall semiconducting jacket. These cables were employed in the test program.

The test program consisted of accelerated aging of the full size cables for six months under the following conditions:

- Exposure in 100°C air oven
- Immersion in 75°C tap water
- Burial in three soils with and without ac test voltage applied between copper concentric neutral conductor and ground

In addition, tests were performed to determine the rectification effect of the semiconducting compounds in galvanic contact with the concentric copper conductors.

Physical properties of the semiconducting jacket compounds, unaged and after accelerated aging on the completed cables with the tests on specimens of the jackets removed from completed cables, are presented graphically. Measurements of ac radial resistance and capacitance at room and elevated temperatures were performed on the semiconducting jackets of completed cable samples unaged and after the above accelerated agings. In addition, measurements of ac radial resistance and capacitance were made initially and after selected periods of accelerated aging on semiconducting jacket compounds removed from the aged cables. Radial resistance data are presented graphically. Capacitance data are presented in tabular form.

Section 2

CONCLUSIONS

The following conclusions have been drawn based on data obtained in this investigation:

1. Semiconducting thermoplastic compounds are complex structures. Their physical, electrical and moisture transmission characteristics may vary significantly from one formulation to another.

2. The capacitive reactance of a semiconducting thermoplastic compound is generally at least ten times higher than the radial resistance. Hence, radial resistance is the critical parameter in the determination of the influence of the semiconducting jacket on the transient voltage gradient in the earth under fault conditions.

3. Accelerated aging of the semiconducting thermoplastic jacketed concentric tinned copper neutral 15kV cables in an air oven at 100°C, in 75°C water and buried in three different soils at 50°C did not significantly affect their physical properties. In general, the air oven test at 100°C was the most stringent aging condition and Compound D exhibited the poorest results.

4. The 75°C water immersion test performed on full size semiconducting jacketed concentric tinned copper neutral 15kV cables had the most pronounced adverse affect on the radial resistance of the compounds tested. Only Compound A exhibited stable performance for the last three months of the six month test program.

5. The radial resistance characteristics of the six semiconducting thermoplastic compounds tested on full size concentric tinned copper neutral 15kV cables tested in Florida, Georgia and Wisconsin soils under controlled moisture content and 50°C temperature were essentially the same as obtained with the cables aged in an oven at 100°C. Based on criteria of initially

low radial resistance and essentially stable or declining radial resistance characteristic over the last three months of the six month aging period, Compounds A, C and H performed satisfactorily in the air oven aging test. Compound D performed best, followed closely by Compounds A, C and H in the soil burial tests.

6. There were no significant differences in the radial resistance characteristics of the six semiconducting thermoplastic compounds aged in Florida, Georgia and Wisconsin soils.

7. There were no significant differences in room temperature measured values of radial resistances of the six semiconducting compounds aged in Florida, Georgia and Wisconsin soils with and without voltage (5 volt rms) applied between the concentric copper wires and ground.

8. The semiconducting thermoplastic jacketed full size concentric tinned copper neutral cables subjected to the various aging conditions exhibited contact resistance between the concentric copper wires and the inner surface of the semiconducting jacket. The contact resistance was most pronounced on the cables subjected to the water immersion test and least on the cables subjected to the air oven test. The contact resistance was generally highest when the measurement of radial resistance was made at room temperature and normally decreased with increasing temperature of measurement. Since the contact resistance is associated with a very thin, physically weak nonuniform coating on the surface of the copper wires, it is not expected to influence the performance of the cable insofar as transient voltage gradients in the earth under fault conditions.

9. Since the six semiconducting thermoplastic compounds tested exhibited initially low and comparable radial resistance values, the test results obtained in Phase II of RP 671 performed on cables jacketed with Compound B, can be considered to apply to equivalent cables jacketed with any of the six compounds and to other semiconducting jacket compounds exhibiting comparable radial resistances.

10. All six semiconducting jacket compounds exhibited rectification properties of about the same magnitude. Consequently, a small portion of the a-c current flowing through the jacket, approximately 1.6% on average, is being

rectified. Since the d-c current is very detrimental in electrochemical corrosion, this phenomenon may enhance the corrosion of the concentric neutral wires. However, the six-month soil aging test results indicate that it is of a small practical significance. To verify this observation, it is recommended that consideration be given to the performance of an in-depth investigation of the rectifiaction effect of semiconducting compounds over bare and tinned copper wires in URD cables.

Section 3

INSTRUMENTATION AND SAMPLE PREPARATION

The General Cable AC Impedance Bridge was re-designed and re-built to facilitate accurate measurement of 60Hz radial resistance and capacitance of low impedance semiconducting thermoplastic compounds for which the capacitive current is small as compared to the resistive current. A detailed schematic diagram of the bridge is included as Figure 3-1 in this report. A photograph of the bridge in the course of measurement is included as Figure 3-2.

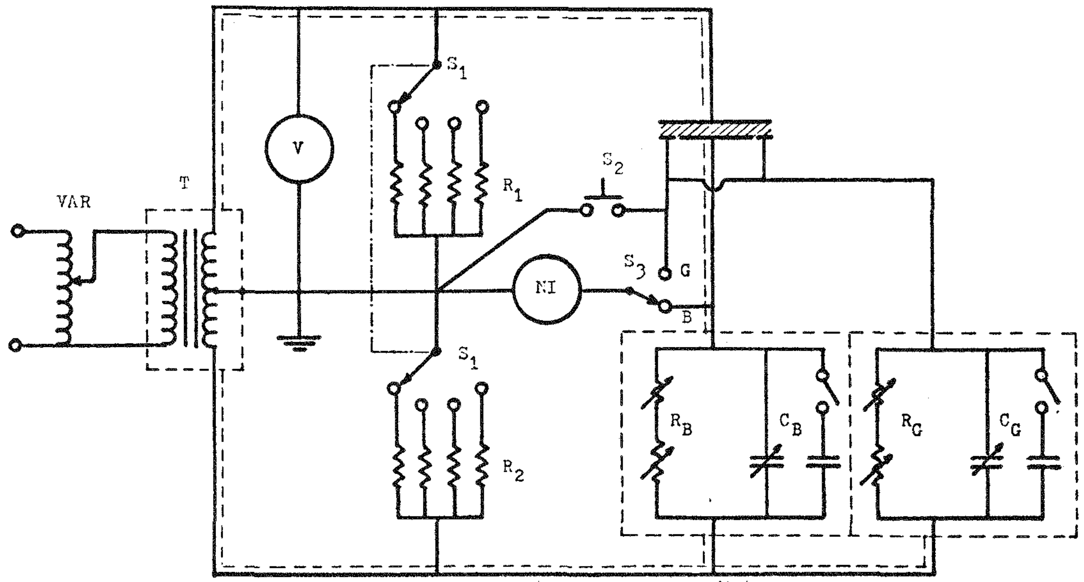


Figure 3-1. AC RESISTANCE BRIDGE - SCHEMATIC

Identification of Symbols

VAR	120V Variac
T	Balanced Transformer with Secondary Center Tap
V	Hewlet-Packard Model 400-F Electronic Voltmeter 0.1mV to 300V
S_1	Ratio Arm Selector Switch
R_1, R_2	Non-inductive Resistors up to 1000 ohms
NI	General Radio Model 1232-A Null Indicator
S_2	Balance Check Push-Button Switch
S_3	Bridge-Guard Selector Switch
R_B, R_G	General Radio Resistance Decade up to 110,000 ohms in Series with 0.03 ohm Slide Wire for Fine Adjustment
C_B, C_G	General Radio Capacitance Decade up to 1.1 Micro-Farads with a Switch Station for Extension of the Capacitance Range up to 41.1 Micro-Farads

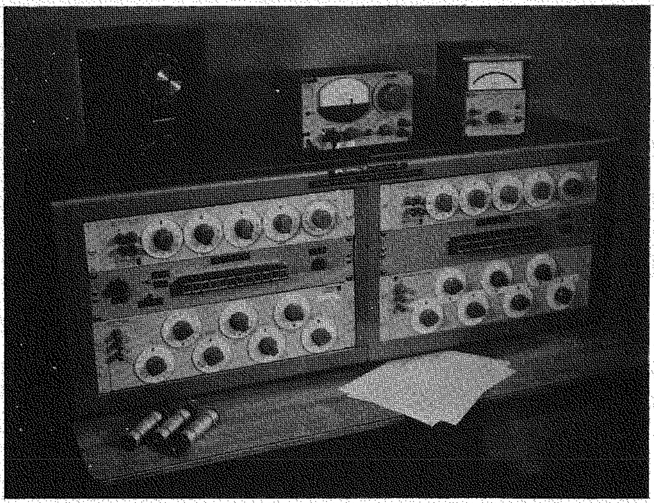


Figure 3-2. TESTING OF CABLES UTILIZING PRECISION A-C RESISTANCE-REACTANCE BRIDGE

Preliminary measurements on semiconducting jacketed full size cables using measuring current densities in the jacket from 10 μA through $50 mA/cm^2$ of the test specimen were conducted to determine variations of electrical characteristics with current density. It was determined that the radial resistance was essentially stable at current densities up to 1 mA/cm^2 beyond which it started to decrease with increasing current density. The capacitance decreased and the a-c resistance varied significantly with change in current density. Therefore, in order to obtain meaningful and comparable test results, all measurements were conducted at a constant voltage of 50 mV and current densities less than 1 mA/cm^2. The Impedance Bridge was modified to incorporate instrumentation permitting measurement and adjustment of current density.

The design of an optimized full size cable test sample to permit in situ measurement of a-c radial resistance and capacitance of the semiconducting jackets at room and at elevated temperatures during the course of the test program is shown in Figure 3-3. The concentric wires form one electrode, silver paint on the surface of the jacket the second electrode and two separate bands of silver paint on the surface of the jacket form the guard electrodes.

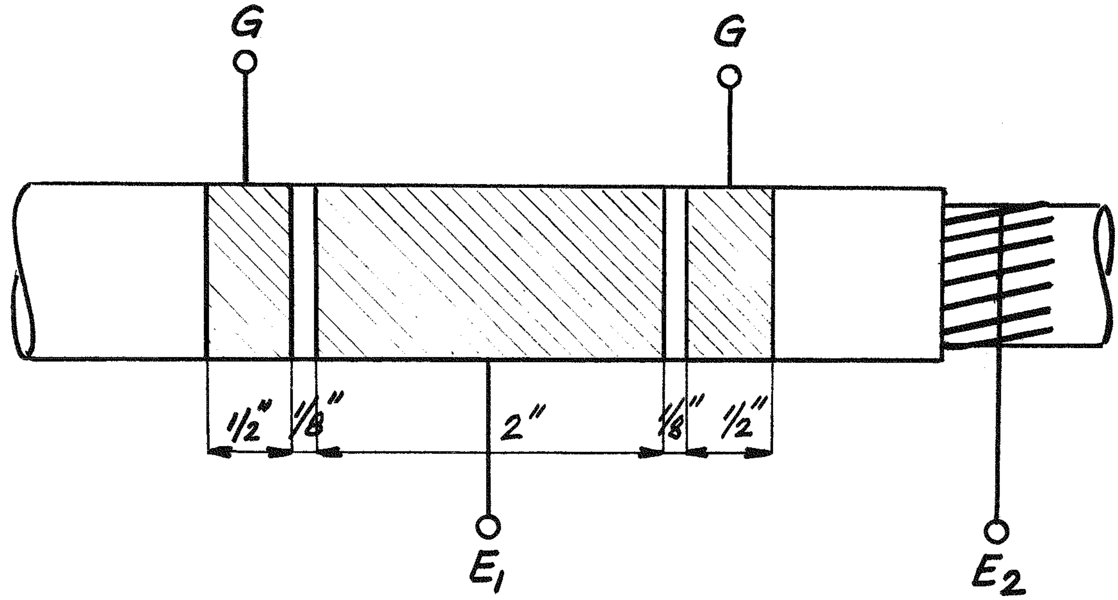


Figure 3-3. ELECTRODE CONFIGURATION FOR IMPEDANCE MEASUREMENTS OF CONDUCTING JACKET

Legend: E_1 - measuring electrode, silver paint on the surface of the jacket

E_2 - measuring electrode, concentric neutral wires tied together

G - guard electrode, silver paint on the surface of the jacket

Based on analysis of room temperature a-c radial resistance measurements of the semiconducting jacket compounds on unaged full size cables, it was determined that contact resistance between the concentric copper wires and the surrounding surface of the semiconducting jacket compound could significantly influence resistance measurements. Under the circumstances, it was apparent that the calculation of resistivities from resistance measurements would not yield significant results insofar as determining the effect of environmental conditioning on the electrical characteristics of the semiconducting jacket compounds. Therefore, in addition to the measurement of radial resistance on semiconducting jacket compounds on full size cable test samples, it was decided to also measure radial resistance of semiconducting jacket compounds removed from cables initially, and after selected periods of conditioning in cases of significant increase in resistance on full size cable test samples. For this measurement, the semiconducting jacket was carefully removed from the cable and straightened by forming between steel plates with mild application of heat. The electrode configuration of Figure 3-4 was employed for measurement of radial resistance.

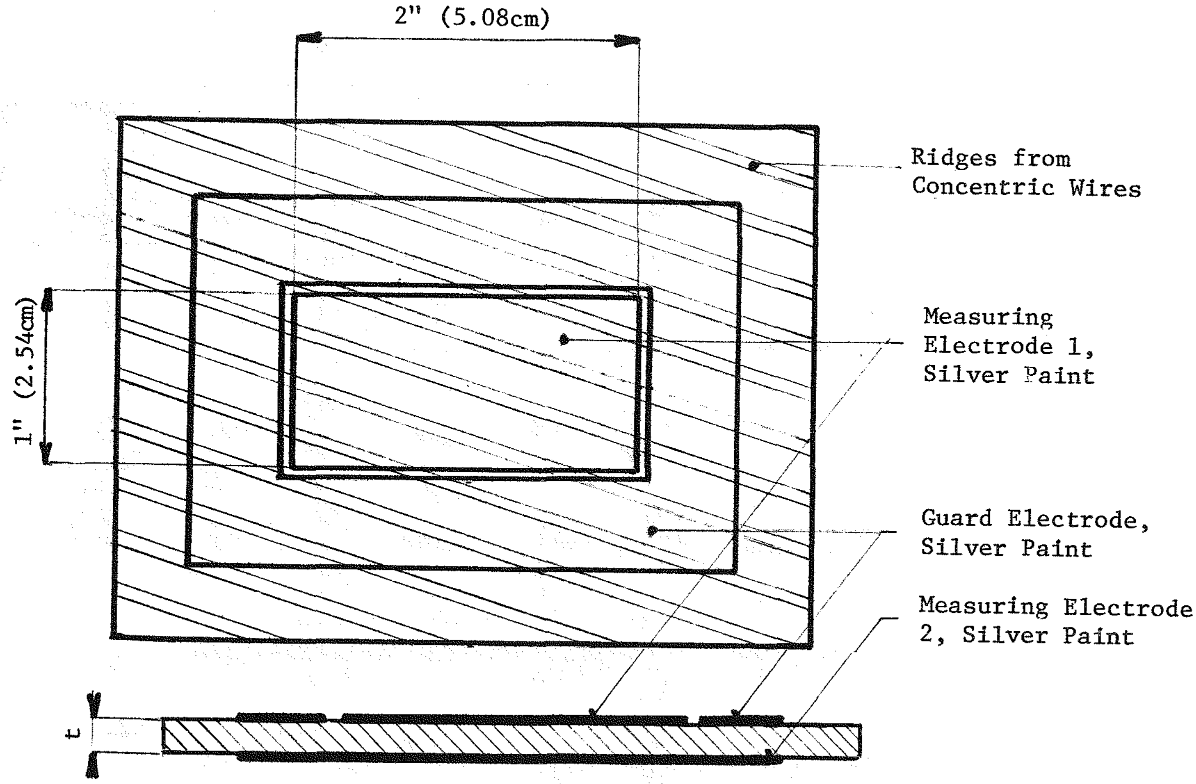


Figure 3-4. ELECTRODE CONFIGURATION FOR MEASUREMENT OF RADIAL RESISTANCE ON SEMICONDUCTING JACKETS REMOVED FROM FULL SIZE CABLE TEST SAMPLES

The corresponding resistivity was then calculated using the conventional formula for flat plate electrodes:

$$\rho = \frac{R_{SB}\ A}{t} \text{ ohm cm}$$

where:

R_{SB} = measured resistance of slab in ohms

A = area of electrode in cm^2

t = average thickness of jacket in cm

The calculated resistivities were then used for the calculation of resistances of the respective semiconducting jacket compounds for the full size cable test sample employing the following formula:

$$R = \frac{\rho}{2\pi L} \ln \frac{D}{d} \text{ ohms}$$

where:

ρ = resistivity in ohms

L = length of specimen in cm

D = diameter over the semiconducting jacket in cm

d = pitch diameter over the concentric wires in cm

Justification for the use of the pitch diameter of the concentric wires in this formula was based on capacitance measurements on identical cables with an insulating jacket. The calculated values of capacitance using the formula for two co-axial cylinder configuration employing pitch diameter of the concentric wires for the diameter of the inner cylinder agreed with the measured values.

Calculated values of radial resistance employing the above formula are plotted on the same graphs as the measured values on complete full size cable test samples. See dashed curves in Figures in Section 4. Test Program. The effect of contact resistance between the surface of the concentric copper wires and the semiconducting jacket is readily identifiable by comparison of the two values.

Values of dielectric constant were calculated from the capacitance measurements on full size cables employing the following formula:

$$SIC = \frac{C.\ \log {}^{D}/d}{1.23}$$

where:

C = measured capacitance on 2 inch sample in pF

D = diameter over the semiconducting jacket in cm

d = pitch diameter of concentric wires in cm

Physical tests on the semiconducting jackets removed from full size cables and screening tests on molded slabs and extruded wires were performed in accordance with ASTM Standards referenced in notes following the tabulated data. The moisture permeability constants of the eight semiconducting compounds and two commercial insulating type polyethylene jackets were determined in accordance with ASTM E 96-66 Procedure A at 23°C and 50% relative humidity. The detailed test procedure is included as Appendix 1 to this report.

Section 4

TEST PROGRAM

SELECTION OF SEMICONDUCTING THERMOPLASTIC COMPOUNDS

Eleven semiconducting thermoplastic compounds were received from six manufacturers. One compound was rejected without test due to severe gassing during extrusion with resultant porosity. The remaining ten compounds were subjected to all or part of the screening test program depending on whether they were rejected part way through due to deficiency in one or more important characteristics. The screening test program included the tests shown in Tables 1 - 4.

Six compounds were finally accepted as exhibiting suitable physical, electrical and moisture permeation characteristics. These compounds were subsequently extruded over a 2AWG stranded aluminum conductor crosslinked poleythylene (XLP) insulated 15kV concentric tinned copper neutral (10 #14AWG wires) cable core in 50 mils minimum point thickness so as to embed the copper wires.

TABLE 1

BASIC CHARACTERISTICS OF SEMICONDUCTING COMPOUNDS

Compound Designation / Test Performed	A	B	C	D	E	F	G	H	I	J
Carbon Black, Content, % (1)	32.9	35.2	34.7	32.9	31.1	34.9	32.2	37.2	36.8	10.8
Weight Loss - % (2)	0.25	0.35	0.26	0.21	0.22	0.46	0.23	0.09	.39	.01
Melt Index Grams/10 mins. (3)	0	0.026	0.005	0.008	0	0.086	0.0075	0.025	.0925	.009
Melting Point(s) °C (4)	85, 126	83, 130	82, 127	93	94	94	77,127	130	73	86, 174
Crystallization Point(s) °C (4)	108, 70	110, 65	108, 63	78	80	78	109, 60	112	57	75, 111

(1) Tested per ASTM D-1603

(2) Tested per ASTM D-280, except heating period 1 hour at 105°C

(3) Tested per ASTM D-1238

(4) Tested in accordance with standard Differential Scanning Calorimeter procedure

TABLE 2

TEST RESULTS ON SEMICONDUCTING COMPOUNDS ON WIRE+ AND SLABS AS INDICATED

Compound Designation Type of Test	A	B	C	D	E	F	G	H	I	J
Tensile Strength*										
Unaged, psi	1701	1893	2071	2367	2232	2544	1388	1955	1858	2483
After Aging at 100°C										
48 hrs, psi/% of Unaged	1535/96	1836/97	2012/97	2249/95	2130/95	2426/95	1374/99	1959/100	1895/102	2309/93
7 days, psi/% of Unaged	1760/103	1882/99	1930/93	2278/96	3282/98	3473/97	1410/102	2092/107	2044/110	1332/94
Elongation*										
Unaged, %	245	275	280	300	242	250	290	323	387	553
After Aging at 100°C,										
48 hrs, %/% of Unaged	223/91	230/84	300/107	250/83	193/80	215/86	213/73	342/106	364/94	481/87
7 days, %/% of Unaged	215/88	247/90	207/74	270/90	220/91	220/88	195/67	278/86	348/90	498/90
Heat Deformation**										
at 121°C, 500g. load, %	15	61	62	91	96	94	5	20	88	0
at 100°C, 500g. load, %	2	23	36	30	17	21	3	6	89	0
Brittleness Temperature (Slab) ASTM D-746, °C	-40	-28	-28	-28	-30	-30	-44	-46	‡	‡
Density per ASTM D-1505 Modified	1.141	1.156	1.171	1.141	1.104	1.146	1.146	1.130	‡	‡
Moisture Absorption Unaged** 7 days 70°C, mg/sq. in.	11	13	9	13	8	12	11	19	12.6	1.4
Moisture Absorption After Aging*** 7 days 70°C, mg/sq. in.	10	12	9	13	7	--	--	19	--	--
Hardness, Shore A (Slab)	95	95	95	93	95	95	95	96	96	98
Thermal Embrittlement** at 100°C Time to crack (NC= not cracked as of 9/30/75)	NC	NC	NC	NC	NC	NC	2 hrs.	168 hrs.	NC 90 days	NC 90 days
Environmental Stress Cracking (Slab) Cracked/Specimens-days	NC	NC	2/10 20	NC	NC	NC	1/10 13	1/10 7	0/10- 90 days	5/10-2hr 10/10-3hr
Volume Resistivity**										
DC, ohm-cm RT	62.8	26.5	14.4	16.6	18.4	302	29.3	69	‡	24
50°C	129	48.0	25.3	24.3	25.2	650	48.3	122	‡	--
90°C	520	604	449	125	134	2990	213	8000	‡	37
110°C	653	256	489	58.5	486	1410	101	11,000	‡	73
RT	61.9	27.1	23.9	14.9	19.8	105	28	79	‡	52

+Compounds were extruded in 0.050" wall on No. 14AWG Solid Copper

*Extruded tubular insulation tested following procedures of ASTM D-1351

**Insulated conductor tested following procedures of ASTM D-2633

***Aged for 6 months in air oven at 100°C.

‡These compounds were not tested. They were previously rejected from consideration

TABLE 3

MOISTURE VAPOR TRANSMISSION THROUGH SEMICONDUCTING COMPOUNDS COMPARED TO TRANSMISSION THROUGH POLYETHYLENE JACKET COMPOUNDS AT 22.8°C

Compound Designation	Moisture Vapor Transmitted (cm^3STP) (cm)/cm^2(sec)(cmHg)*
A	8.7×10^{-9}
B	24×10^{-9}
C	25×10^{-9}
D	13×10^{-9}
E	9.4×10^{-9}
F	68×10^{-9}
G	12×10^{-9}
H	22×10^{-9}
Medium Density Black Polyethylene Jacket Compound	3.2×10^{-9}
Low Density Black HMW Polyethylene Jacket Compound	5.8×10^{-9}
I	**
J	**

Tested following a modification (temperature and relative humidity) of ASTM E-96.

*Cubic centimeters of water at standard temperature and pressure per centimeter of specimen thickness per square centimeter of specimen surface per second per centimeter of mercury barometric pressure.

**These compounds were not tested. They were previously eliminated from consideration due to other noted deficiencies.

TABLE 4

AC RADIAL ELECTRICAL CHARACTERISTICS
OF
SEMICONDUCTING COMPOUNDS AT 20°C

Compound Designation	ELECTRICAL CHARACTERISTICS Radial Resistivity Ohm-cm	Dielectric Constant -	Dissipation Factor $\tan\delta$
A	350	2.3×10^5	327
B	50	30×10^5	170
C	292	3.0×10^5	336
D	123	18×10^5	130
E	366	2.3×10^5	345
F	*	*	*
G	*	*	*
H	753	1×10^5	362
I	1738	$.27 \times 10^5$	636
J	728	$.8 \times 10^5$	506

*These compounds were not tested. They were previously eliminated from consideration due to other noted deficiencies.

EVALUATION OF FULL SIZE CABLE SAMPLES

Air Oven Aging

Full size cable samples with semiconducting jacket Compounds A, B, C, D, E and H were placed in an air oven at 100°C. A photograph of the cables mounted on transite trays in the air oven is shown in Figure 4-1.

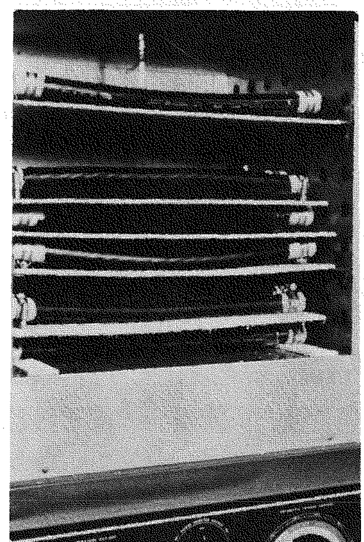


Figure 4-1. CABLES IN 100°C AIR OVEN

Radial resistance measurements were taken at room temperature initially and at intervals of one, two, three and four months and after six months aging. Radial resistance measurements were also taken at 50°C and 80°C initially and after three months and six months aging. Radial resistance values for the six semiconducting compounds, both measured and calculated as described in Section 3. Instrumentation and Sample Preparation, are plotted in Figures 4-2 - 4-7.

Capacitance measurements were taken at the same time as radial resistance. Measured values of capacitance at room temperature, 50°C and 80°C and corresponding calculated values of dielectric constant for the six compounds are shown in Tables 5 - 10.

Physical properties of the six semiconducting jacket compounds were measured at room temperature initially and at intervals at one, two, three and four months and after six months of air oven aging of the full size cables at 100°C. The data are plotted in Figures 4-41 - 4-46.

All plotted and tabulated values are an average of two or three measurements.

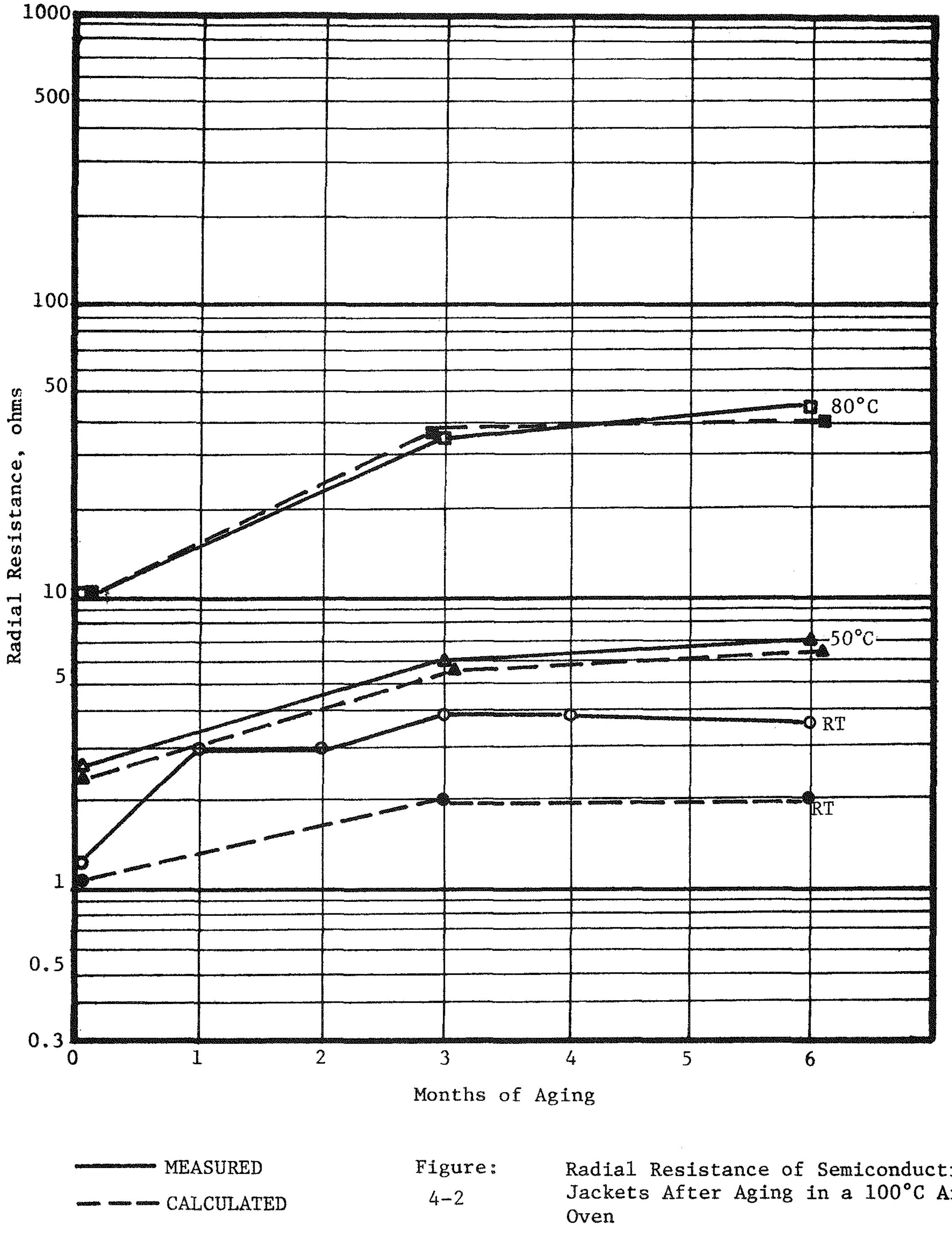
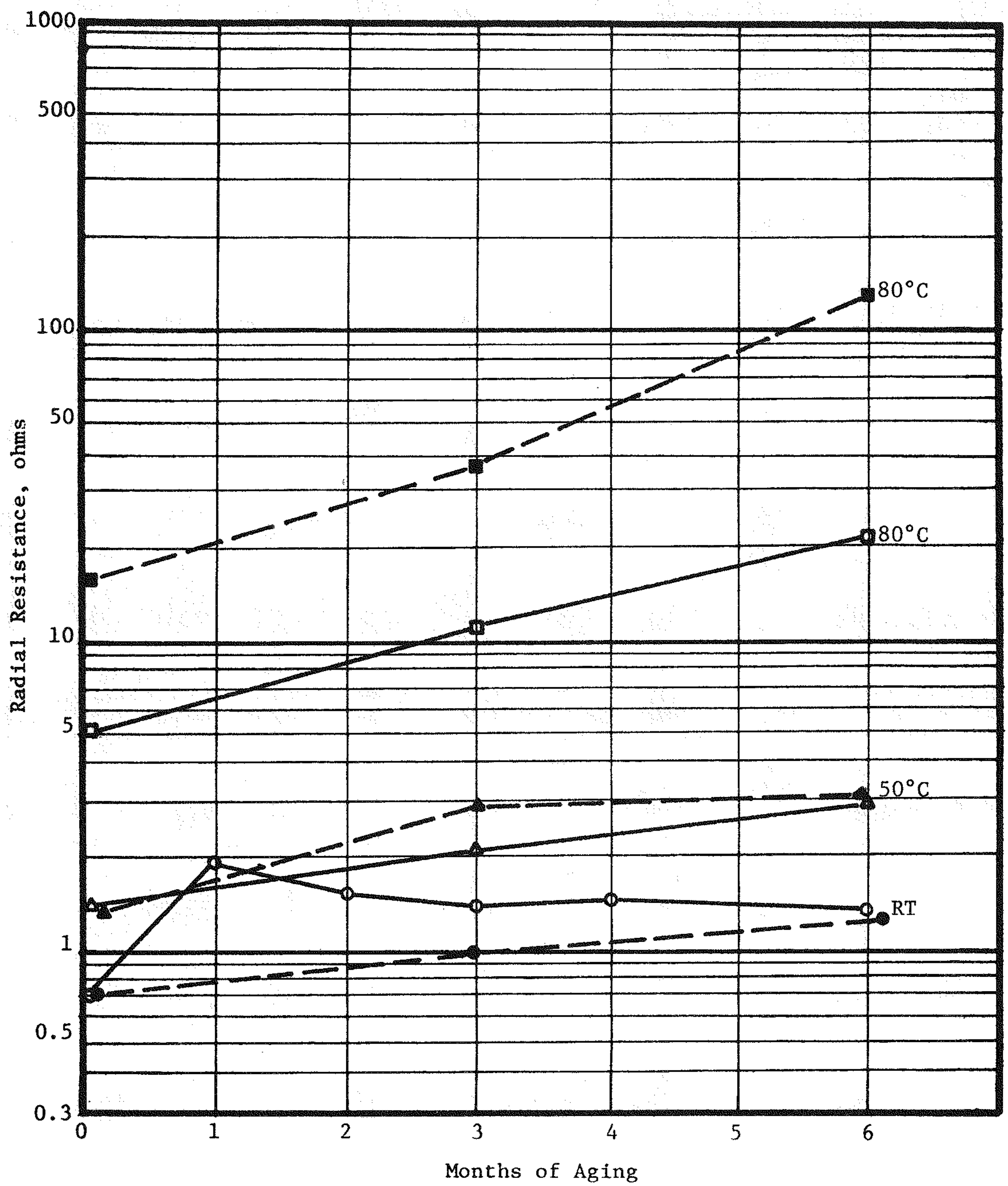


Figure: 4-2

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound A



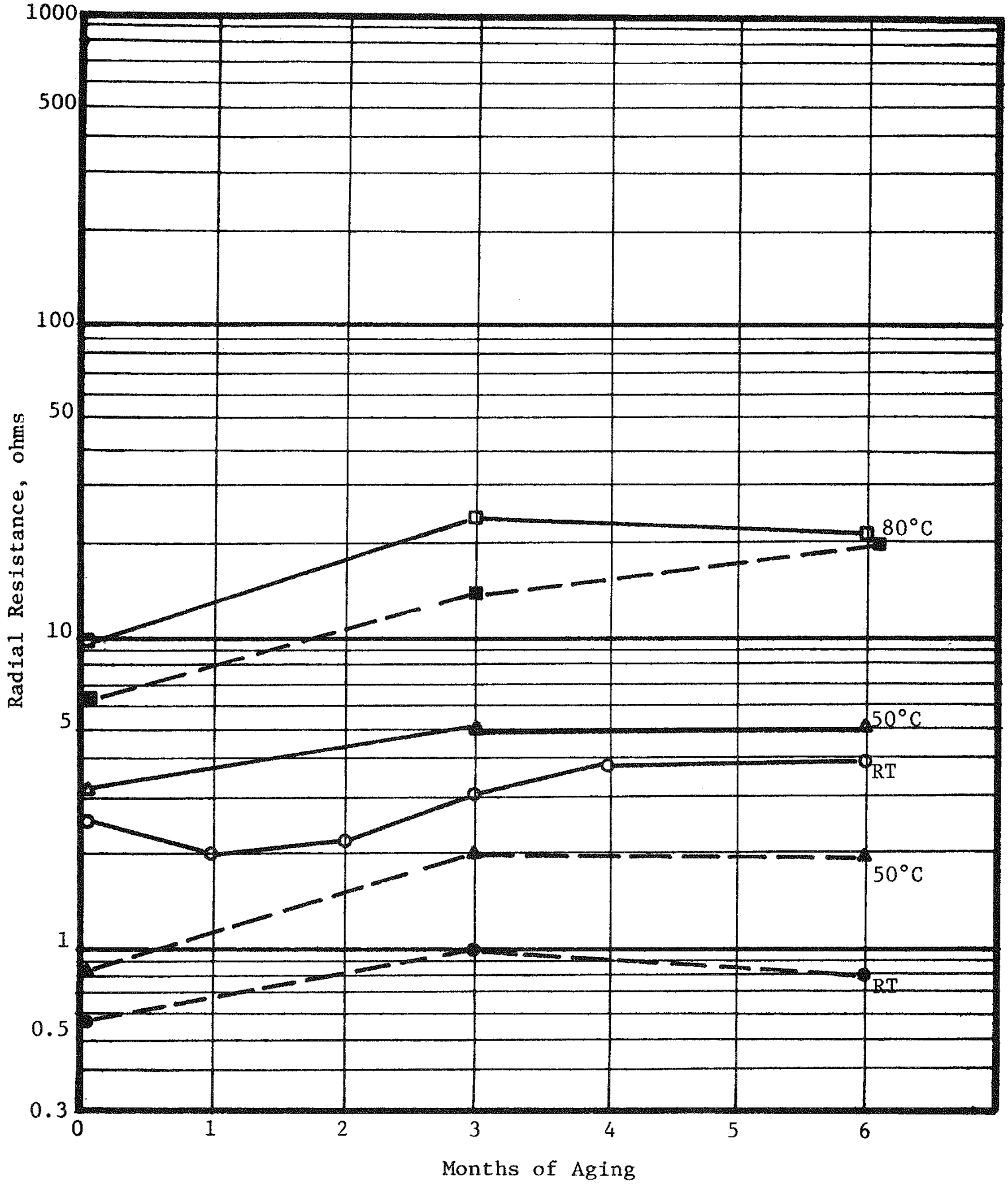
MEASURED

CALCULATED

Figure: 4-3

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound B



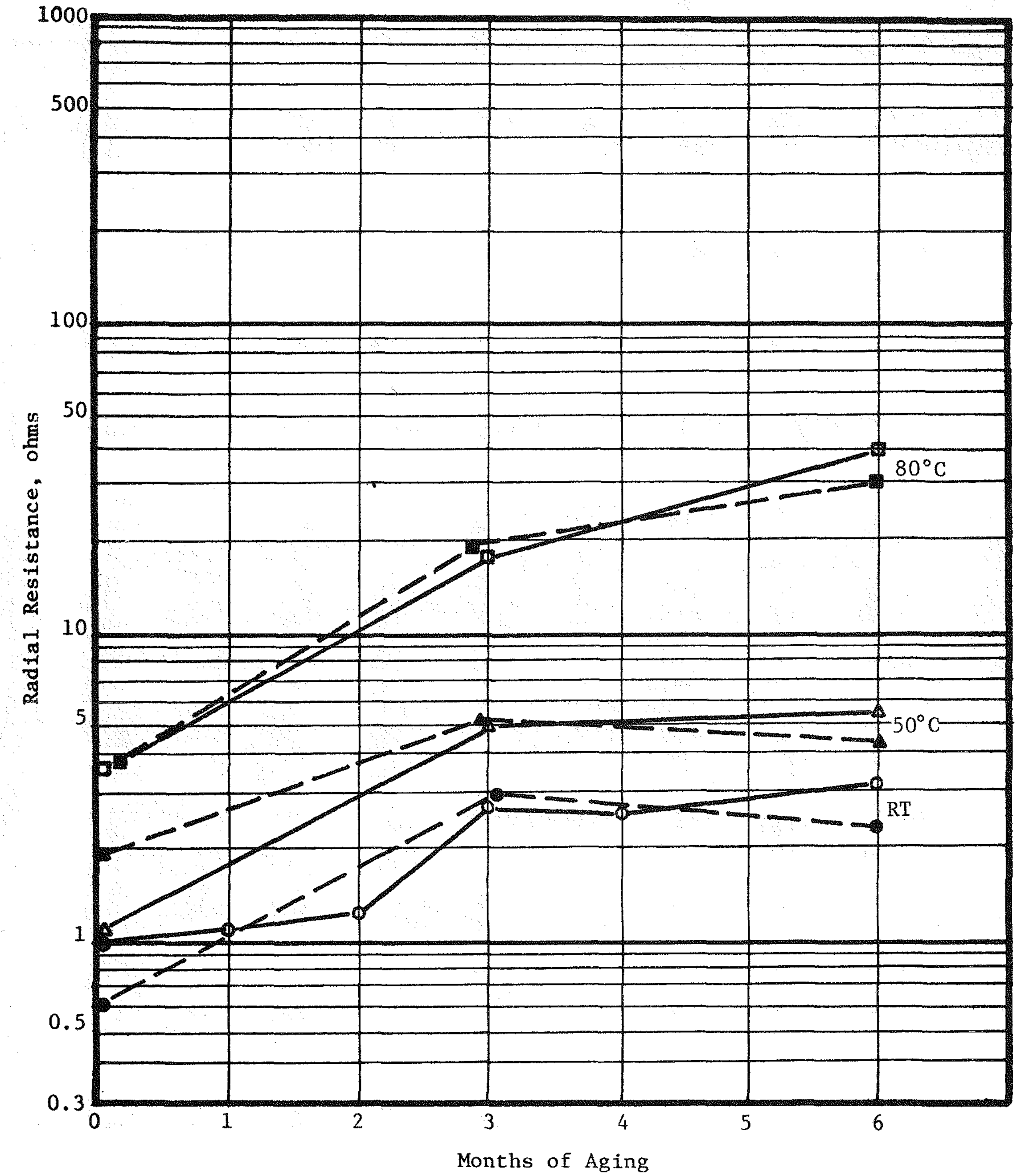
MEASURED

CALCULATED

Figure: 4-4

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound C



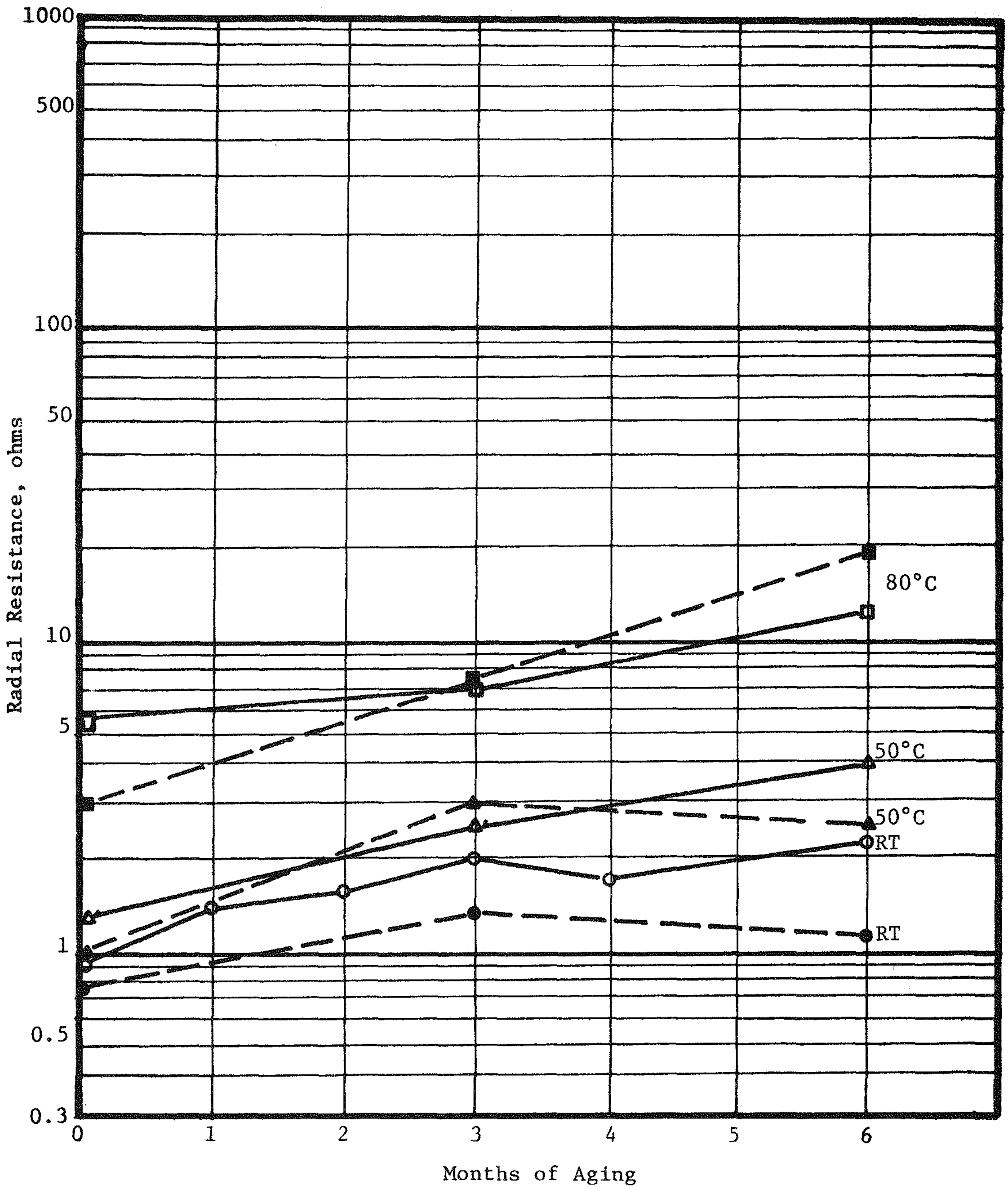
MEASURED

CALCULATED

Figure: 4-5

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound D



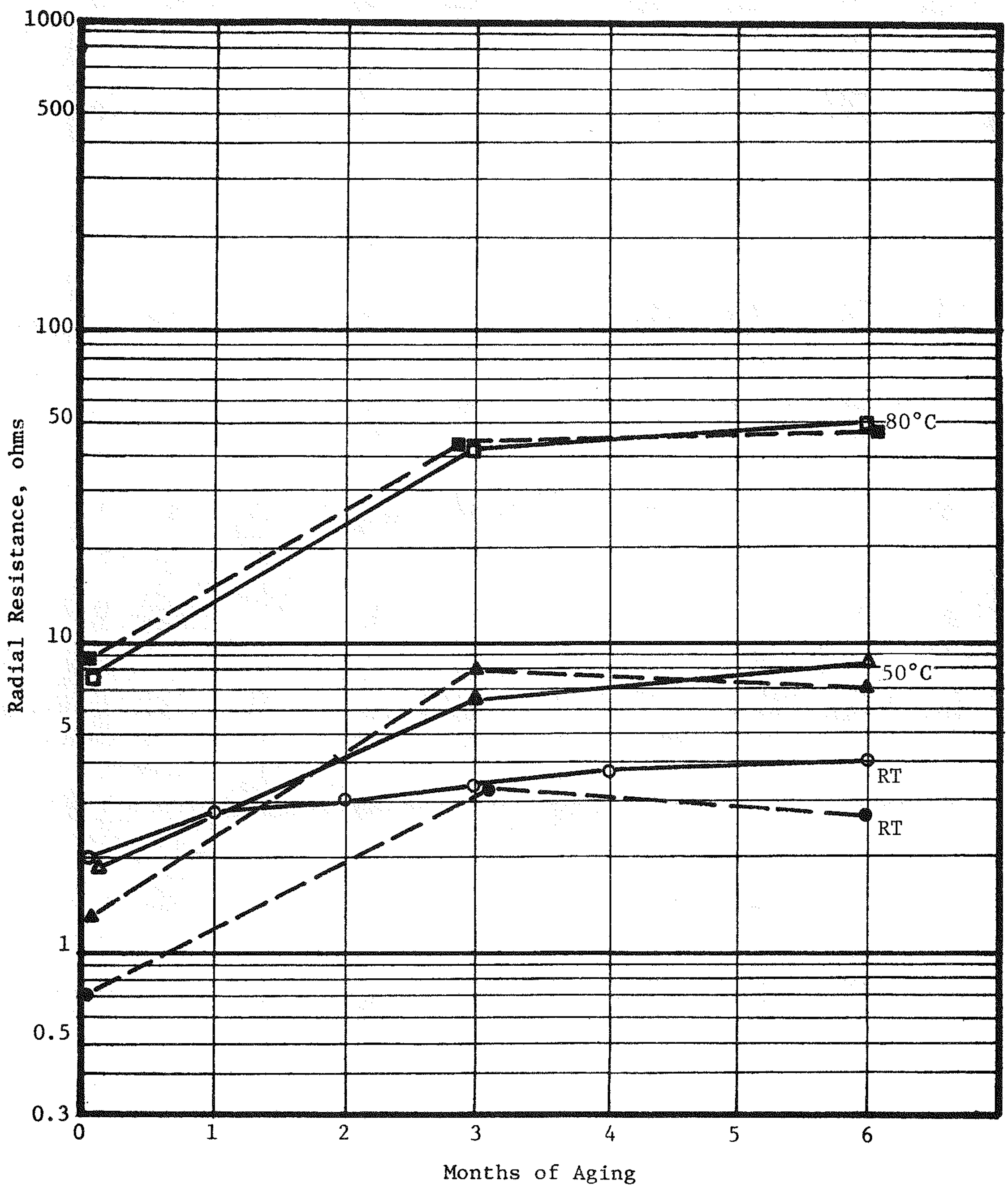
MEASURED

CALCULATED

Figure: 4-6

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound E



MEASURED

CALCULATED

Figure: 4-7

Radial Resistance of Semiconducting Jackets After Aging in a 100°C Air Oven

Compound H

Table 11.

RECTIFICATION TEST DATA

Test Conditions	Jacket Compound	Test Set Number				
		1	2	3	4	5
Aging Environment	A	←— 75°C water —→				Wisconsin Soil, RT
Electrode over jacket	thru	←— None —→		←— 12" tinned copper braid —→		None
Applied AC current, Amps	H	None	1	1	5	None
Aging period		Rectification Effect, %				
2 months	A	-	-	0.95	-	-
	B	-	-	1.03	-	-
	C	-	-	0.85	-	-
	D	-	-	0.36	-	-
	E	-	-	0.08	-	-
	H	-	-	0.53	-	-
4 months	A	-	2.53	-	0.23	0.44
	B	-	0.33	-	-	0.63
	C	-	1.25	-	-	0.79
	D	-	1.23	-	-	0.65
	E	-	2.3	-	-	0.79
	H	-	6.0	-	-	0.59
6 months	A	6.25	2.4	0.8	0.28	0.32
	B	4.2	3.05	1.05	0.2	0.83
	C	3.1	1.6	1.15	0.02	0.94
	D	3.4	1.6	0.12	1.6	0.62
	E	4.2	1.8	0.06	0.1	0.79
	H	5.0	3.3	0.33	0.19	0.55
7-1/2 months	A	4.5	4.6	1.3	0.01	0.24
	B	8.0	1.75	1.2	0.32	0.7
	C	2.4	1.28	0.23	0.05	0.68
	D	3.05	1.5	0.05	0.02	0.58
	E	5.0	1.68	0.19	0.53	0.6
	H	4.75	1.65	0.87	0.34	0.56

Water Immersion Aging

Full size cable samples with semiconducting jacket compounds A, B, C, D, E and H were immersed in tap water at 75°C. A photograph of the cables immersed in the specially constructed water tank is shown in Figure 4-8.

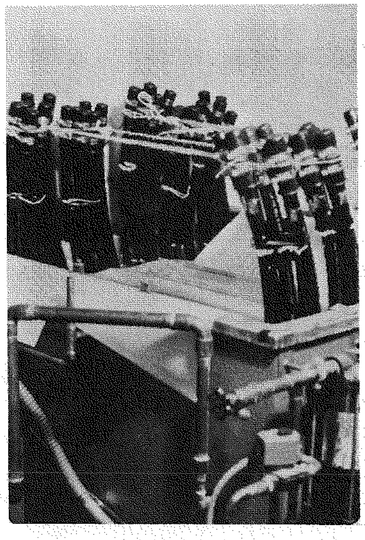


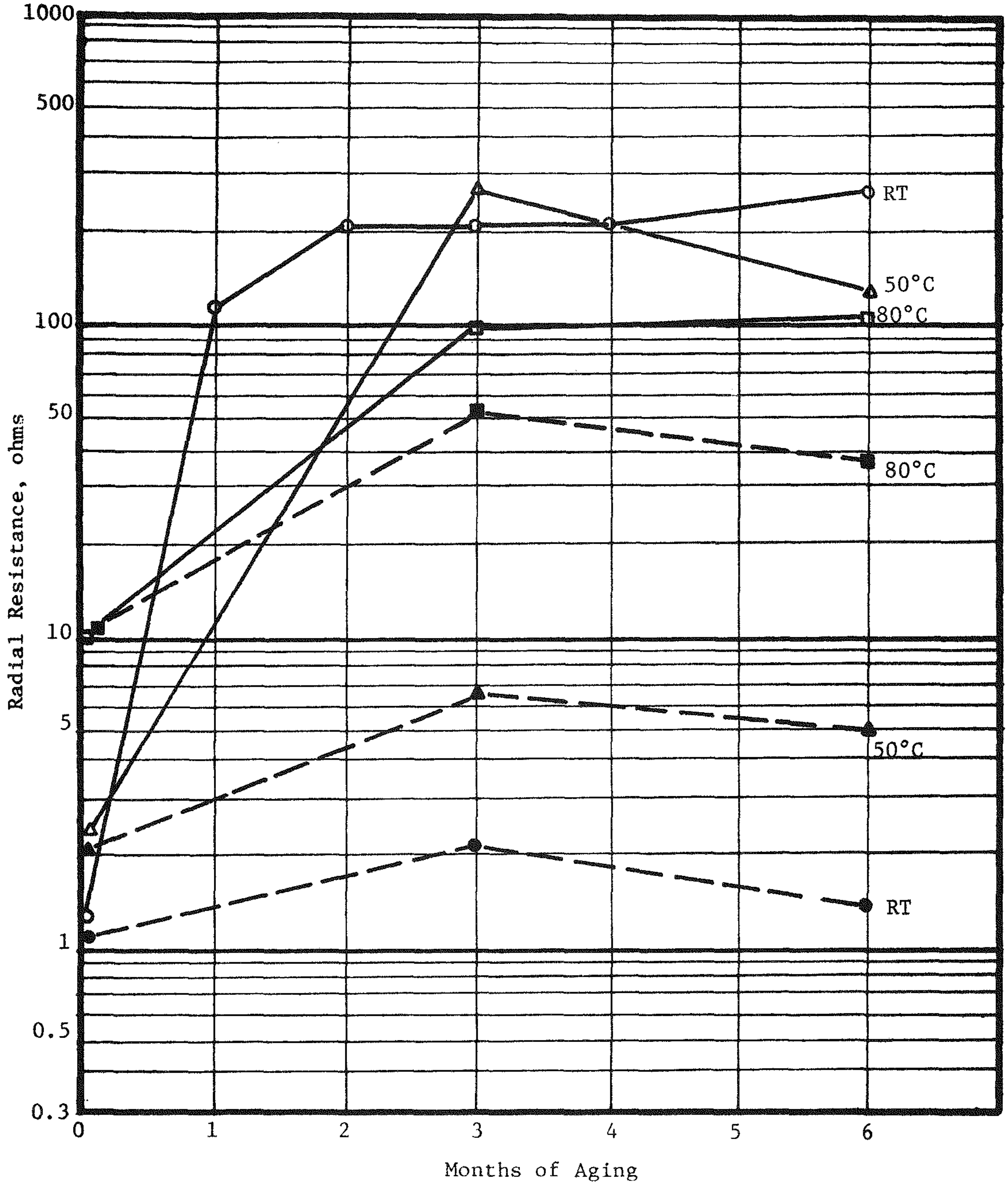
Figure 4-8. CABLES IMMERSED IN 75°C WATER TANK

Radial resistance measurements were taken at room temperature initially and at intervals of one, two, three and four months and after six months aging. Radial resistance measurements were also taken at 50°C and at 80°C initially and after three and six months. Radial resistance values for the six semiconducting compounds, both measured and calculated as described in Section 2, Instrumentation and Sample Preparation, are plotted in Figures 4-9 - 4-14.

Capacitance measurements were taken at the same time as radial resistance. Measured values of capacitance at room temperature, 50°C and 80°C and corresponding calculated values of dielectric constant for the six compounds are shown in Tables 5 - 10.

Physical properties of the six semiconducting jacket compounds were measured at room temperature initially and at intervals of one, two, three and four months and after six months of immersion of the full size cable samples in the 75°C water. The data are plotted in Figures 4-41 - 4-46.

All plotted and tabulated values are an average of two or three measurements.



MEASURED
CALCULATED

Figure: 4-9 Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound A

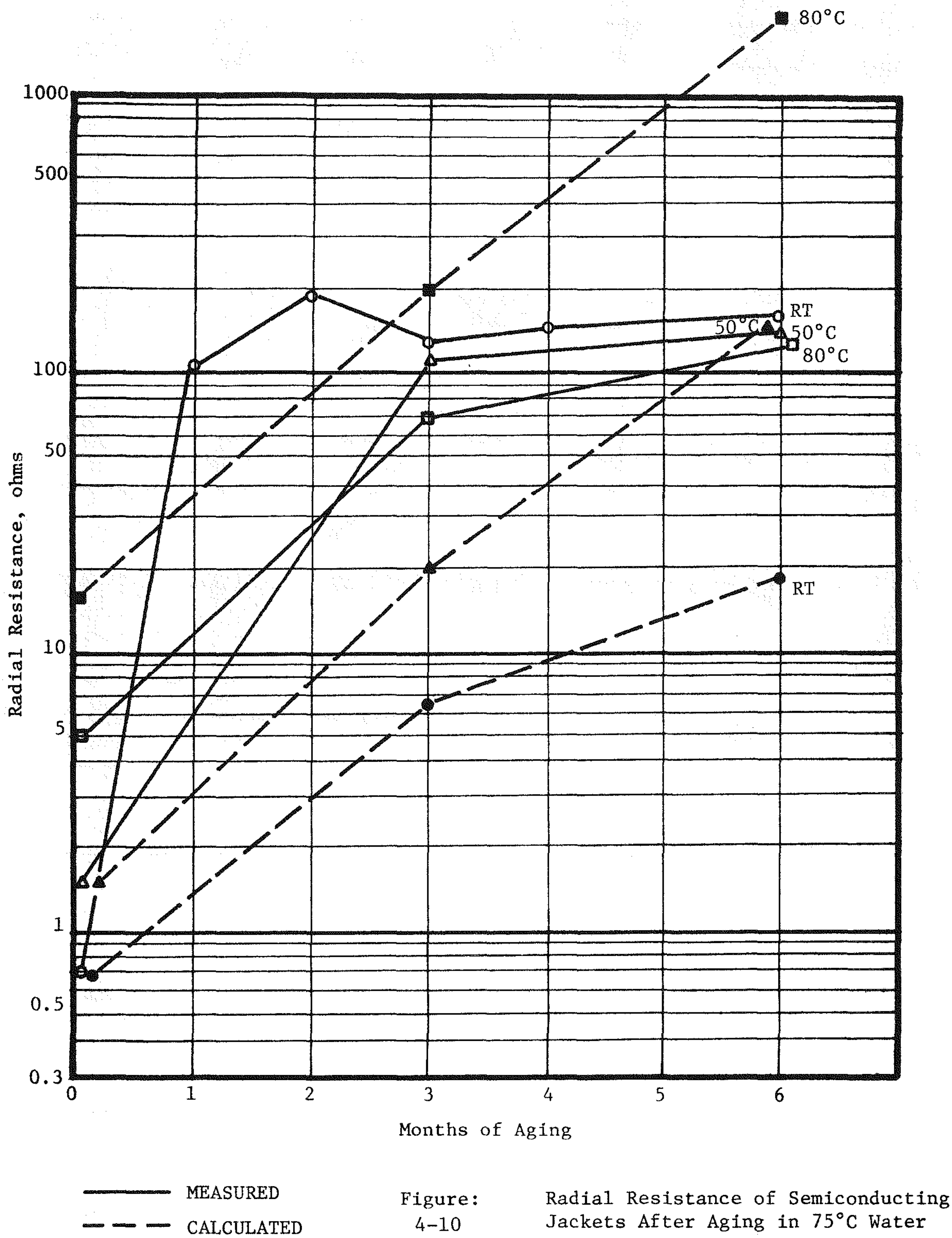


Figure: 4-10 Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound B

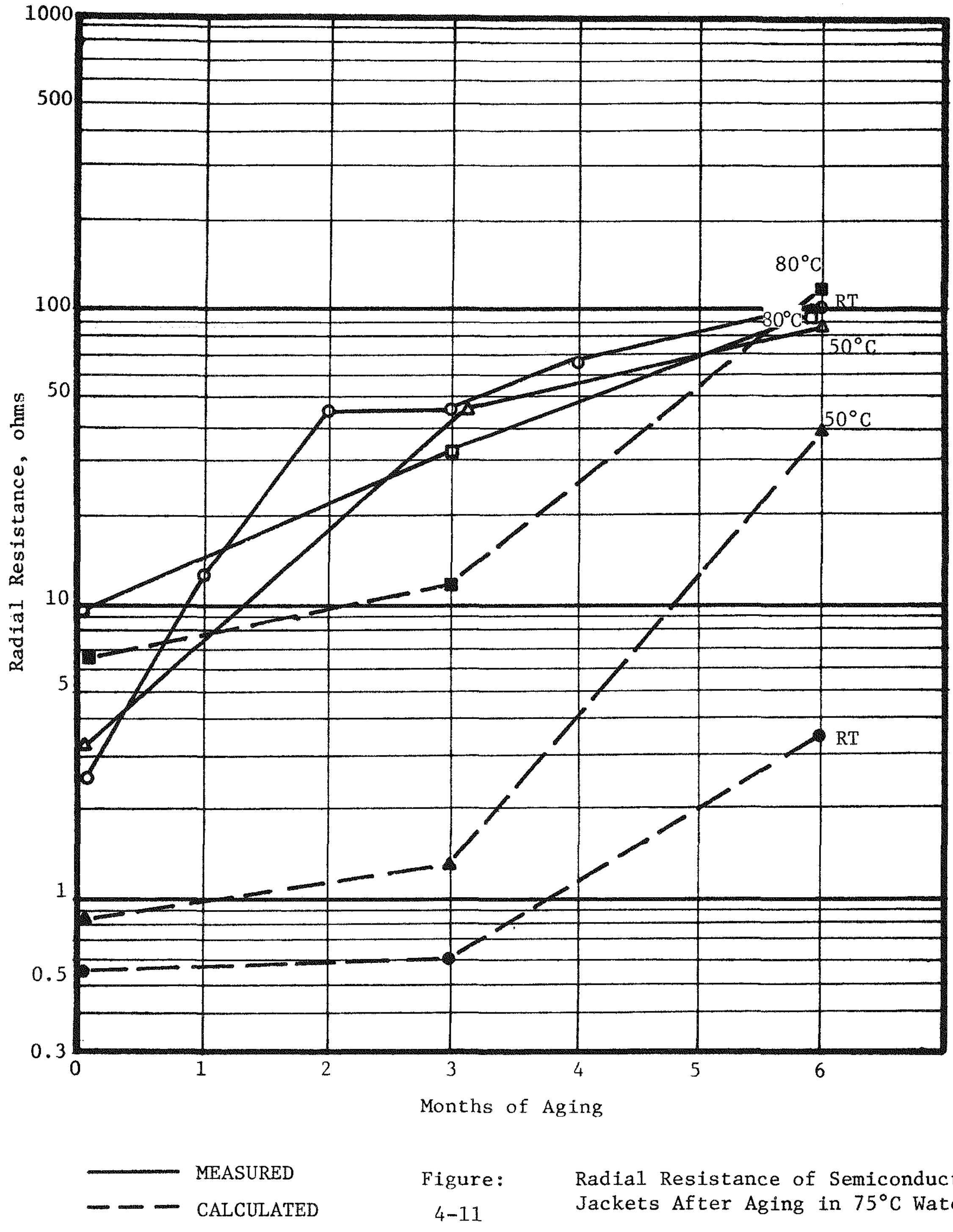


Figure: 4-11 Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound C

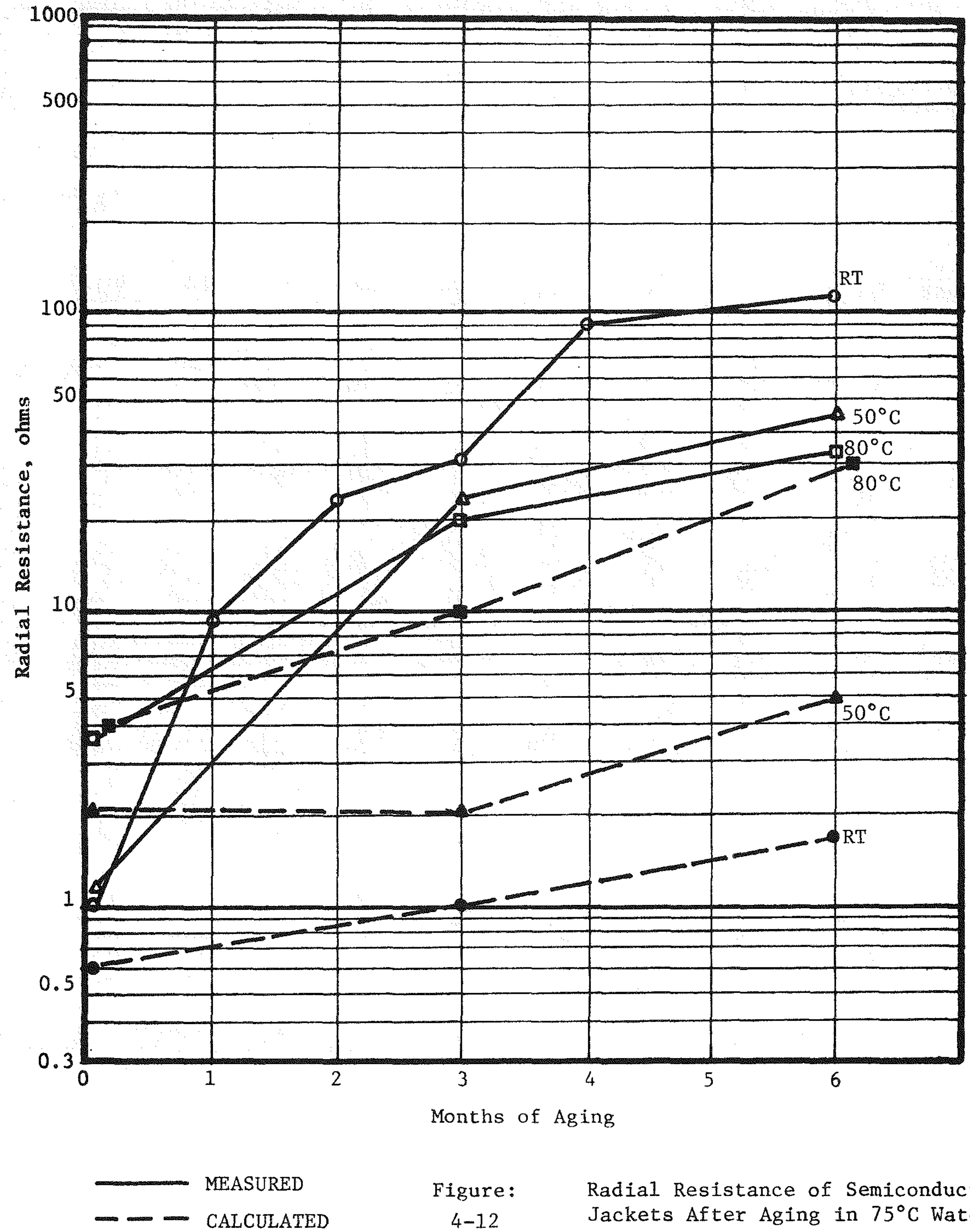
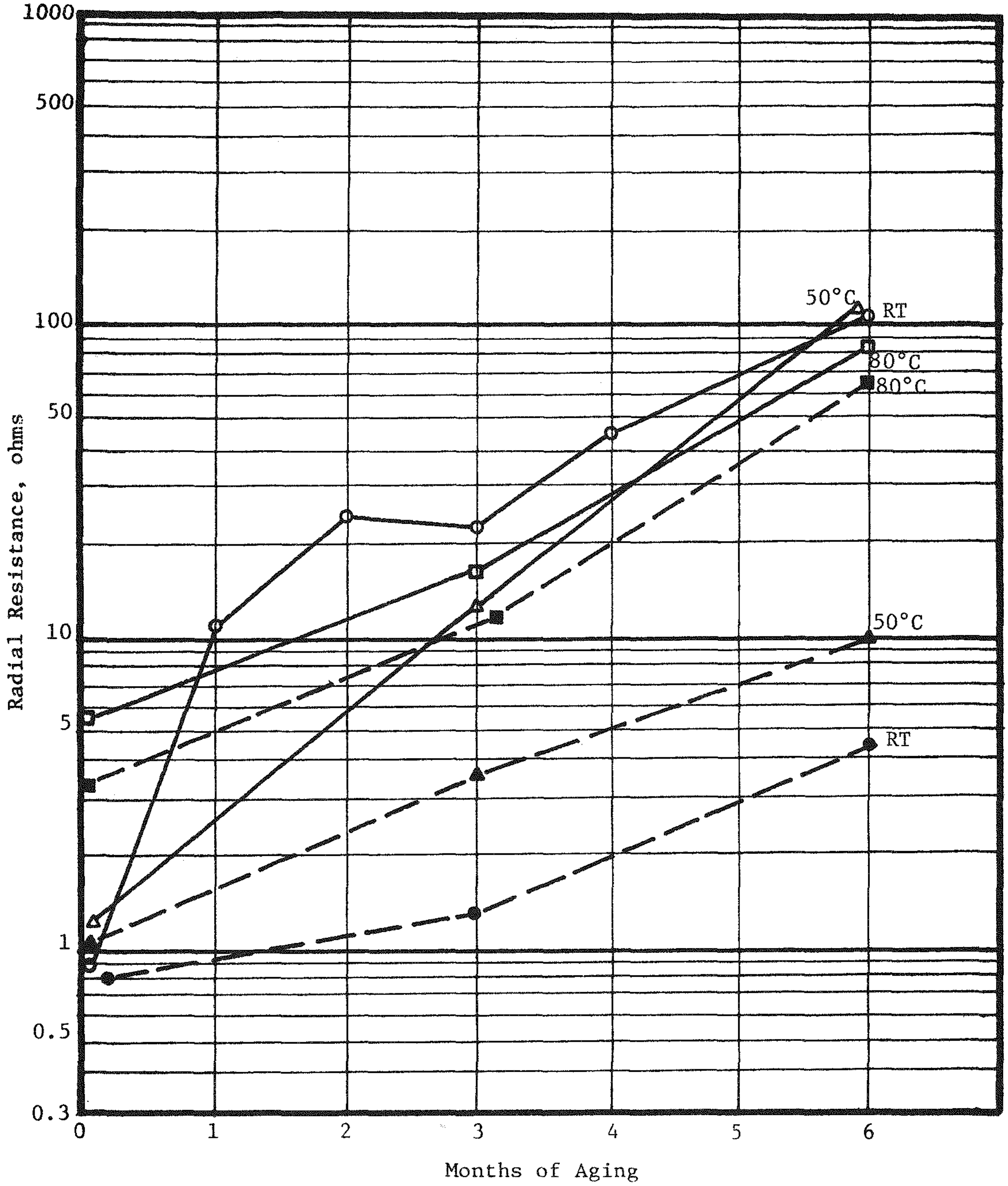


Figure: 4-12 Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound D

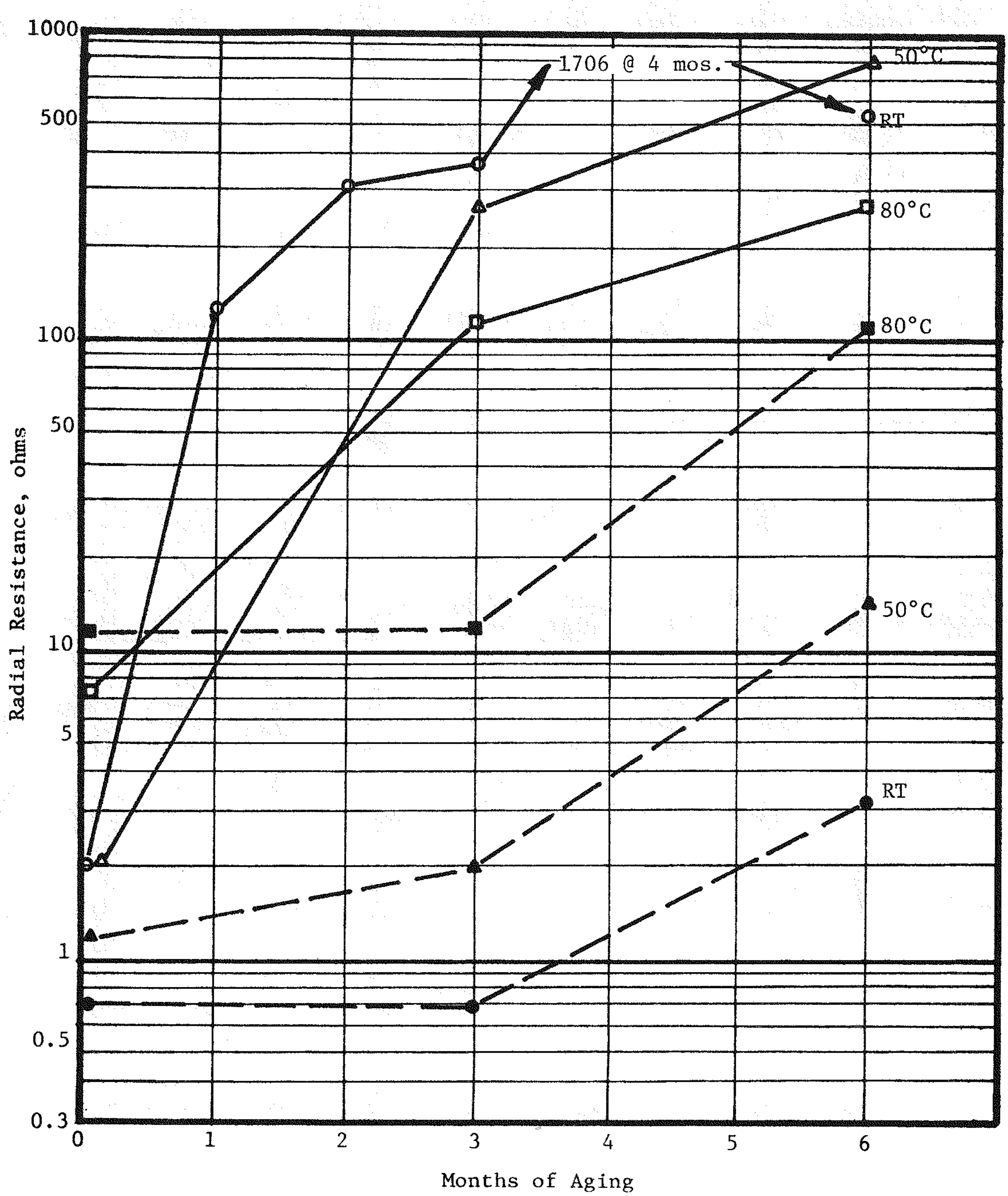


MEASURED

CALCULATED

Figure: 4-13 Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound E



MEASURED

CALCULATED

Figure: 4-14

Radial Resistance of Semiconducting Jackets After Aging in 75°C Water

Compound H

Soil Burial Aging

Full size cable samples with semiconducting jacket compounds A, B, C, D, E and H were buried in three soils obtained from Georgia, the Wisconsin test site for Phase II of RP 671-1 and from Florida. The characteristics of the three soils are indicated below:

Soil Source	Normal Density Pounds/Cubic Foot	Moisture[1] Content %	ph[2]
Florida	100	3.5	7.66
Georgia	100	15	6.35
Wisconsin	90	20	5.94

[1]Percent of dry weight

[2]ASTM D-2976 with measurement made in dilute calcium chloride solution

Special containers measuring 36 inches by 15 inches by 4 inches were constructed for the purpose of embedment of 36 inch long full size cable samples. The bottoms of the containers were lined with copper sheet to function as the ground electrode and provision was made to maintain the earth in each container at the desired moisture content. The containers were placed in an isolated enclosure and the temperature maintained at 50°C.

A sufficient number of containers were constructed to accommodate a total of 180 test specimens corresponding to six test samples of three soils under two test conditions for five aging periods with twelve test specimens per container. The two test conditions corresponded to aging of the cables with and without voltage applied between the copper concentric neutral wires and earth.

Photographs of the cables in the process of being placed in the special container for soil embedment and the humidity controlled room in which the polyethylene covered containers were aged are shown in Figures 4-15 and 4-16.

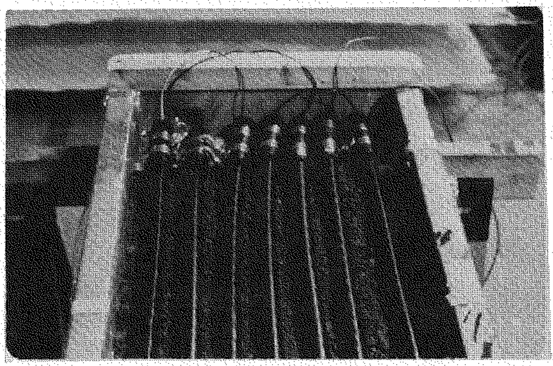


Figure 4-15. CABLES PLACED IN TRAYS BURIED IN SOIL FOR CONDITIONING AT 50°C WITH AND WITHOUT VOLTAGE

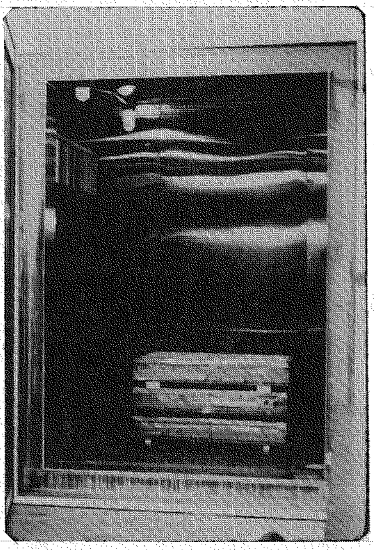


Figure 4-16. CABLES BURIED IN SOIL IN TRAYS COVERED WITH POLYETHYLENE AND PLACED IN AN ENVIRONMENTAL CHAMBER TO MAINTAIN MOISTURE CONTENT AND 50°C TEMPERATURE FOR CONDITIONING.

The cables were aged in the three soils for six months with and without a-c voltage applied between the copper concentric neutral wires and ground. The applied voltage was 5 volts a-c.

Radial resistance measurements were taken at room temperature initially and at intervals of one, two, three and four months and after six months aging on the samples which were aged with and without voltage applied. Radial resistance measurements were also taken at 50°C and 80°C initially and after three and six months on the samples which were aged only with voltage applied. Radial resistance values for the six semiconducting compounds, both measured and calculated as described in Section 2, Instrumentation and Sample Preparation, are plotted in Figures 4-17 - 4-40.

Capacitance measurements were taken at the same time as radial resistance. Measured values of capacitance at room temperature, 50°C and 80°C and corresponding calculated values of dielectric constant for the six compounds are shown in Tables 5 - 10.

Physical properties of the six semiconducting jacket compounds were measured at room temperature initially and at intervals of one, two, three and four months and after six months of soil burial. The data are plotted in Figures 4-41 - 4-46.

All plotted and tabulated values are an average of two or three measurements.

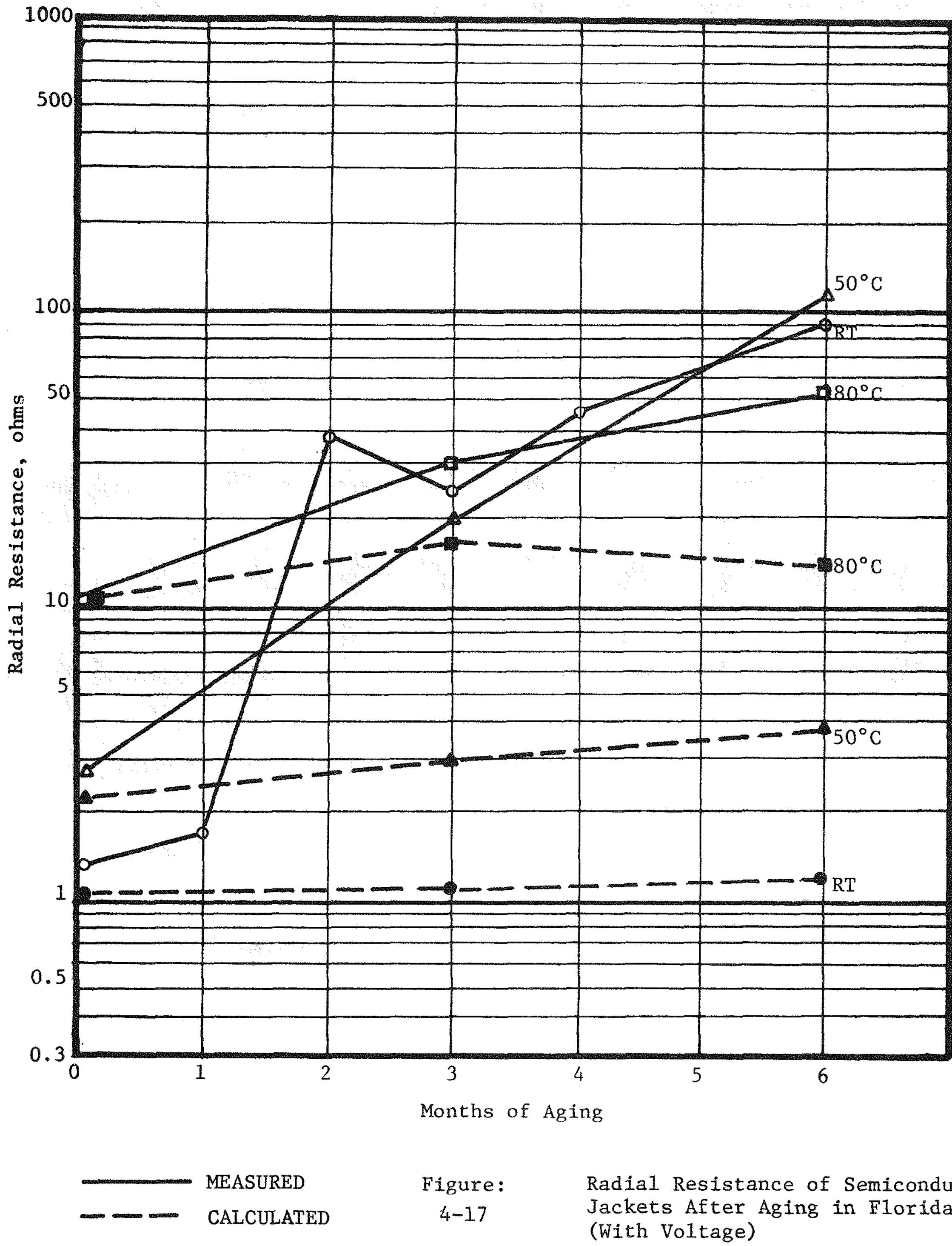
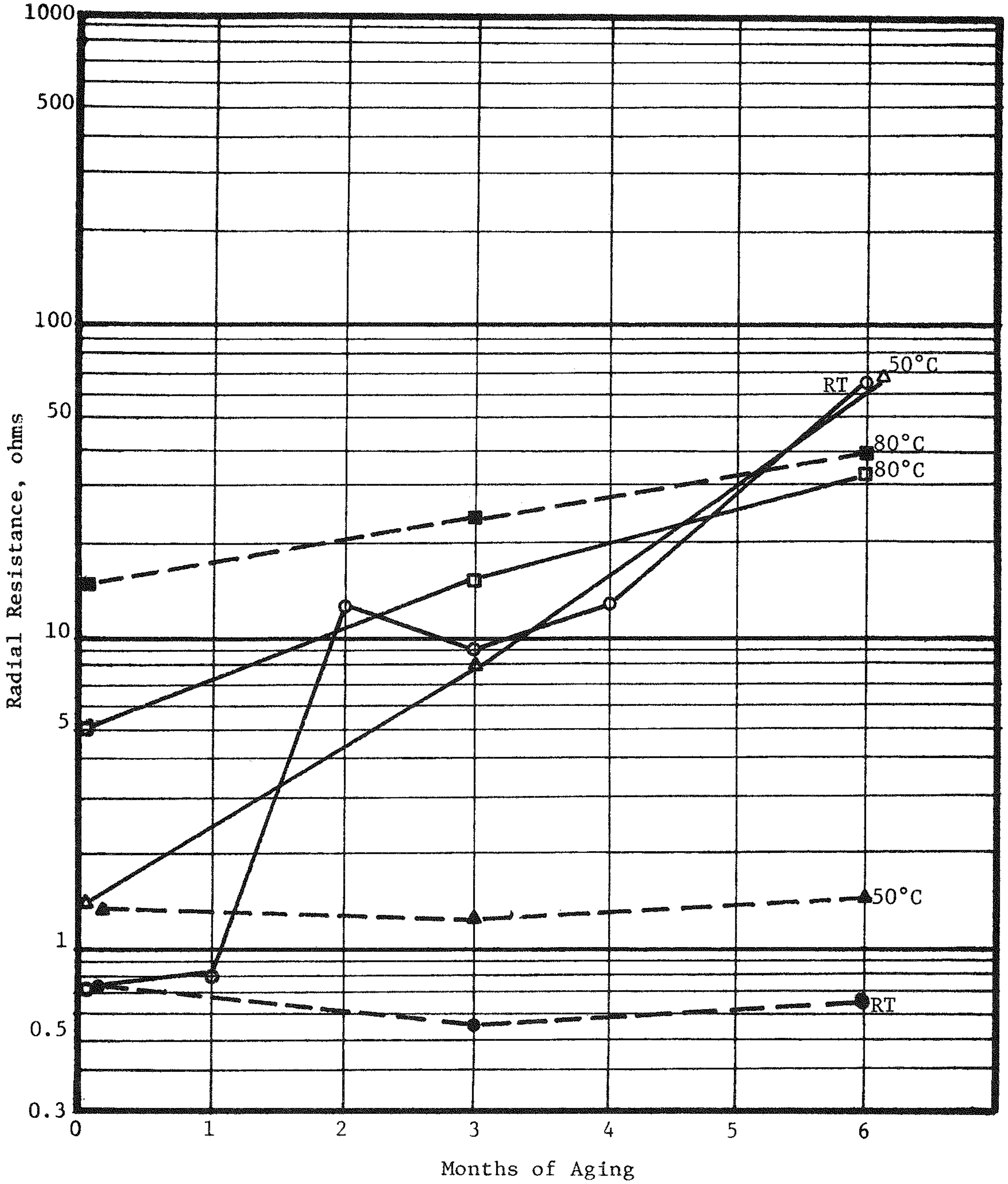


Figure: 4-17

Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

Compound A



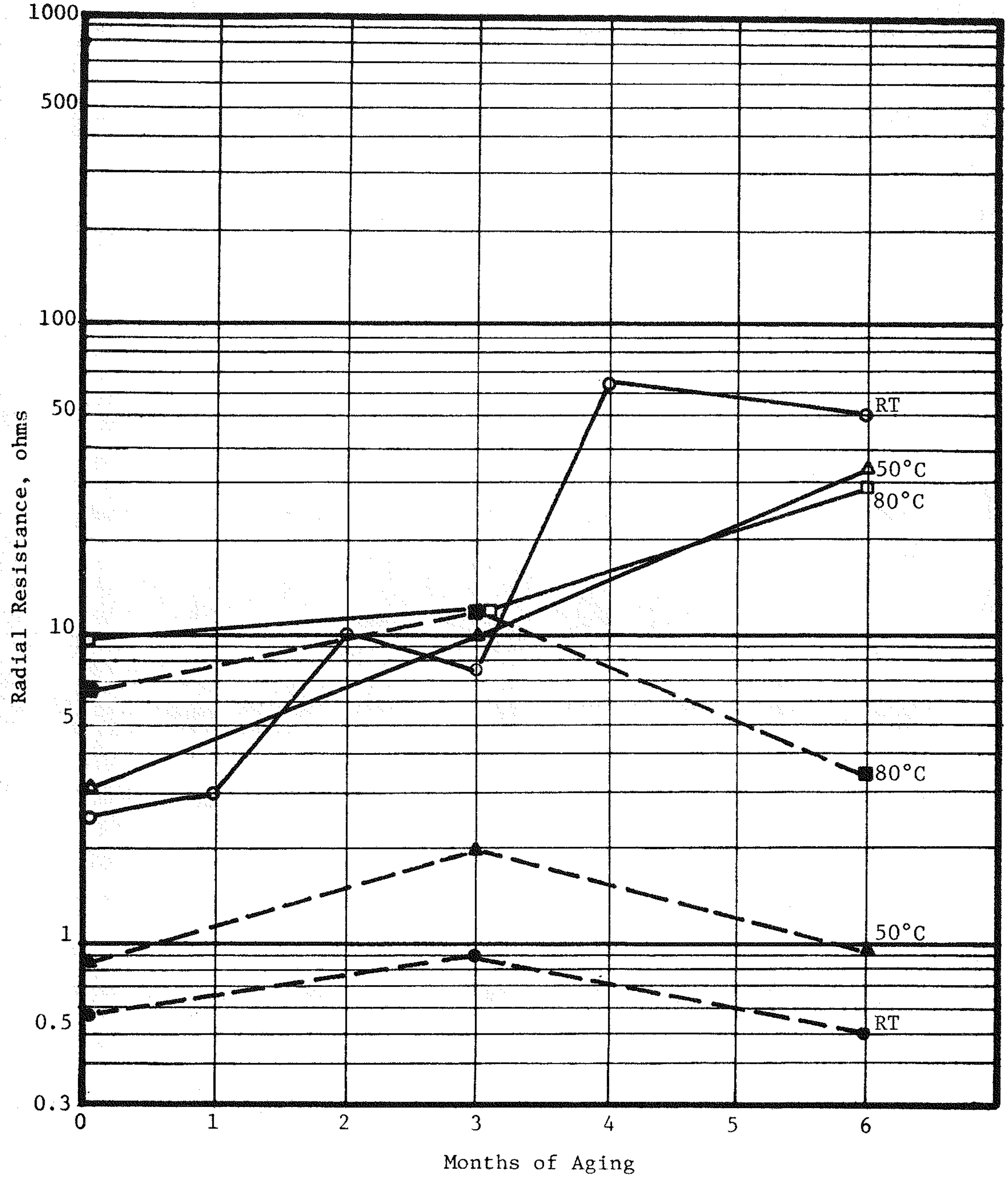
MEASURED

CALCULATED

Figure: 4-18

Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

Compound B



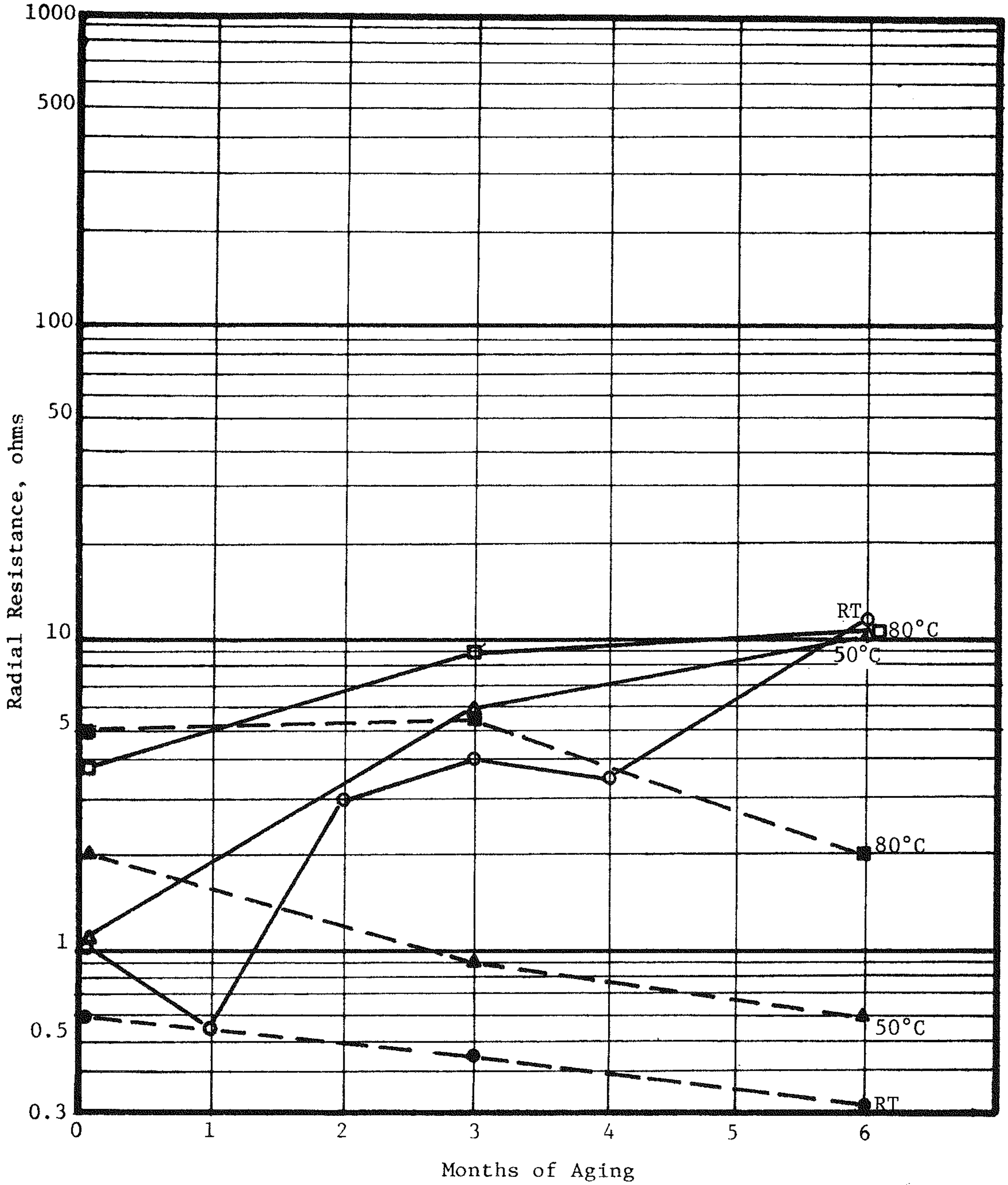
——— MEASURED

— — — CALCULATED

Figure: 4-19

Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

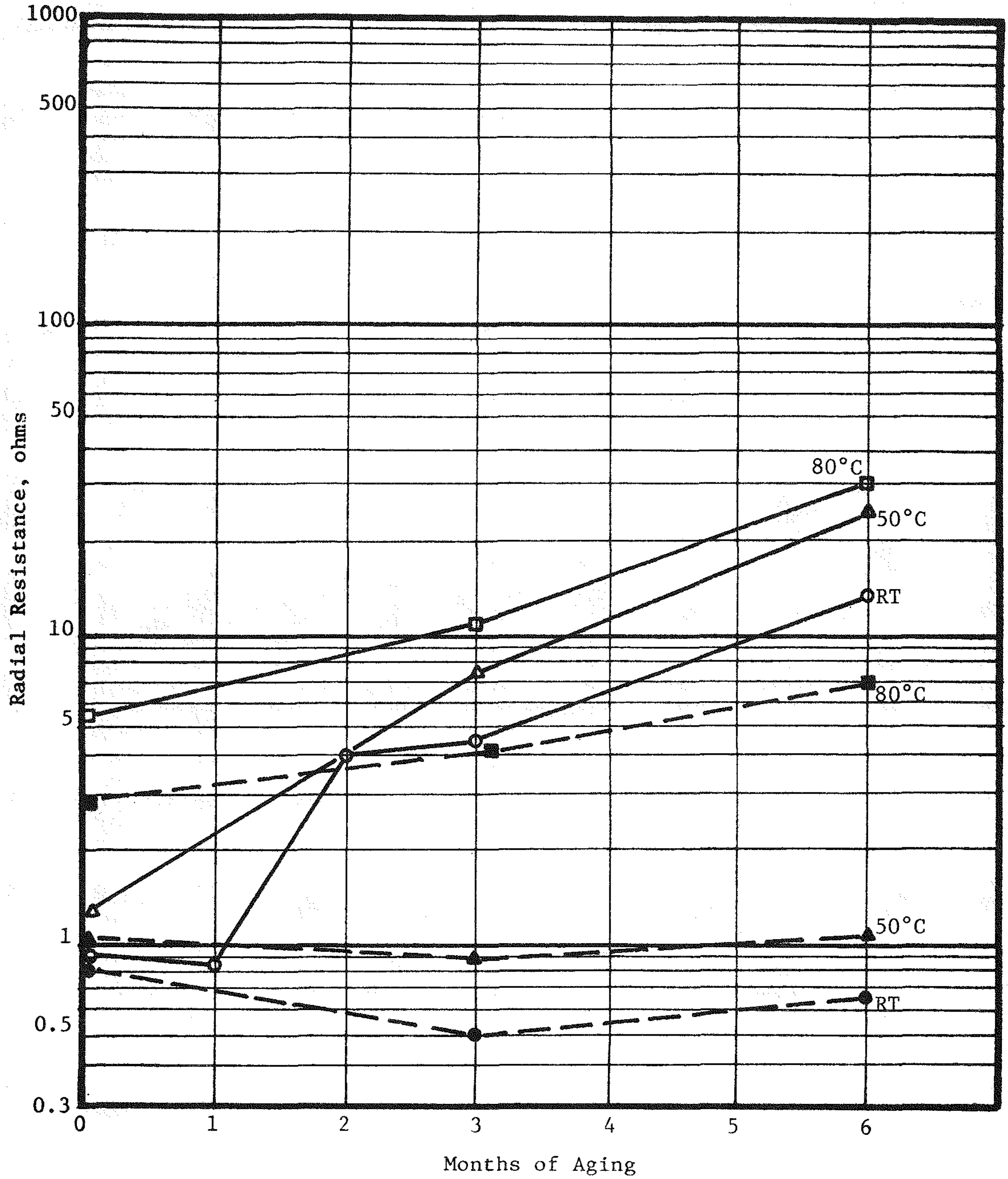
Compound C



MEASURED
CALCULATED

Figure: 4-20 Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

Compound D



MEASURED
CALCULATED

Figure: 4-21

Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

Compound E

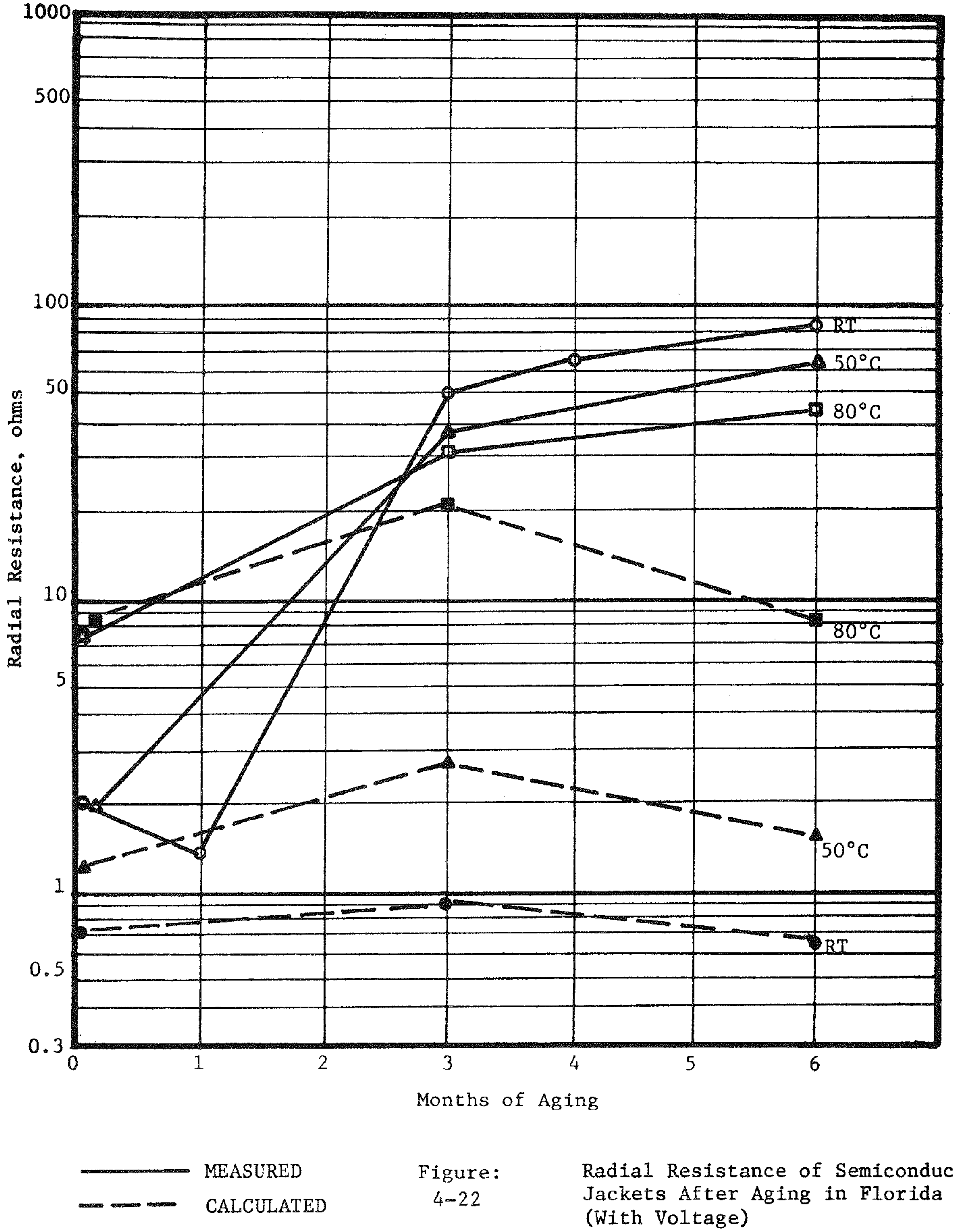


Figure: 4-22

Radial Resistance of Semiconducting Jackets After Aging in Florida Soil (With Voltage)

Compound H

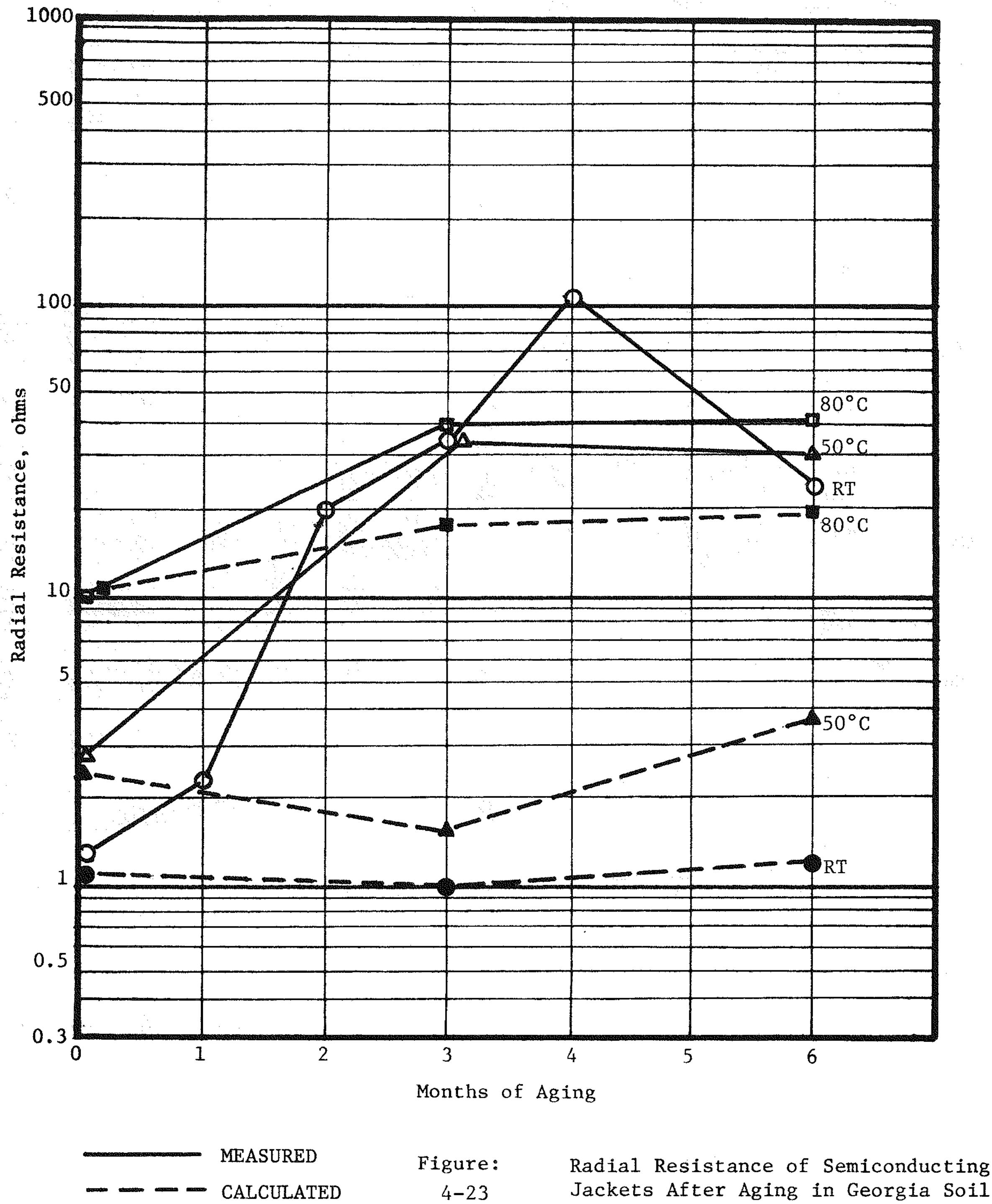


Figure: 4-23 Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

Compound A

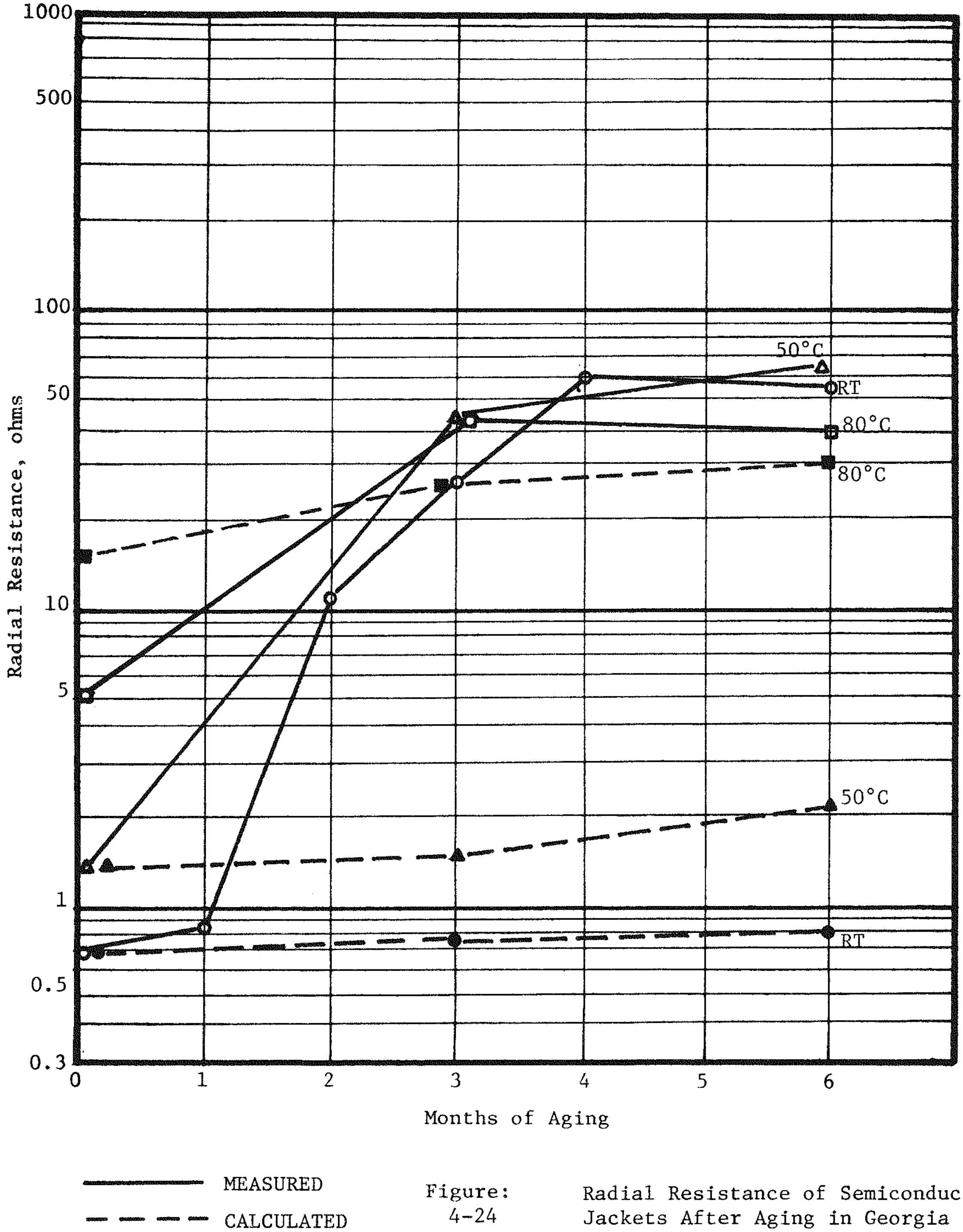
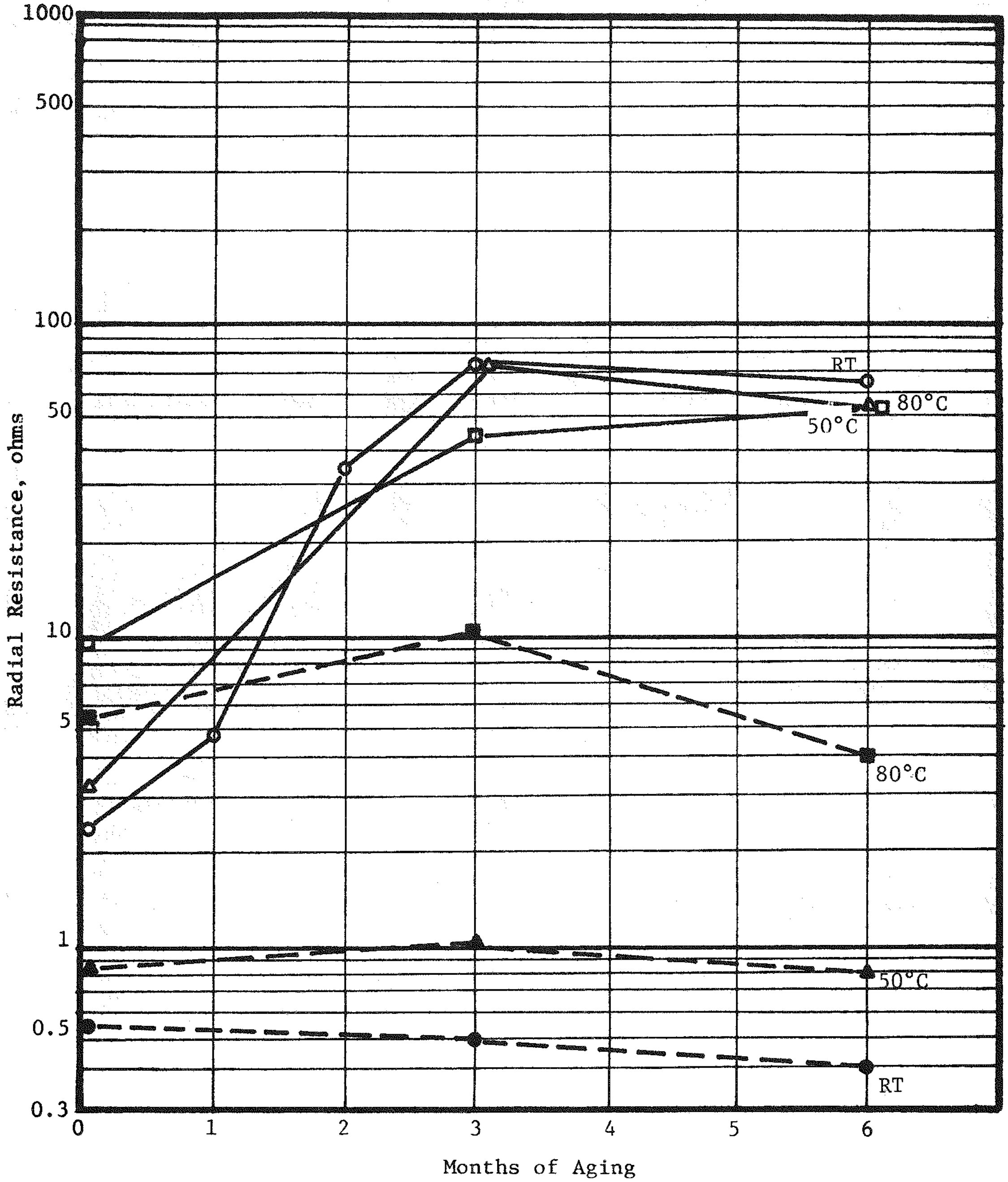


Figure: 4-24

Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

Compound B



MEASURED

CALCULATED

Figure: 4-25 Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

Compound C

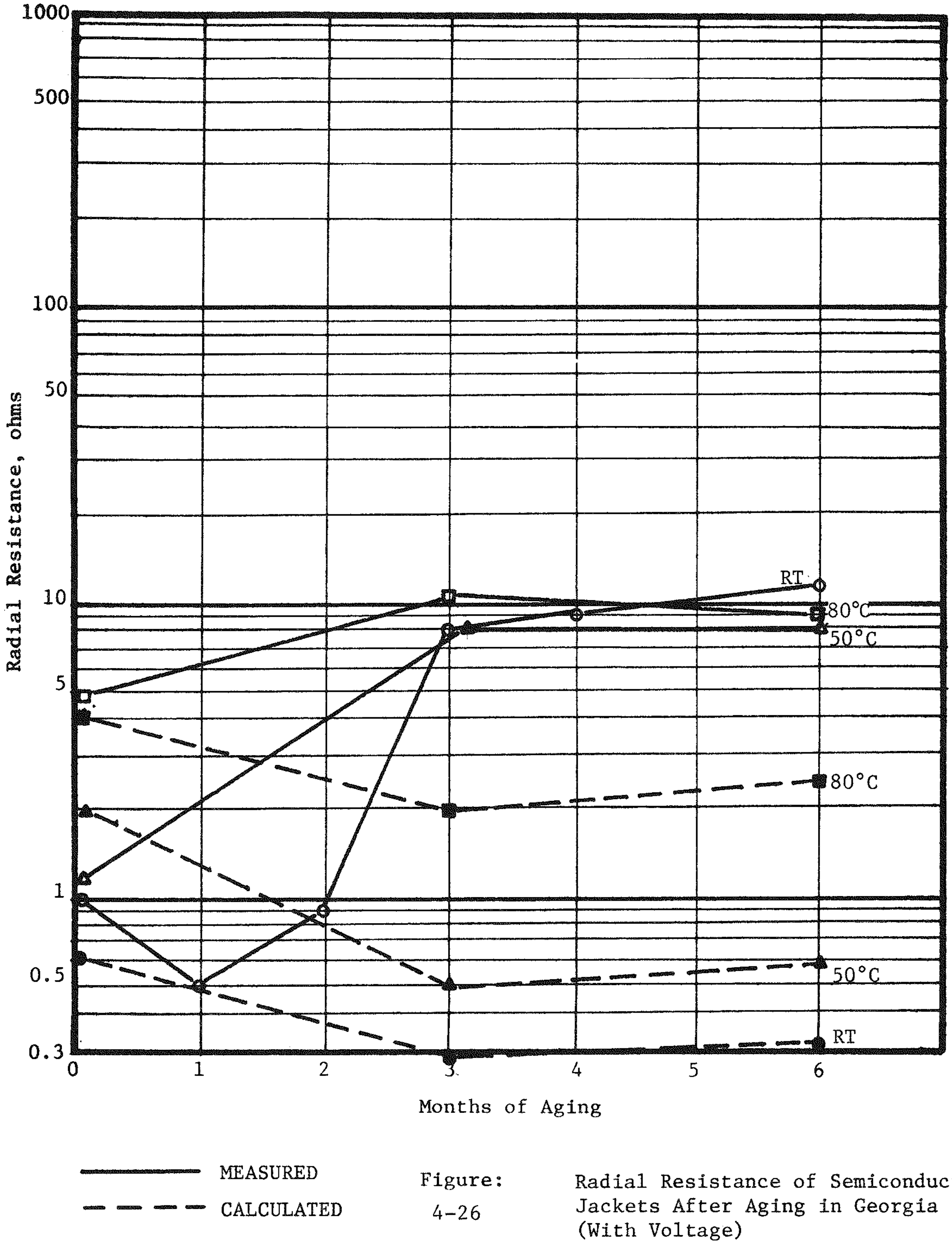


Figure: 4-26

Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

Compound D

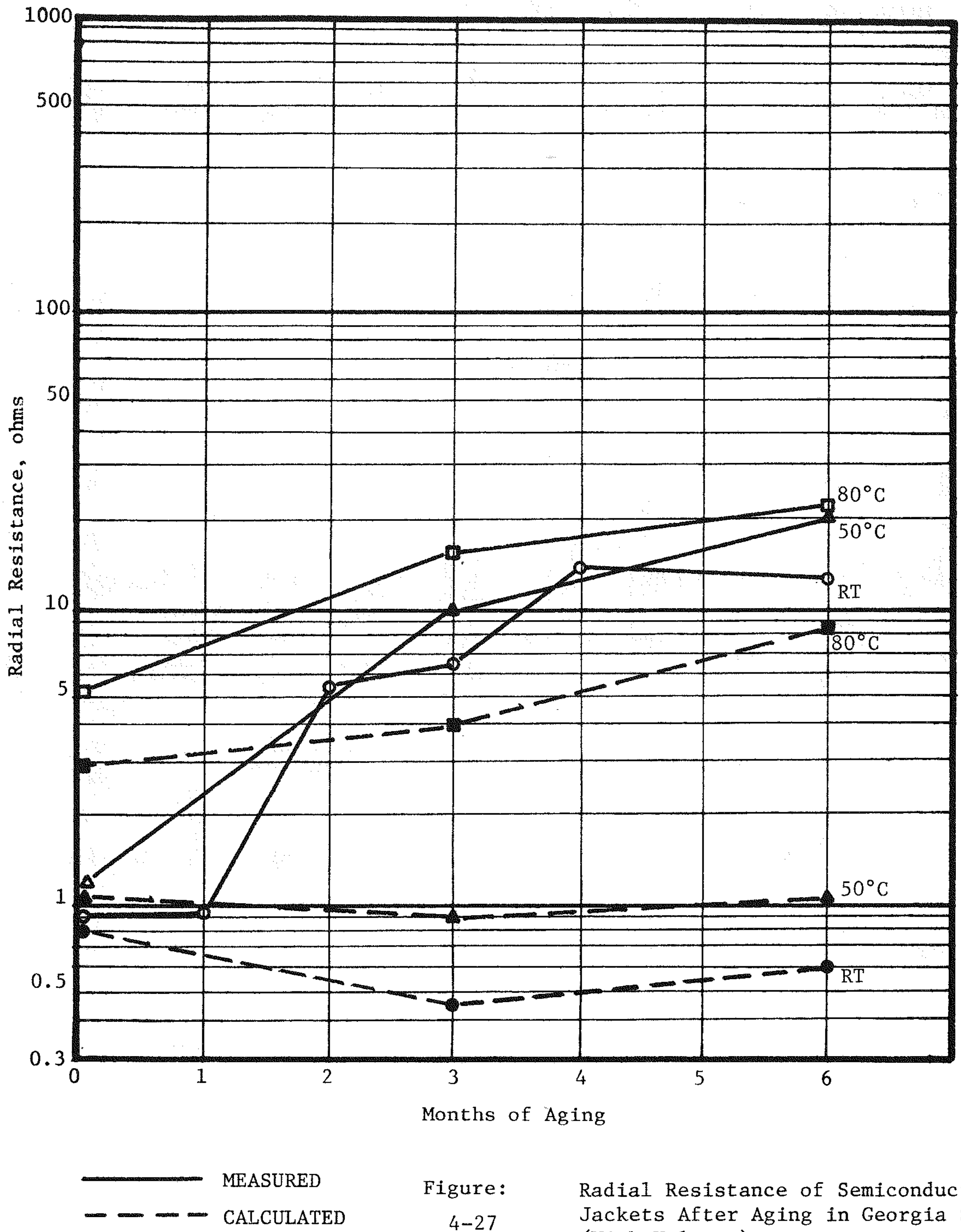
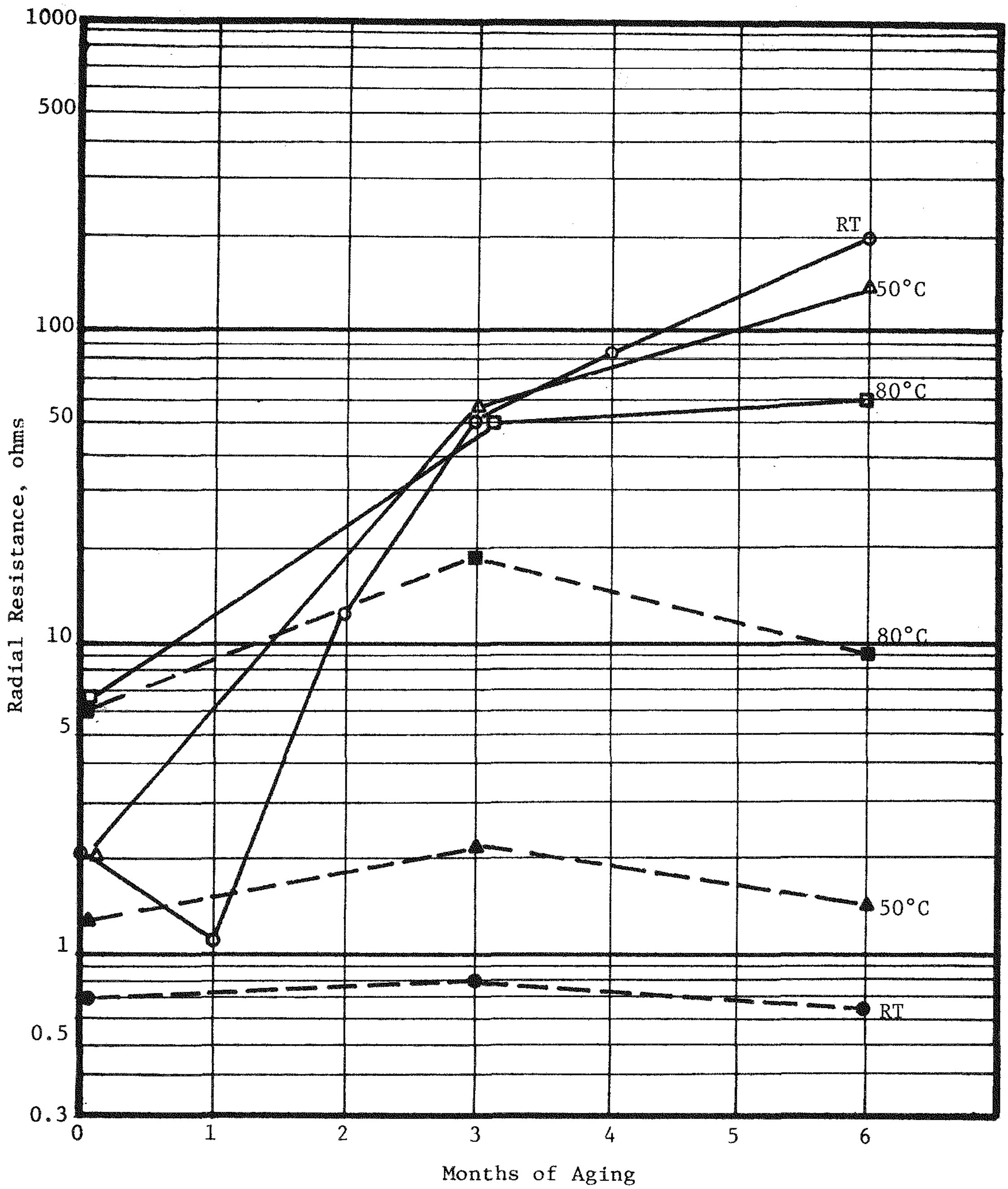


Figure: 4-27

Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

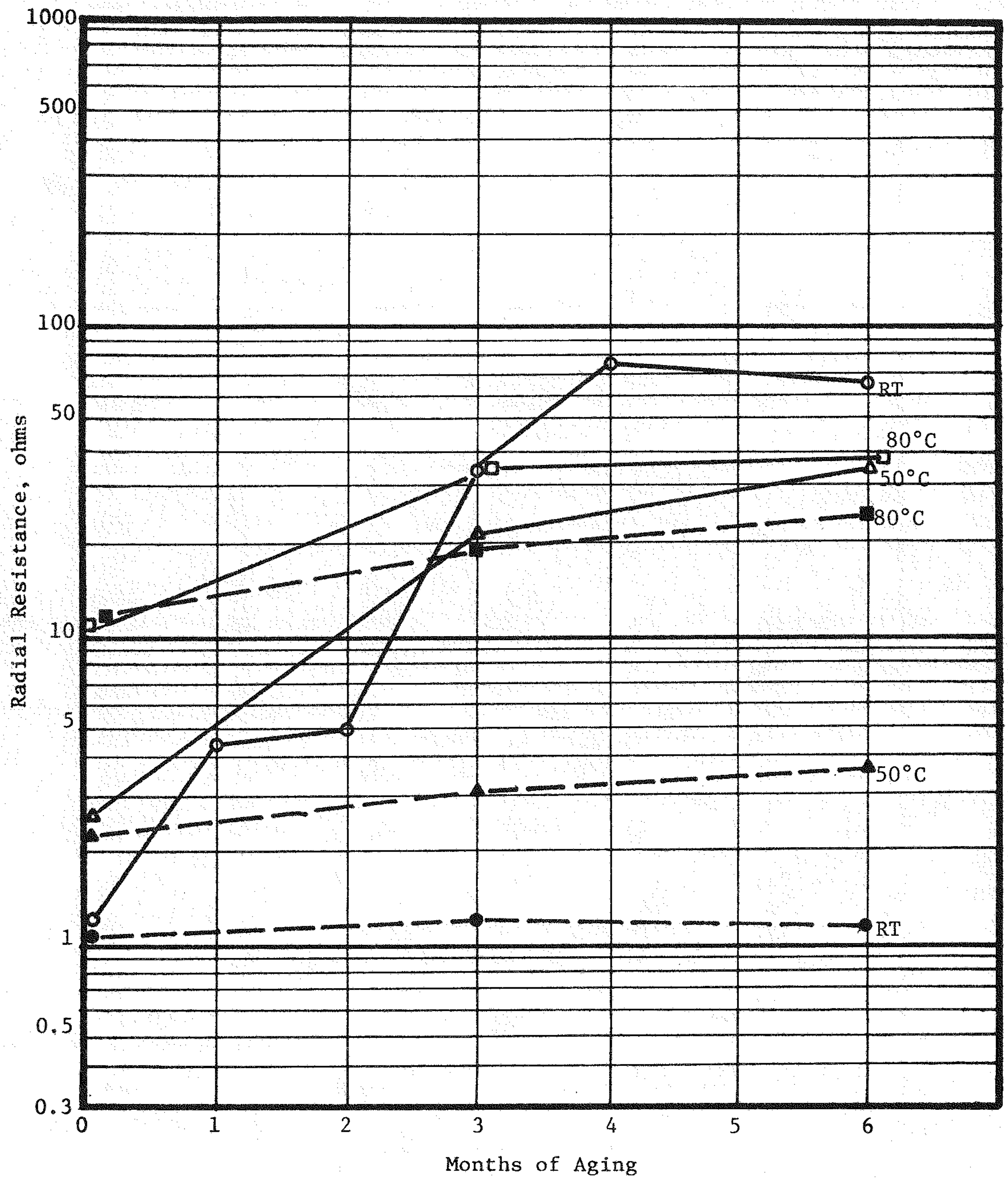
Compound E



MEASURED
CALCULATED

Figure: 4-28 Radial Resistance of Semiconducting Jackets After Aging in Georgia Soil (With Voltage)

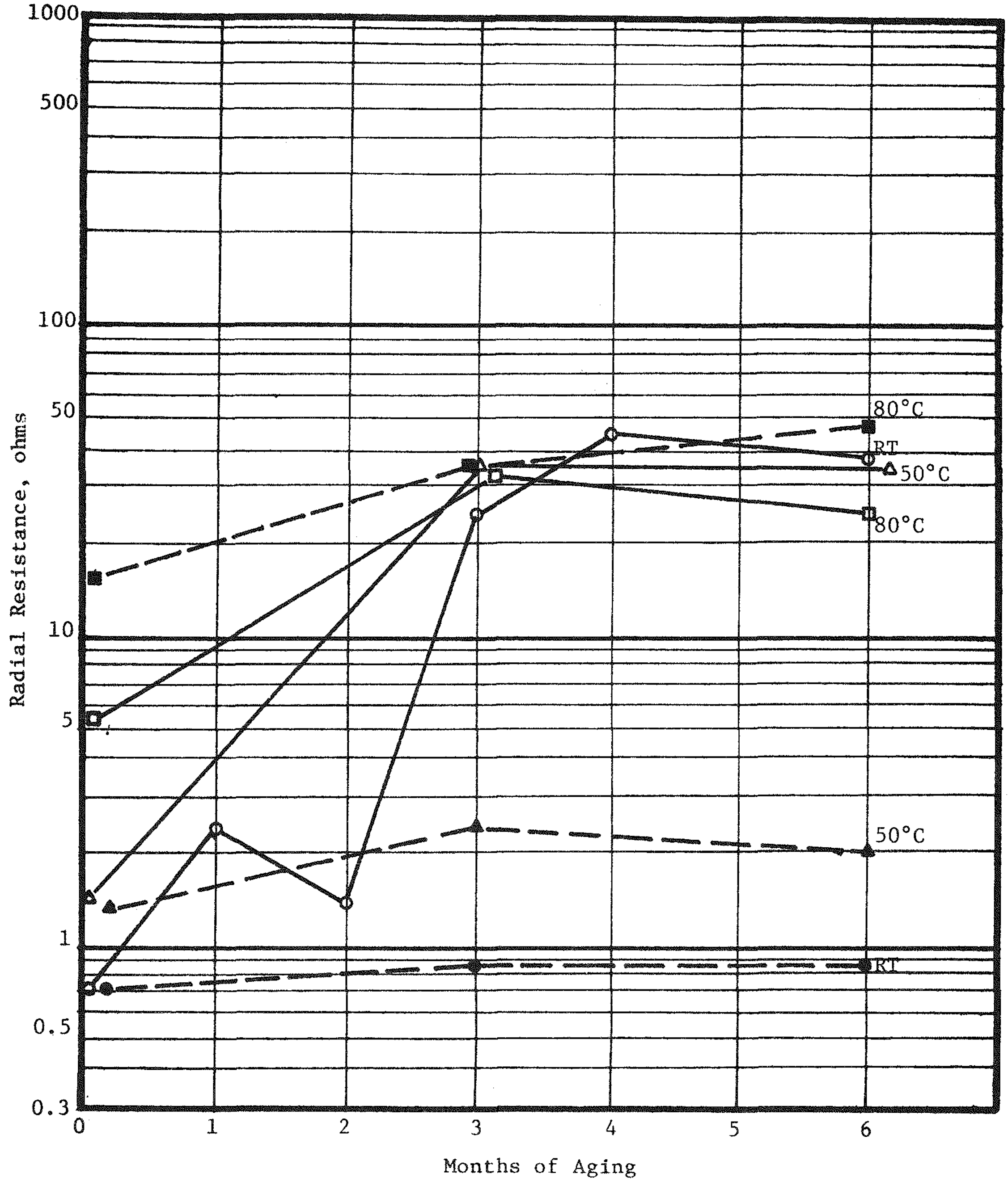
Compound H



MEASURED
CALCULATED

Figure: 4-29 Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

Compound A



MEASURED
CALCULATED

Figure: 4-30

Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

Compound B

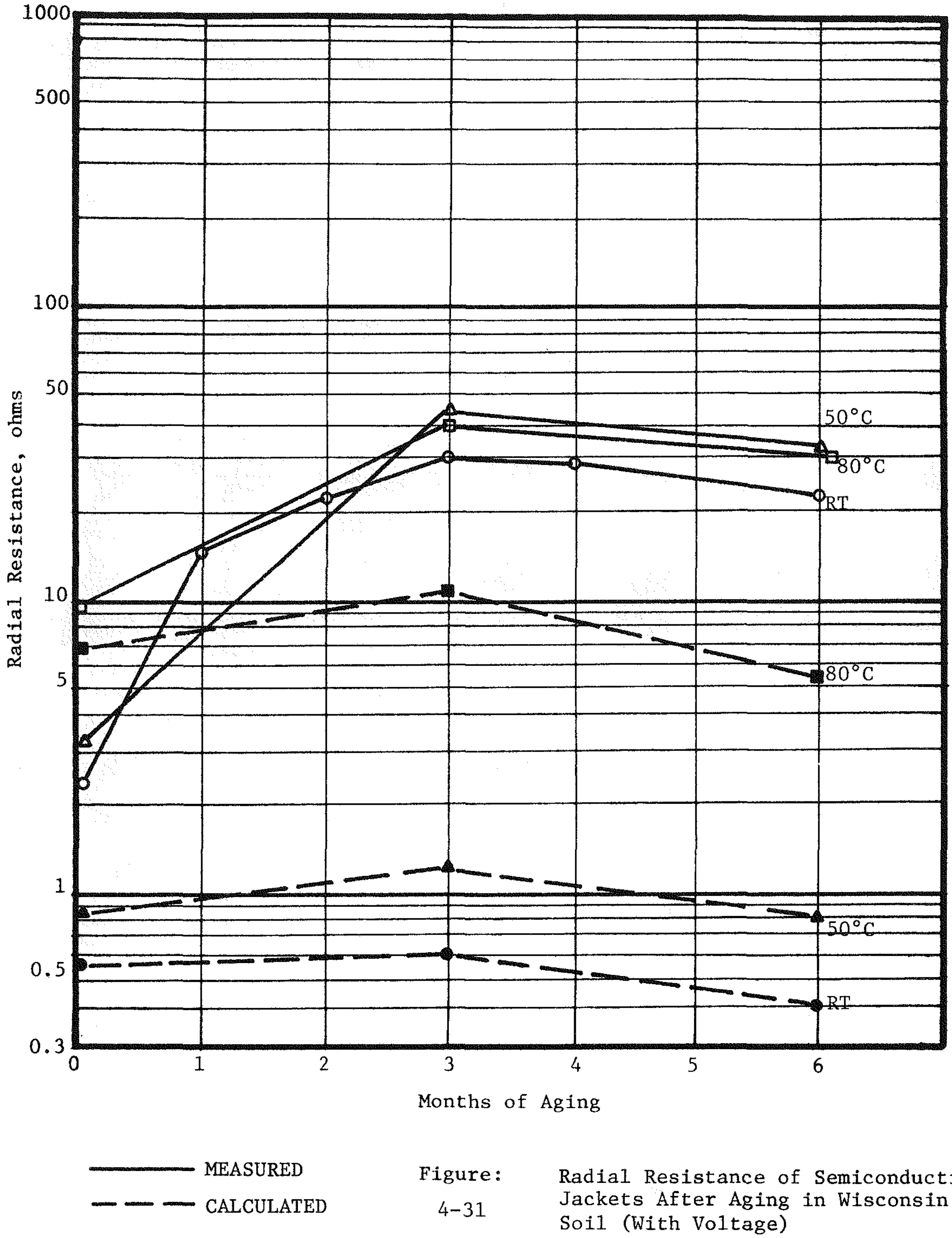
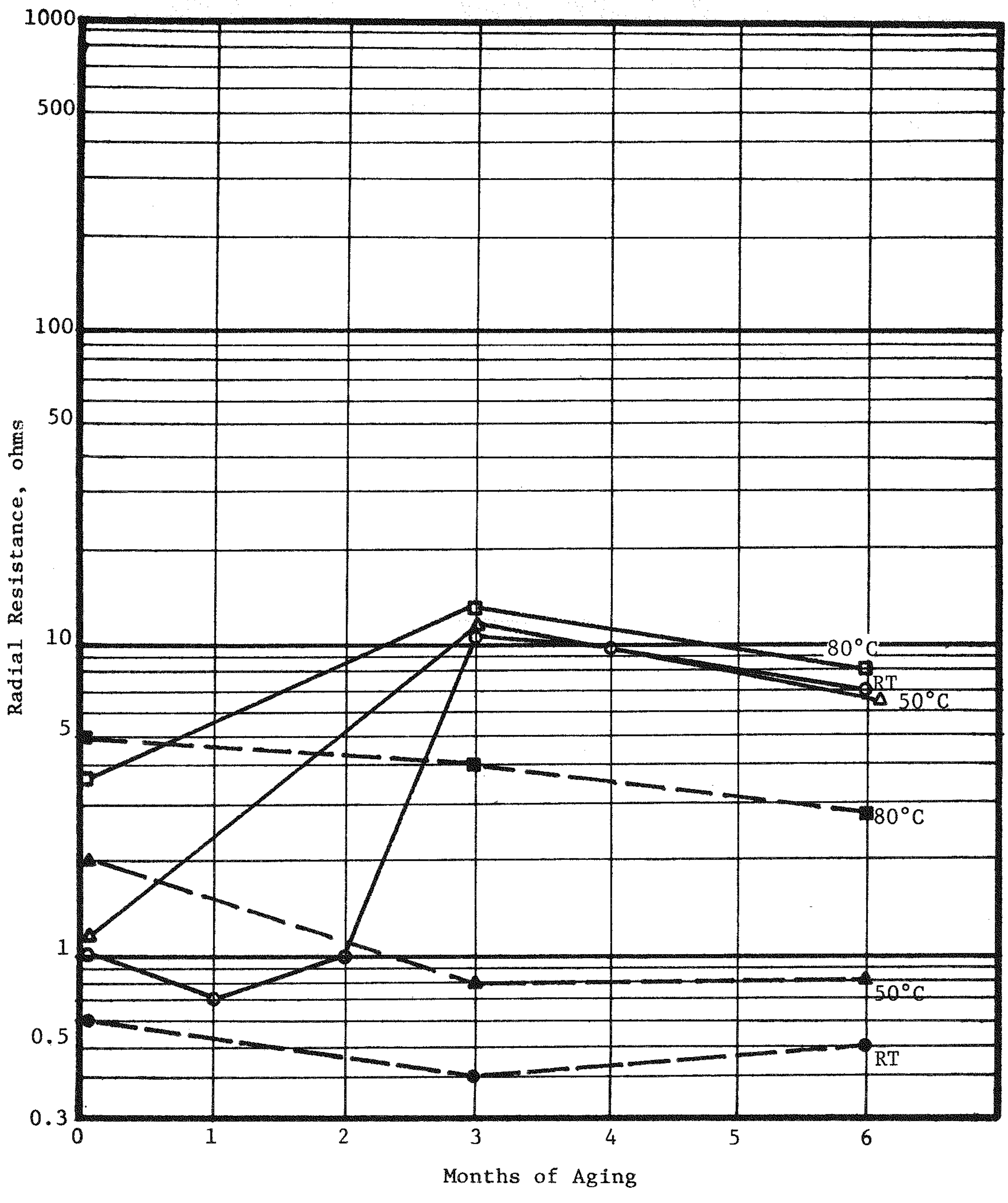


Figure: 4-31

Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

Compound C



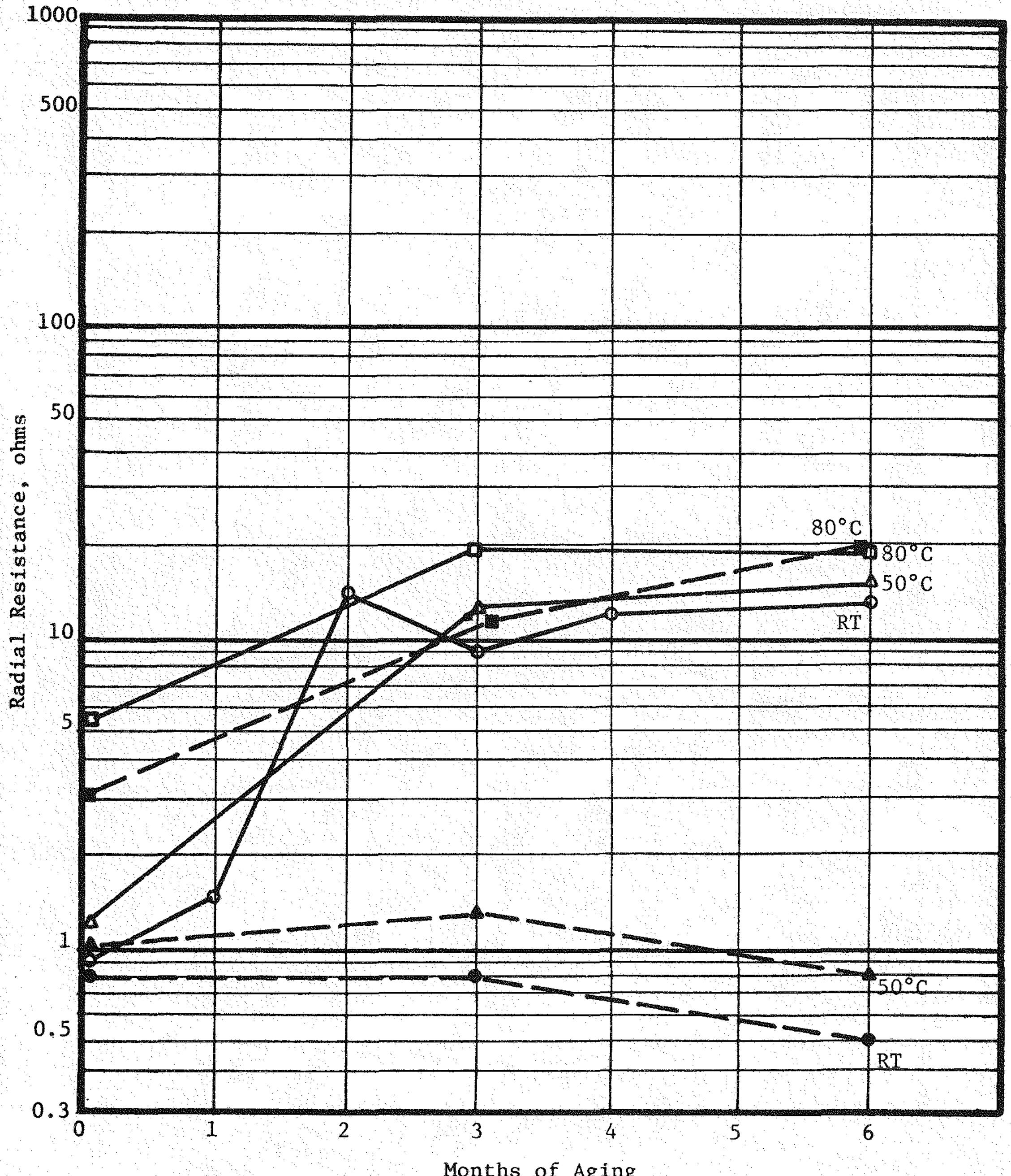
MEASURED

CALCULATED

Figure: 4-32

Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

Compound D



MEASURED
CALCULATED

Figure: 4-33 Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

Compound E

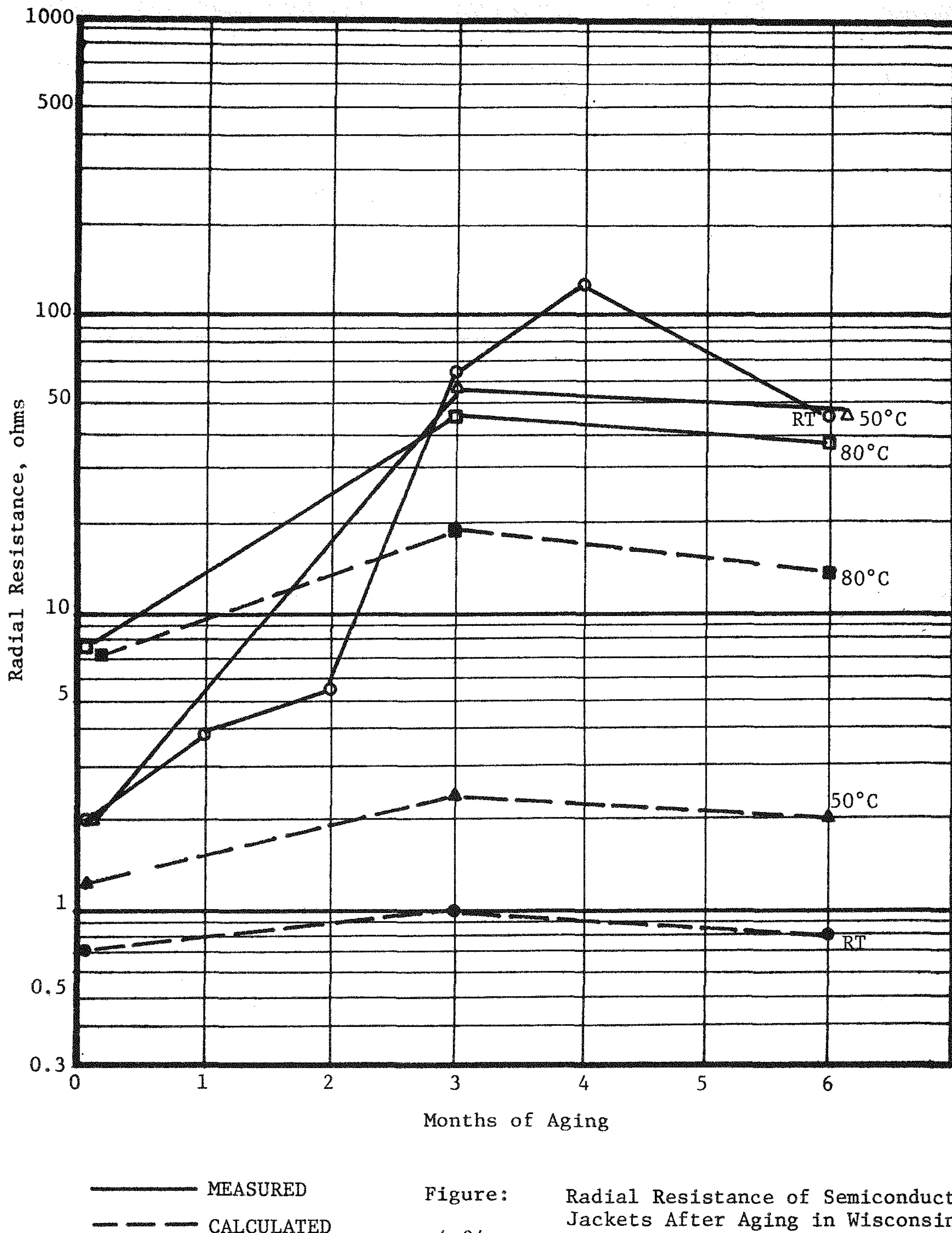
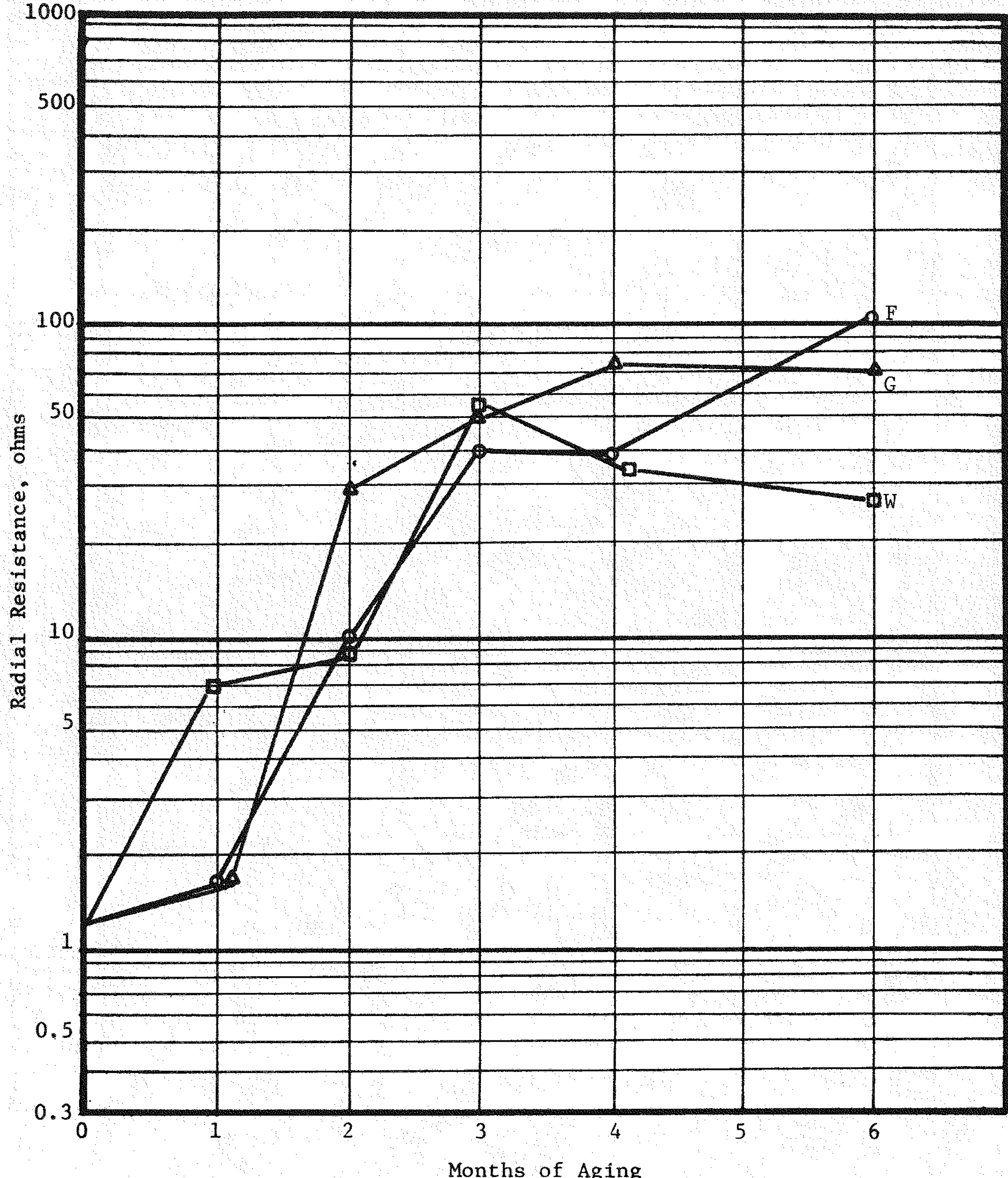


Figure: 4-34 Radial Resistance of Semiconducting Jackets After Aging in Wisconsin Soil (With Voltage)

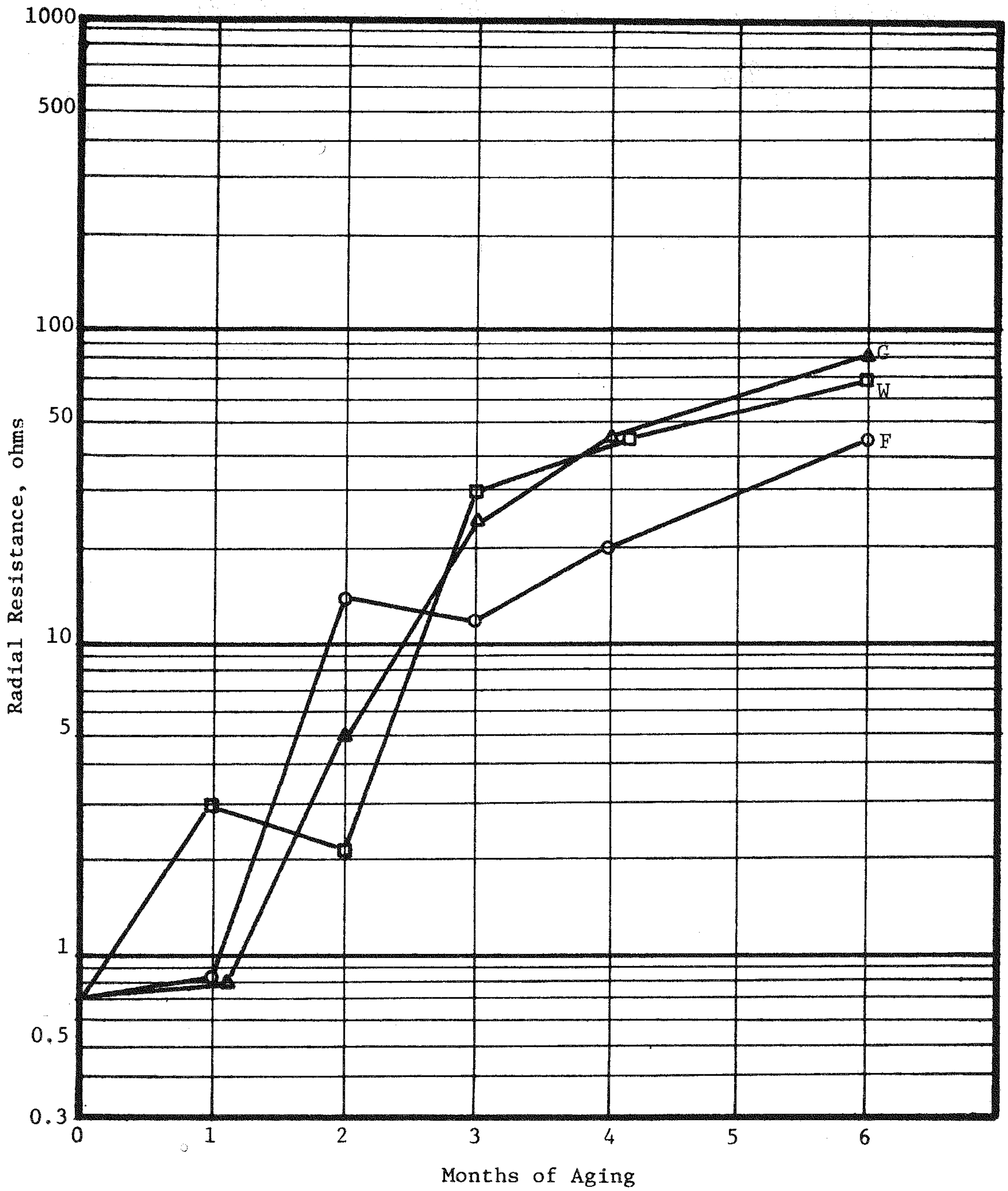
Compound H



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-35 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

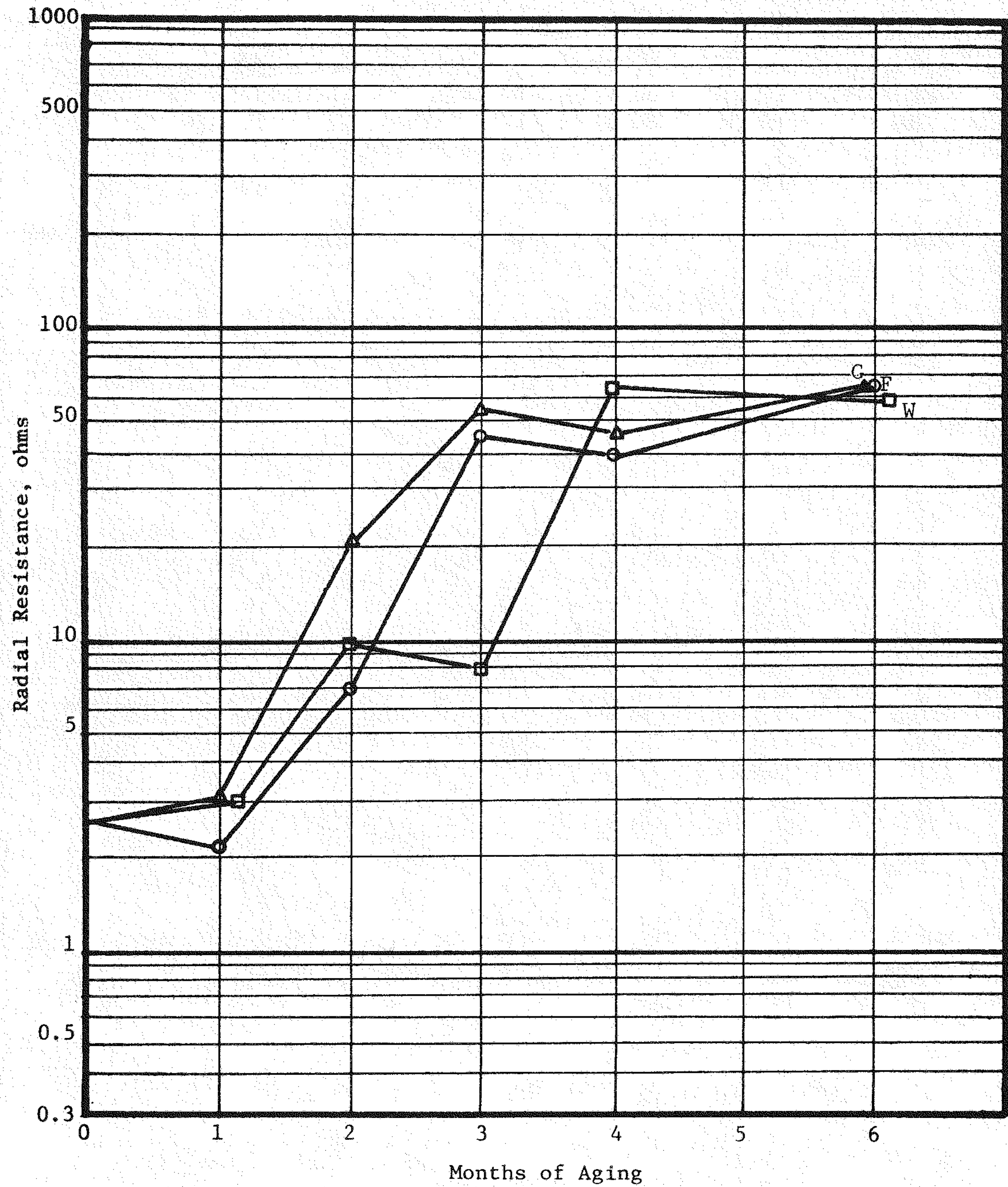
Compound A



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-36 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

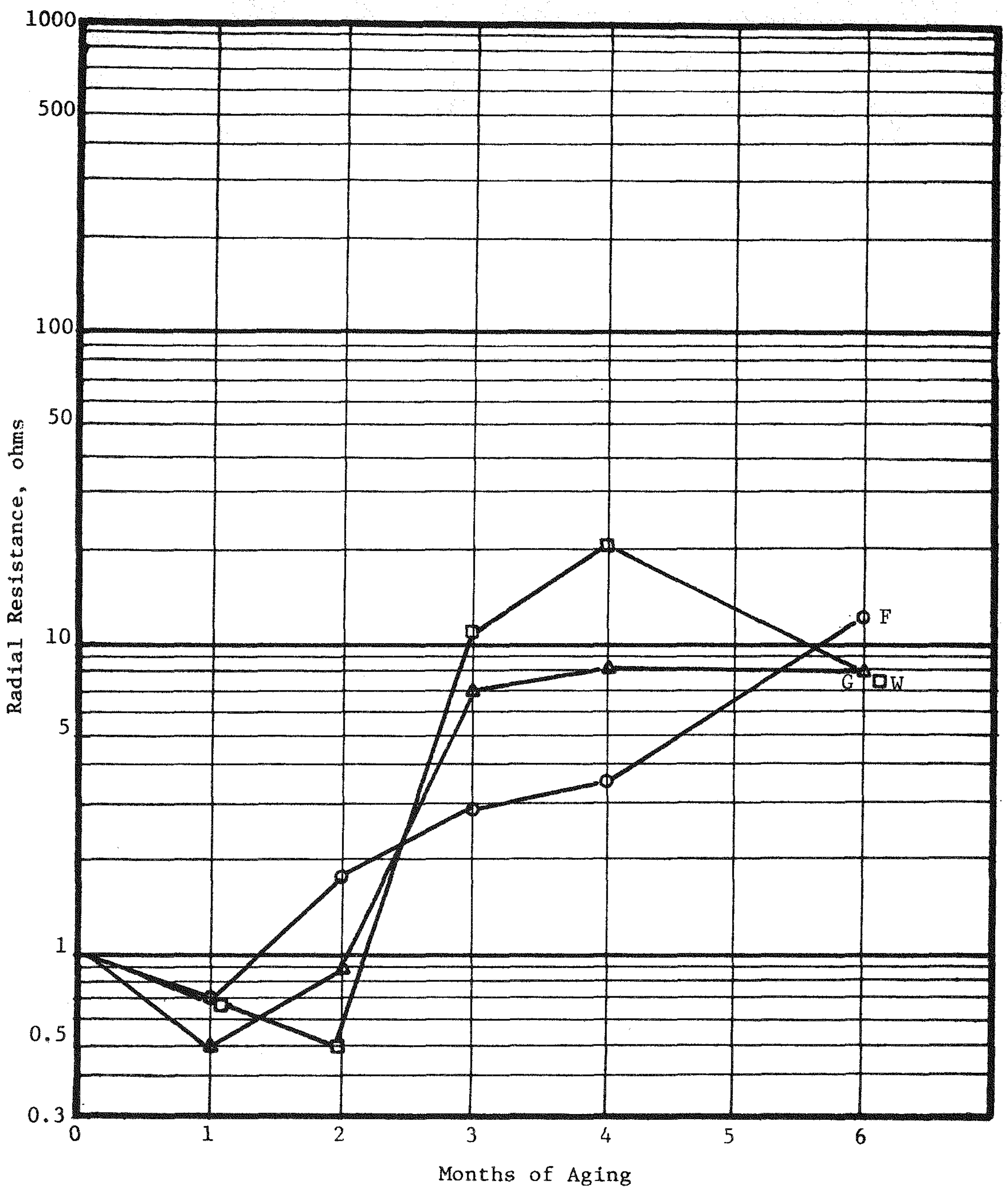
Compound B



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-37 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

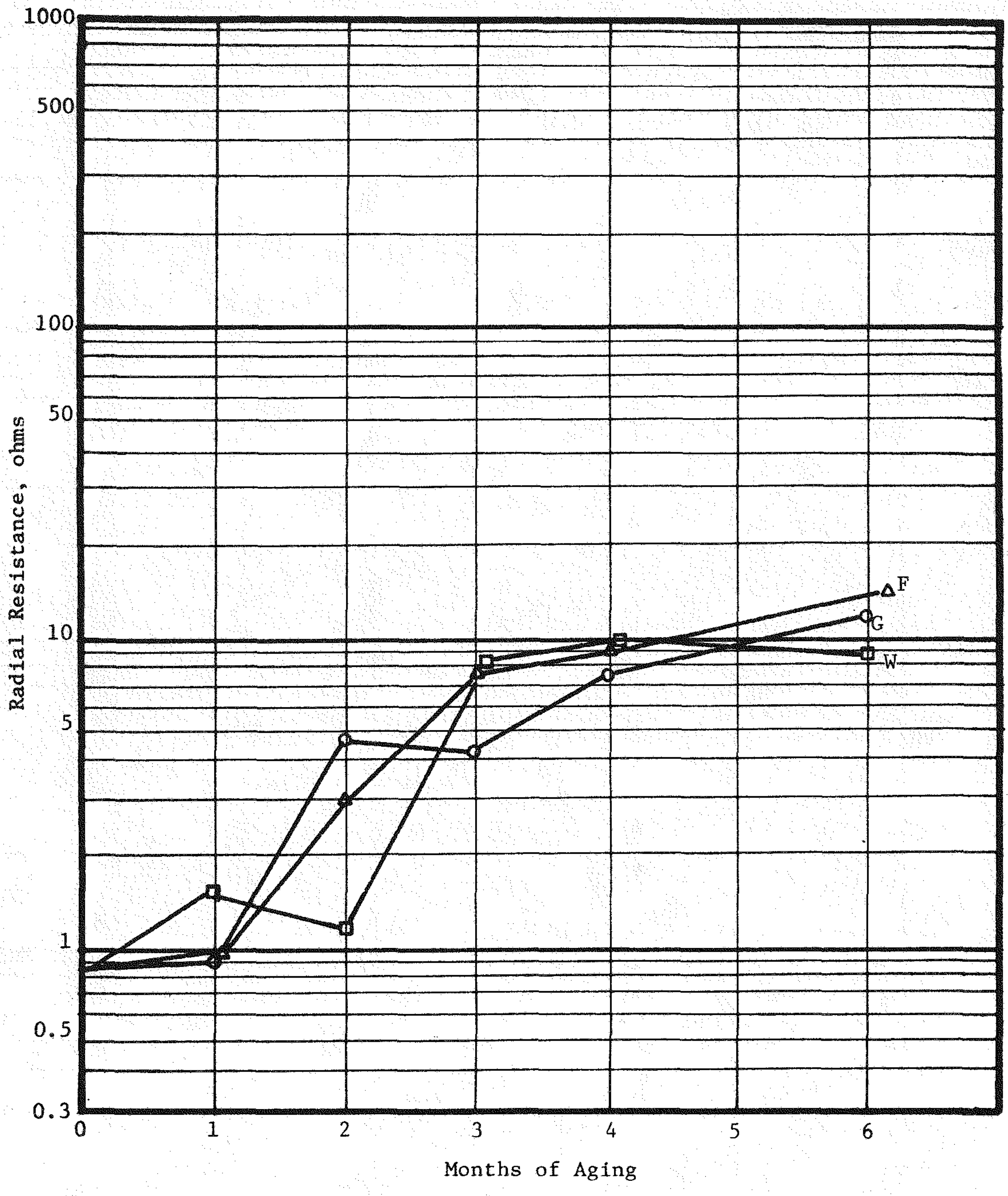
Compound C



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-38 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

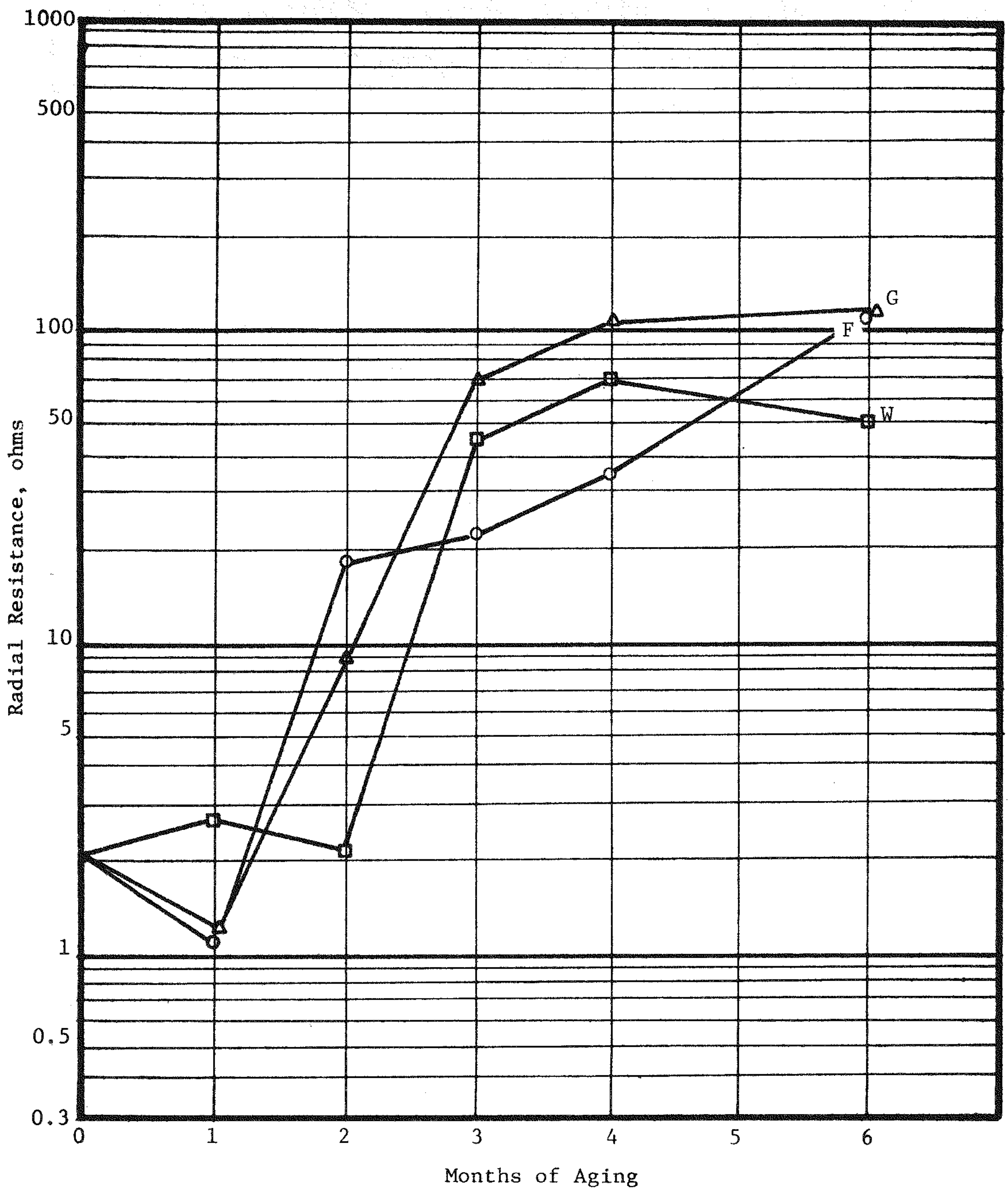
Compound D



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-39 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

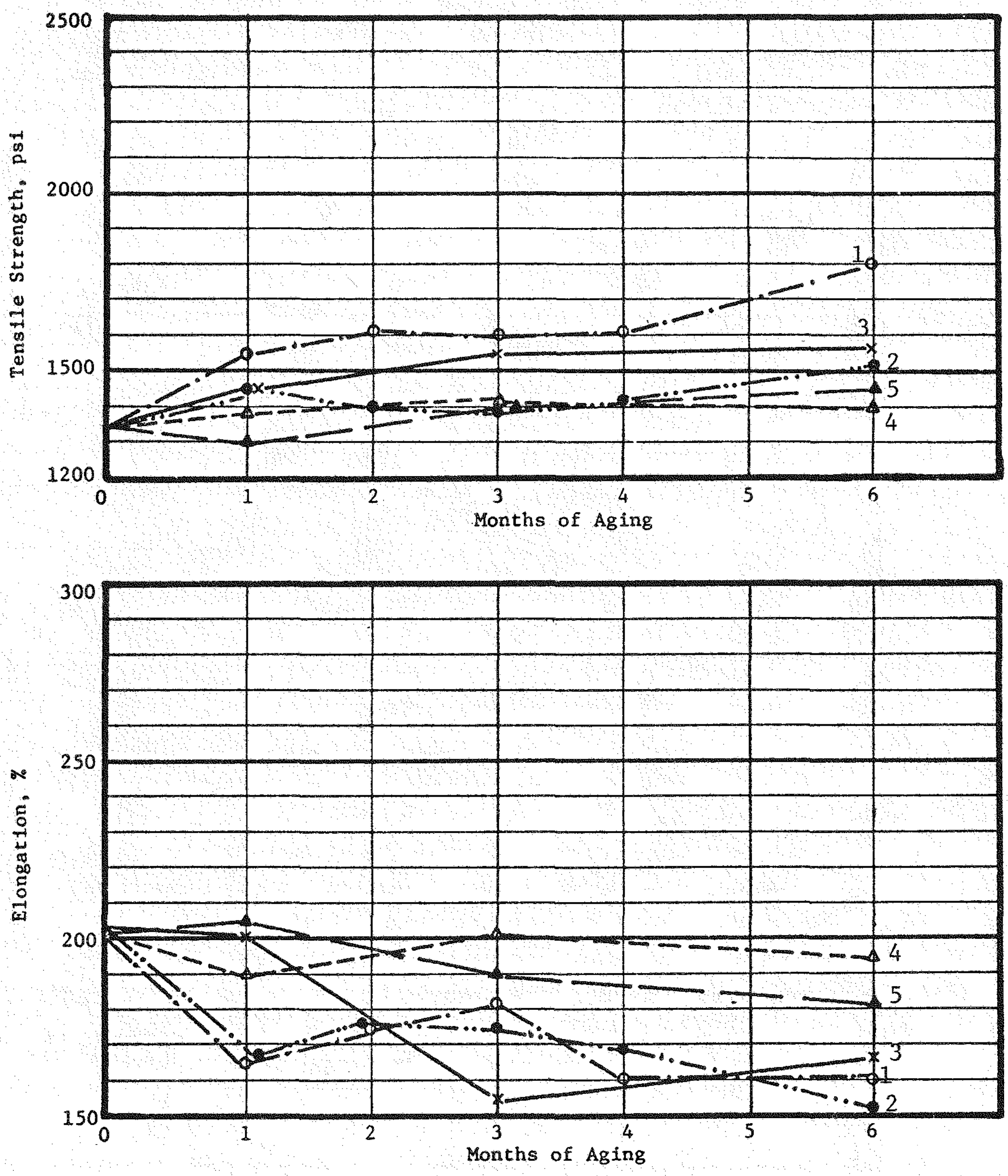
Compound E



F: In Florida Soil
G: In Georgia Soil
W: In Wisconsin Soil

Figure: 4-40 Measured Radial Resistance At Room Temperature of Semiconducting Jackets After Aging in Soil Without Voltage.

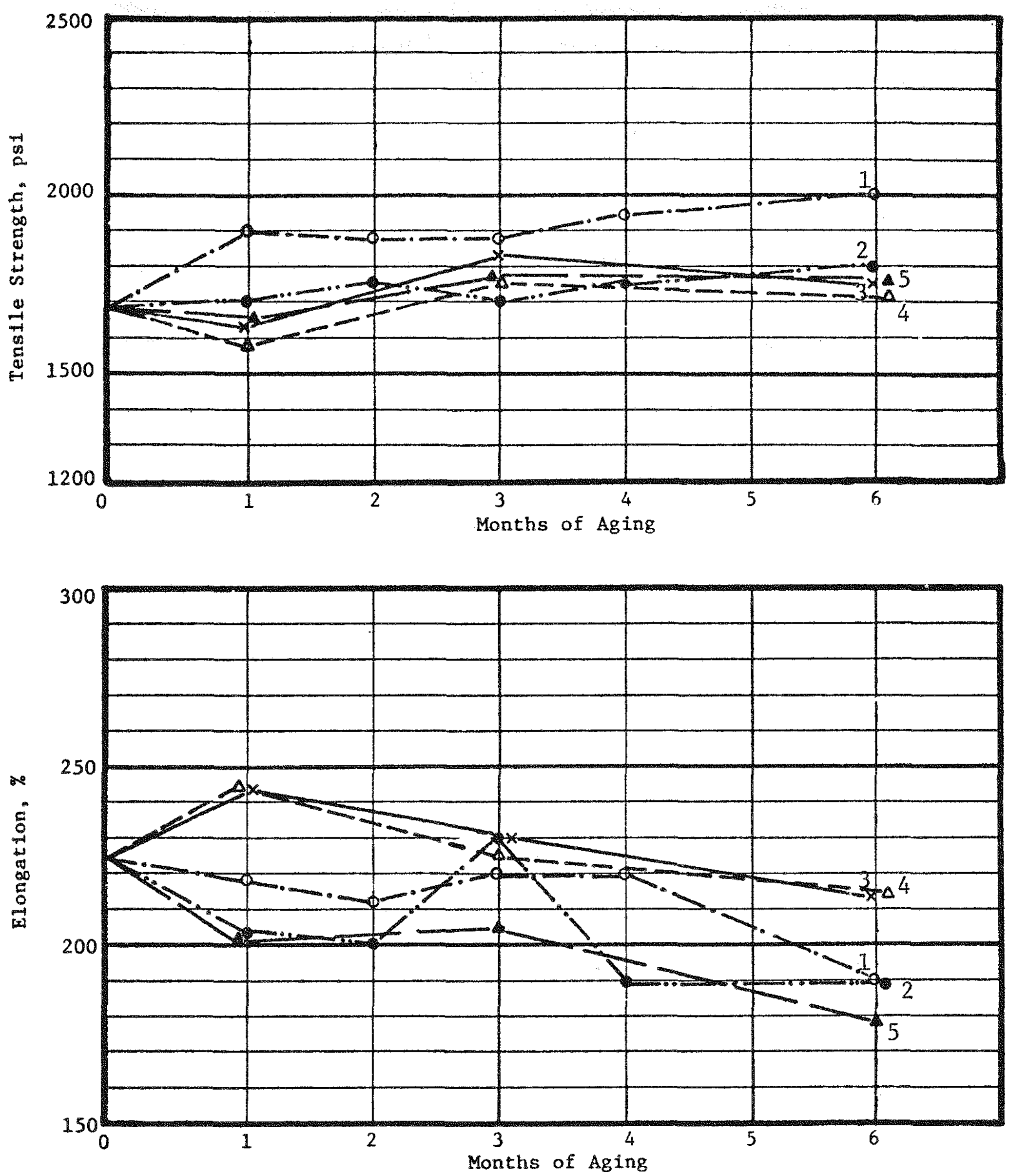
Compound H



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-41 Physical Properties of Semiconducting Jackets After Aging

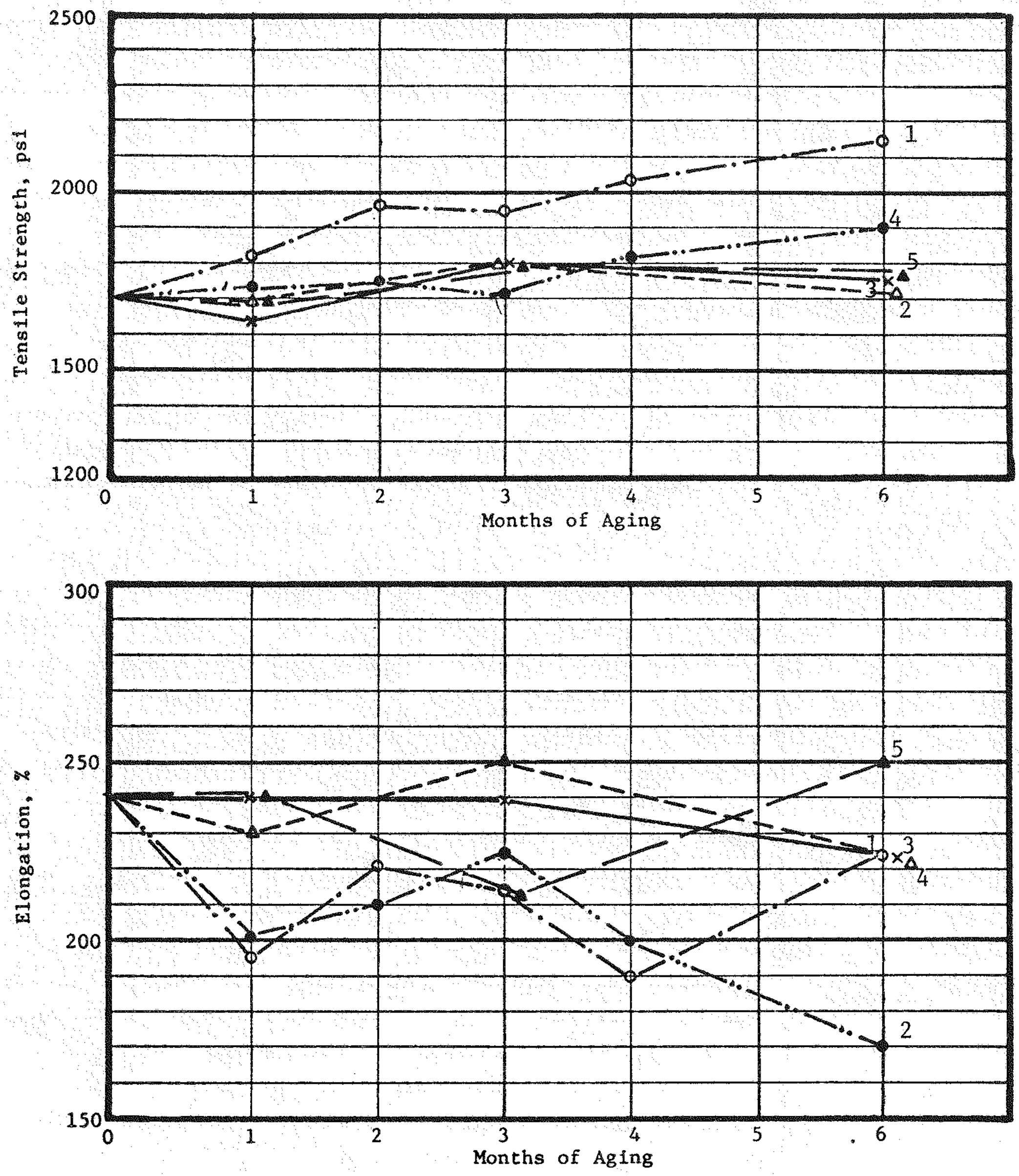
Compound A



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-42 Physical Properties of Semiconducting Jackets After Aging

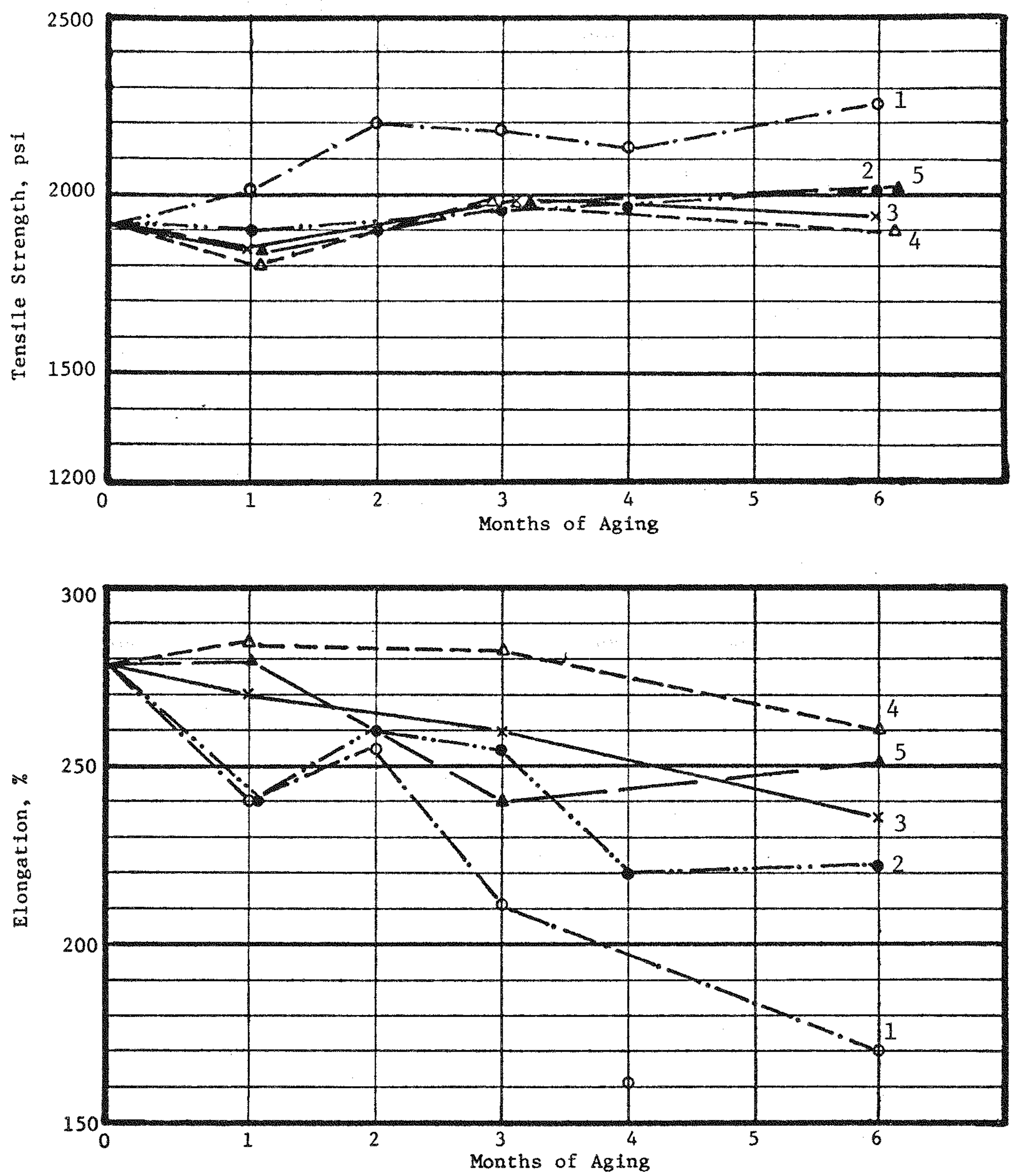
Compound B



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-43 Physical Properties of Semiconducting Jackets After Aging

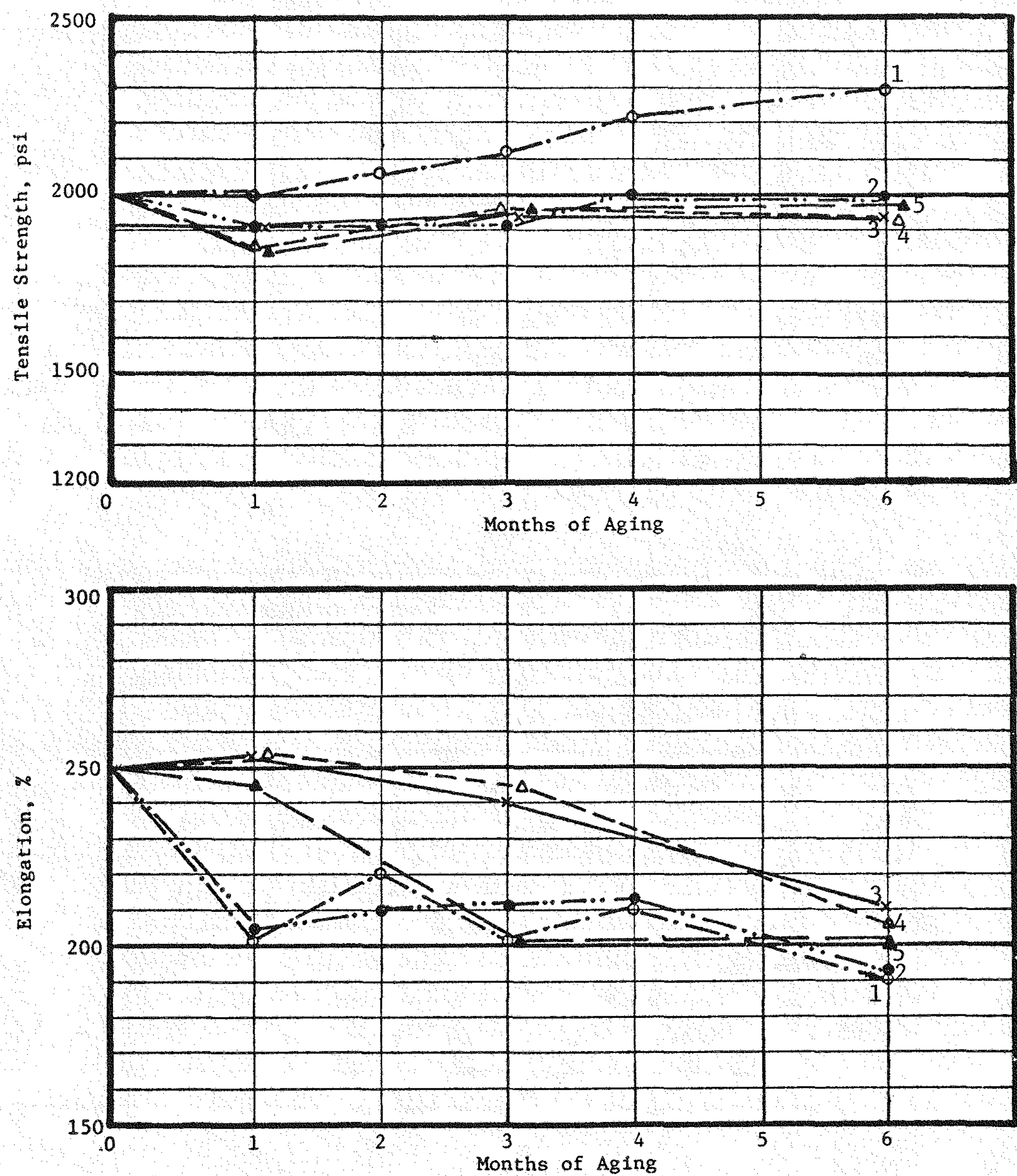
Compound C



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-44 Physical Properties of Semiconducting Jackets After Aging

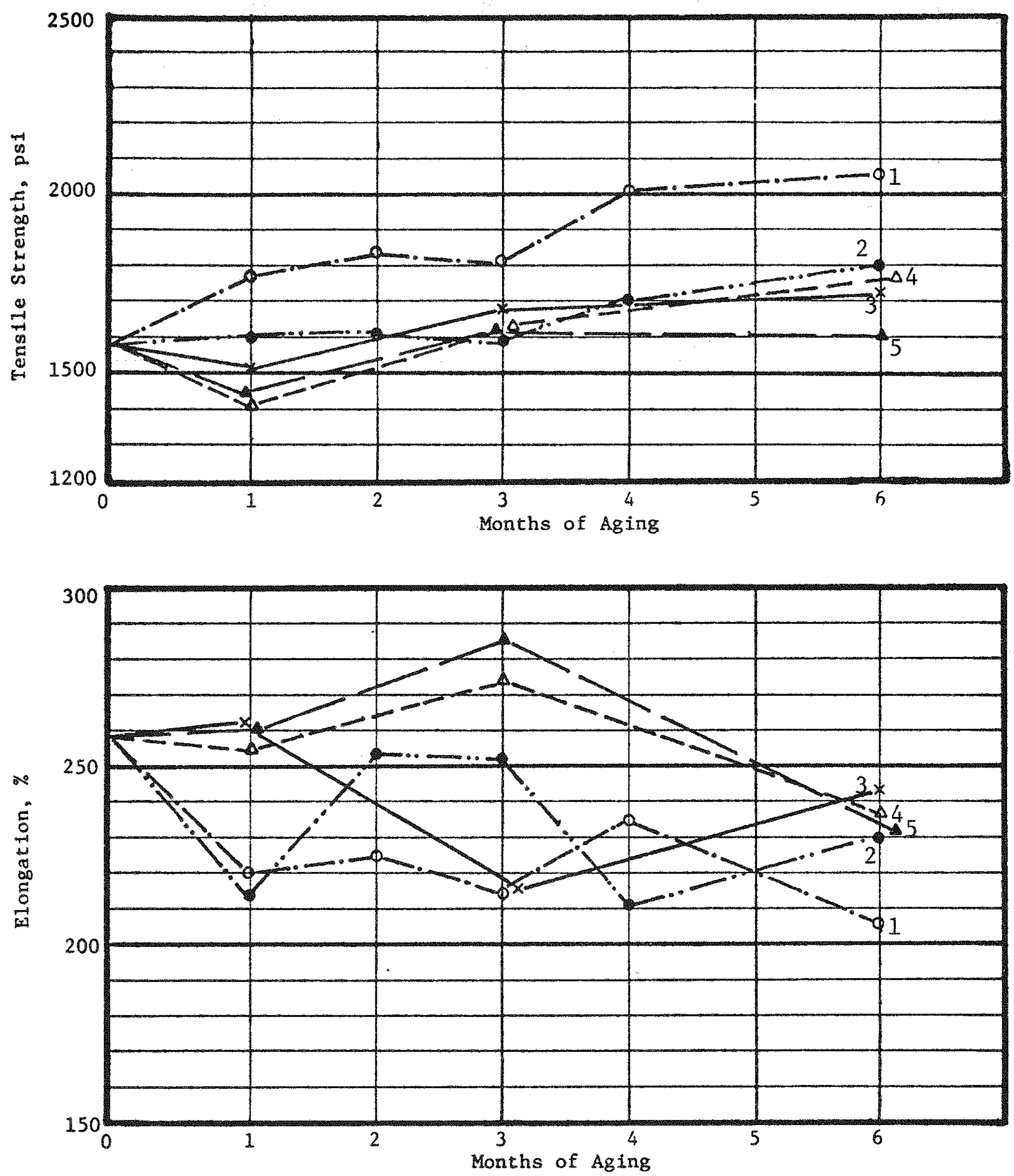
Compound D



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-45 Physical Properties of Semiconducting Jackets After Aging

Compound E



1: Air Oven @ 100°C
2: Water @ 75°C
3: Florida Soil @ 50°C (with voltage)
4: Georgia Soil @ 50°C (with voltage)
5: Wisconsin Soil @ 50°C (with voltage)

Figure: 4-46 Physical Properties of Semiconducting Jackets After Aging

Compound H

Table 5

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND A

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS 1	2	3	4	6	CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS 1	2	3	4	6
Unaged	----	RT	<0.1					<6.8				
		50°C	<0.1					<6.8				
		80°C	<0.01					<0.7				
Air Oven @ 100°C	----	RT	<0.1	<0.1	<0.05	<0.1	<0.1	<6.8	<6.8	<3.4	<6.8	<6.8
		50°C	–	–	<0.01	–	<0.1	–	–	<0.7	–	<6.8
		80°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
Water Immersion @ 75°C	----	RT	0.48	0.4	0.5	0.35	0.3	33	27	34	24	20
		50°C	–	–	0.5	–	0.9	–	–	24	–	61
		80°C	–	–	1.1	–	1.8	–	–	75	–	122
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.1	0.28	0.24	0.5	0.3	<6.8	19	16	34	20
	Georgia	RT	<0.1	0.3	0.2	0.2	0.4	<6.8	20	14	14	27
	Wisconsin	RT	<0.05	0.1	0.27	0.4	0.7	<3.4	6.8	18	27	47
Earth Burial @ 50°C With Voltage	Florida	RT	<0.1	0.22	0.27	0.3	0.7	<6.8	15	18	20	47
		50°C	–	–	0.4	–	0.4	–	–	27	–	27
		80°C	–	–	0.2	–	0.8	–	–	14	–	54
	Georgia	RT	<0.1	0.32	0.31	0.1	0.7	<6.8	22	21	6.8	47
		50°C	–	–	0.3	–	0.7	–	–	20	–	47
		80°C	–	–	0.27	–	0.5	–	–	18	–	34
	Wisconsin	RT	<0.02	0.1	0.25	0.2	0.3	<1.4	6.8	17	14	20
		50°C	–	–	0.6	–	0.6	–	–	41	–	41
		80°C	–	–	0.4	–	0.6	–	–	27	–	41

Table 6

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND B

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS					CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS				
			1	2	3	4	6	1	2	3	4	6
Unaged	----	RT	<1.0					<68				
		50°C	<0.2					<14				
		80°C	<0.1					<6.8				
Air Oven @ 100°C	----	RT	<0.1	<0.1	<0.1	<0.1	<0.1	<6.8	<6.8	<6.8	<6.8	<6.8
		50°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
		80°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
Water Immersion @ 75°C	----	RT	3.5	2.57	3.43	3.25	1.9	237	174	232	220	129
		50°C	–	–	4.9	–	3.0	–	–	332	–	203
		80°C	–	–	9.1	–	2.9	–	–	616	–	196
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.1	2.95	2.7	3.45	4.5	<6.8	200	183	234	305
	Georgia	RT	<0.1	1.05	1.57	2.4	3.4	<6.8	71	106	163	230
	Wisconsin	RT	1.7	1.7	2.55	3.75	3.8	115	115	173	254	257
Earth Burial @ 50°C With Voltage	Florida	RT	<0.1	2.65	2.4	3.1	3.0	<6.8	180	163	210	203
		50°C	–	–	2.9	–	5.2	–	–	196	–	352
		80°C	–	–	1.9	–	8.4	–	–	129	–	569
	Georgia	RT	<0.2	1.5	1.85	2.45	2.8	< 14	102	125	166	190
		50°C	–	–	1.8	–	5.0	–	–	122	–	339
		80°C	–	–	1.9	–	6.6	–	–	129	–	447
	Wisconsin	RT	1.37	<0.15	2.45	4.15	3.9	93	< 10	166	281	264
		50°C	–	–	4.1	–	7.2	–	–	278	–	488
		80°C	–	–	4.9	–	10.5	–	–	332	–	711

Table 7

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND C

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS					CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS				
			1	2	3	4	6	1	2	3	4	6
Unaged	-----	RT	<0.1					<6.8				
		50°C	<0.1					<6.8				
		80°C	<0.1					<6.8				
Air Oven @ 100°C	----	RT	<0.1	<0.1	<0.1	<0.1	<0.1	<6.8	<6.8	<6.8	<6.8	<6.8
		50°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
		80°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
Water Immersion @ 75°C	----	RT	2.5	1.59	2.45	3.0	1.7	169	108	166	203	115
		50°C	–	–	3.0	–	2.2	–	–	203	–	149
		80°C	–	–	4.5	–	2.7	–	–	305	–	183
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.1	0.8	0.2	0.5	1.0	<6.8	54	14	34	67
	Georgia	RT	<0.1	0.44	0.2	<0.6	0.8	<6.8	30	14	<40	54
	Wisconsin	RT	<0.2	0.25	0.7	0.2	1.5	< 14	17	47	14	102
Earth Burial @ 50°C With Voltage	Florida	RT	<0.1	1.7	2.9	0.43	1.2	<6.8	115	196	29	81
		50°C	–	–	4.1	–	1.6	–	–	278	–	108
		80°C	–	–	3.8	–	2.8	–	–	257	–	190
	Georgia	RT	<0.1	0.45	0.12	0.3	0.4	<6.8	30	8.1	20	27
		50°C	–	–	0.3	–	0.4	–	–	20	–	27
		80°C	–	–	0.4	–	1.3	–	–	27	–	88
	Wisconsin	RT	0.17	0.4	1.0	1.7	1.6	12	27	68	115	108
		50°C	–	–	1.0	–	1.6	–	–	68	–	108
		80°C	–	–	1.2	–	2.8	–	–	81	–	190

Table 8

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND D

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS					CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS				
			1	2	3	4	6	1	2	3	4	6
Unaged	----	RT	<0.7					< 47				
		50°C	<0.1					<6.8				
		80°C	<0.1					<6.8				
Air Oven @ 100°C	----	RT	<0.1	<0.1	<0.1	<0.1	<0.1	<6.8	<6.8	<6.8	<6.8	<6.8
		50°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
		80°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
Water Immersion @ 75°C	----	RT	1.13	0.93	1.3	1.1	1.0	77	63	88	75	68
		50°C	–	–	1.7	–	4.9	–	–	115	–	332
		80°C	–	–	2.6	–	7.0	–	–	176	–	474
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.2	<0.9	<0.65	<0.25	1.8	< 14	< 61	< 44	< 17	122
	Georgia	RT	<1.0	<0.5	1.5	1.85	2.2	< 68	< 34	102	125	149
	Wisconsin	RT	<0.5	<1.0	1.6	3.7	2.9	< 34	< 68	108	251	196
Earth Burial @ 50°C With Voltage	Florida	RT	0.47	1.05	<0.95	0.7	1.4	32	71	< 64	47	95
		50°C	–	–	3.9	–	2.6	–	–	264	–	176
		80°C	–	–	2.9	–	2.3	–	–	196	–	156
	Georgia	RT	<1.0	0.65	1.2	1.5	2.0	< 68	44	81	102	135
		50°C	–	–	3.4	–	3.3	–	–	230	–	224
		80°C	–	–	2.8	–	2.9	–	–	190	–	196
	Wisconsin	RT	<0.7	<0.6	1.05	2.5	3.3	< 47	< 41	71	169	224
		50°C	–	–	1.3	–	9.1	–	–	88	–	616
		80°C	–	–	1.2	–	11.0	–	–	81	–	745

Table 9

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND E

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS 1	2	3	4	6	CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS 1	2	3	4	6
Unaged	----	RT	<1.0					<68				
		50°C	<0.2					<14				
		80°C	<0.1					<6.8				
Air Oven @ 100°C	----	RT	<0.15	<0.1	<0.1	<0.1	<0.1	<10	<6.8	<6.8	<6.8	<6.8
		50°C	-	-	<0.1	-	<0.1	-	-	<6.8	-	<6.8
		80°C	-	-	<0.1	-	<0.1	-	-	<6.8	-	<6.8
Water Immersion @ 75°C	----	RT	1.67	1.37	1.7	1.7	1.1	113	93	115	115	75
		50°C	-	-	2.6	-	1.6	-	-	176	-	108
		80°C	-	-	3.1	-	2.5	-	-	210	-	169
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.1	1.3	1.25	1.15	1.8	<6.8	88	85	78	122
	Georgia	RT	<0.1	<0.6	1.4	2.05	2.2	<6.8	<41	95	139	149
	Wisconsin	RT	<0.1	<0.15	1.95	2.45	2.7	<6.8	<10	132	166	183
Earth Burial @ 50°C With Voltage	Florida	RT	<0.1	1.3	1.6	-	1.8	<6.8	88	108	-	122
		50°C	-	-	2.2	-	2.5	-	-	149	-	169
		80°C	-	-	0.9	-	3.2	-	-	61	-	217
	Georgia	RT	<0.1	0.9	1.55	1.8	1.8	<6.8	61	105	122	122
		50°C	-	-	2.0	-	2.9	-	-	136	-	196
		80°C	-	-	0.8	-	2.8	-	-	54	-	190
	Wisconsin	RT	<0.1	<0.1	1.45	2.25	2.4	<6.8	< 6.8	98	152	163
		50°C	-	-	2.0	-	3.8	-	-	136	-	257
		80°C	-	-	1.3	-	3.9	-	-	88	-	264

Table 10

CAPACITANCE AND DIELECTRIC CONSTANT AT RT, 50°C AND 80°C

COMPOUND H

AGING CONDITION	SOIL	MEASUREMENT TEMPERATURE	MEASURED CAPACITANCE, uF AGING PERIOD, MONTHS					CALCULATED DIELECTRIC CONSTANT ($x10^3$) AGING PERIOD, MONTHS				
			1	2	3	4	6	1	2	3	4	6
Unaged	----	RT	<0.1					<6.8				
		50°C	<1.0					<68				
		80°C	<1.0					<68				
Air Oven @ 100°C	----	RT	<0.1	<0.1	<0.1	<0.1	<0.1	<6.8	<6.8	<6.8	<6.8	<6.8
		50°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
		80°C	–	–	<0.1	–	<0.1	–	–	<6.8	–	<6.8
Water Immersion @ 75°C	----	RT	0.49	0.45	0.7	0.53	0.2	33	30	47	36	14
		50°C	–	–	0.74	–	0.2	–	–	50	–	14
		80°C	–	–	1.7	–	1.0	–	–	115	–	68
Earth Burial @ 50°C W/O Voltage	Florida	RT	<0.1	0.35	0.4	0.55	0.5	<6.8	24	27	37	34
	Georgia	RT	<0.1	<0.1	0.25	0.55	0.5	<6.8	<6.8	17	37	34
	Wisconsin	RT	<0.1	<0.1	0.65	0.7	1.1	<6.8	<6.8	44	47	75
Earth Burial @ 50°C With Voltage	Florida	RT	<0.1	–	0.25	0.15	0.8	<6.8	–	17	10	54
		50°C	–	–	0.3	–	1.2	–	–	20	–	81
		80°C	–	–	0.4	–	1.4	–	–	27	–	95
	Georgia	RT	<0.1	0.35	0.35	0.35	0.3	<6.8	24	24	24	20
		50°C	–	–	0.4	–	0.2	–	–	27	–	14
		80°C	–	–	0.5	–	0.7	–	–	34	–	47
	Wisconsin	RT	<0.1	<0.15	0.35	0.15	0.9	<6.8	<10	24	10	61
		50°C	–	–	0.3	–	2.1	–	–	20	–	142
		80°C	–	–	0.5	–	1.9	–	–	34	–	129

Rectification Test on Full Size Cables

Five sets of six full size cable samples jacketed with semiconducting Compounds A, B, C, D, E and H, respectively, were subjected to the Rectification Test as outlined in Table 11.

As shown in Table 11, four of the five sets of samples were immersed in 75°C water and one set was buried in Wisconsin soil. In Sets 3 and 4, one foot in the center of a four foot length of cable immersed in water was covered with tinned copper braid. One ampere of a-c current was impressed on Sets 2 and 3 and five amperes on Set 4, with the six samples connected in parallel such that the indicated current would divide among the samples. The Rectification Effect, defined as the ratio of the direct current component to the alternating expressed current in percent, was determined utilizing the circuit illustrated in the figure below:

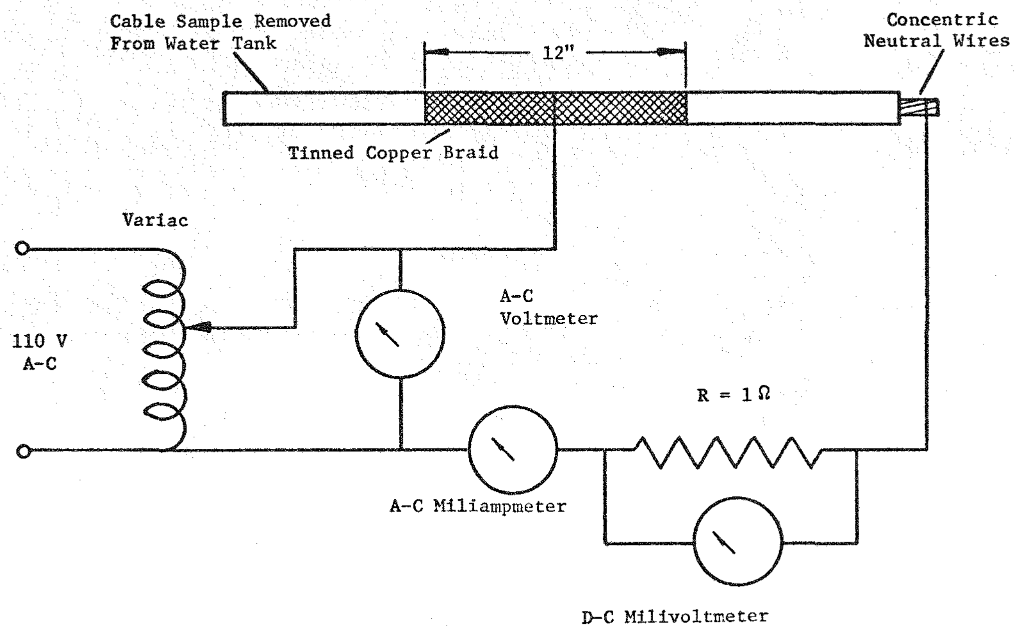


Figure 4-47. CIRCUIT FOR DETERMINATION OF RECTIFICATION EFFECT

An attempt was made initially to measure the Rectification Effect on samples immersed in water. It was found that these measurements were in error due to electrochemical potentials existing between the electrodes and the metal water tank. Therefore, all measurements on Sets 1 through 4 were conducted on samples removed from the water tank and wrapped with a new tinned copper braid shield as the outer measuring electrodes. The readings were taken after the a-c and d-c currents became stable which usually occurred within two to three hours after application of the a-c voltage across the jacket. Set 5 was measured with samples buried in the soil.

Measurements were conducted at an arbitrary a-c current of 200 mA, providing the a-c voltage did not exceed 15 volts which is considered to be the highest voltage across the jacket that could occur in service. Otherwise, the a-c current component was measured at an impressed voltage of 15 volts resulting in an a-c current lower than 200 mA.

Since, after the six month immersion period, no significant changes in Rectification Effect were observed, the test was extended and the final measurements were made on all five test sets after 7-1/2 months.

Section 5

DISCUSSION OF RESULTS

SELECTION OF SEMICONDUCTING THERMOPLASTIC COMPOUNDS

The test results obtained on the ten compounds which were subjected to all or part of the screening test program are shown in Tables 1 - 4.

The ten compounds tested exhibited satisfactory initial and aged physical properties with Compound D poorest in retention of elongation after aging.

Compounds A, G, H and J exhibited excellent deformation resistance at 100°C and 121°C and can be classified as deformation resistant thermoplastic compounds. Compound I, submitted as a deformation resistant version of Compound D was rejected from the test program when its deformation resistance was poorer than that of Compound D. Its deformation resistance ranked among the worst of all compounds tested.

The moisture absorption characteristics of compounds tested were comparable except for Compound H which exhibited the highest value of 19 mgms per square inch and Compound J which exhibited the lowest value of 1.4 mgms per square inch. The compounds retained their original values of moisture absorption after six months aging in an air oven at 100°C.

Compound G exhibited marked thermal embrittlement when aged at 100°C. It was therefore eliminated from the test program. Compound H exhibited a tendency towards thermal embrittlement. However, in view of the severity of the test and the results obtained, it was left in the test program.

Compound J exhibited a marked susceptibility to environmental stress cracking and was therefore eliminated from the test program.

All of the compounds tested exhibited low surface/volume resistivities at room temperature and positive thermal coefficient of resistivity. Compound H exhibited the highest and Compound J the lowest coefficients of thermal resistivity.

Compound F exhibited the highest moisture vapor transmission of all compounds tested. In this regard, its moisture vapor transmission was 2.7 times that of the next highest value. Its moisture vapor transmission was twelve times that of the conventional low density high molecular weight black polyethylene jacket compound. Compound F was therefore eliminated from the test program. As expected, the medium density black polyethylene jacket compound exhibited the lowest moisture vapor transmission at slightly more than one-half that of low density polyethylene. Excluding Compound F, moisture vapor transmissions of the semiconducting compounds tested, ranged from 1.5 to 4.3 with a median value of 2.24 times the moisture vapor transmission of conventional low density polyethylene jacket compound.

Compound B exhibited the lowest and Compound I the highest radial resistivity at room temperature. The dielectric constants and dissipation factor values in Table 4 are considered typical of semiconducting compounds at room temperature.

Compound B was selected as the semiconducting jacket compound for the cables to be tested in Phase II of RP 671. This selection was made on the basis of its overall good performance in the screening test program, experience in the manufacture of URD cables employing this compound as the overall jacket and successful service record with these cables.

A summary of the disposition of the ten compounds is indicated below:

Compound Designation	Disposition
A	Accepted for full size cable testing.
B	Accepted for full size cable testing. Also selected as the semiconducting jacket compound for the cables to be tested in Phase II of RP 671-1.
C	Accepted for full size cable testing.
D	Accepted for full size cable testing.
E	Accepted for full size cable testing.
F	Rejected due to poor results on moisture permeation. Compound F also exhibited relatively poor deformation resistance at elevated temperature.
G	Rejected due to susceptibility to thermal embrittlement. Compound G also exhibited the poorest aging characteristic of the compounds tested.
H	Accepted for full size cable testing.

Compound Designation	Disposition
I	Rejected due to poorer deformation resistance as compared to similar Compound D from the same supplier.
J	Rejected due to poor performance to environmental stress cracking.

EVALUATION OF FULL SIZE CABLE SAMPLES

Air Oven Aging

(Figures 4-2 - 4-7 and 4-41 - 4-46; Tables 5 - 10).

All compounds exhibited a positive thermal coefficient of resistivity. The resistance of all compounds increased with air oven aging through three months. The resistance of Compounds A, C and H remained essentially stable between three and six months aging while the resistance of Compounds B, D and E continued to increase but at a slower rate.

In addition to the measurement of radial resistance of the semiconducting jacket compounds on the full size cables, radial resistances of the semiconducting jacket compounds for the full size cables were calculated on the basis of radial resistance measurements performed on the semiconducting jakcet compounds removed from the cables. The procedure employed for the measurements and calculations are described in Section 3, Instrumentation and Sample Preparation. The difference between the measured and calculated values can be attributed to contact resistance between the concentric tinned copper wires and the inner surface of the semiconducting jacket of the cable. Contact resistance in this case can be attributed to less than optimum tightness of the semiconducting jacket surrounding the wires and development of a high resistive coating on the surface of the tinned copper wires (described in detail later in the report) due to temperature accelerated chemical interaction between the tinned copper wires and the specific semiconducting compounds. The calculated resistance of the semiconducting jackets may be higher than actual since removal of the jacket from the cable and flattening it for painting of the electrodes would tend to increase its radial resistance. Hence, the calculated values of radial resistance of the semiconducting jacket compounds are probably somewhat higher than actual and the effect of "working" of the compound may vary with the type of compound. The difference between measured and calculated radial resistances or contact resistance may actually be greater than shown by the data due to the above described increase in calculated resistance.

Except for Compound B, the calculated values of radial resistance were essentially equal to or lower than the measured values. The large spread between the measured and calculated values of radial resistance at 80°C for Compound B, (Figure 4-3) with the calculated resistance the higher value, indicates a susceptibility of this compound to increase in resistance, particularly at elevated temperatures, due to mechanical working. As will be shown later in this report, Compound B consistently exhibited this behaviour in the test program.

The average contact resistance at room temperature, 50°C and 80°C was in the order of three ohms for the two inch active section of the test section.

With the exception of Compound D, the retention of elongation of the semiconducting compounds after six months of air oven aging at 100°C on the full size cables was in excess of 75 percent. The percent retention for Compound D was 62 percent. Tensile strength values remained stable or increased moderately. Generally, air oven aging had a more pronounced affect on the physical properties of the semiconducting compounds tested than water immersion and soil burial.

Compounds A, C and H performed particularly well under this aging condition exhibiting initially low values of radial resistance and essentially stable radial resistance characteristics for the three to six month aging period. Retention of physical properties for the six month aging period for these compounds was acceptable.

Water Immersion Aging

(Figures 4-9 - 4-14 and 4-41 - 4-46; Tables 5 - 10).

Based on calculated values of radial resistance, all compounds exhibited a positive thermal coefficient of resistivity. For the first three months of water immersion aging, all compounds with the exception of Compound B exhibited increases in calculated radial resistance comparable to those for air oven aging. With the exception of Compound A, all compounds exhibited significant increases in calculated radial resistance at room temperature, 50°C and 80°C between three months and six months water immersion aging. For this period, water immersion aging had a more pronounced effect on radial resistance for these compounds as compared to air oven aging.

In the case of water immersion aging, contact resistance between the concentric tinned copper wires and the inner surface of the semiconducting jacket of the cable, evident as the difference between measured and calculated values, was more pronounced than for air oven aging. This is attributed to the influence of the moisture on extent and thickness of the coating formed on the surface of the copper wires. In practically all cases, the contact resistance decreased with increase in the temperature at which the radial resistance was measured. This is attributed to expansion of the cable at the elevated temperatures which resulted in more intimate and increased pressure contact between the concentric wires and overall semiconducting jacket at the elevated temperatures.

Compound B, as in air oven aging, exhibited higher calculated radial resistances at 80°C than the measured values. For all other compounds, the calculated values of radial resistance were significantly lower than the measured values at all temperatures. As indicated previously, the difference between the measured and calculated resistances decreased with increasing temperature.

The contact resistance at room temperature was in the range of several hundred ohms decreasing to several tens of ohms to approximately one hundred ohms at 80°C for the two inch active section of the test section.

The retention of elongation of the six semiconducting compounds after six months of water immersion aging at 75°C on the full size cables was in the range of 71 (Compound C) to 89 (Compound H) percent. Tensile strength values remained stable or increased slightly.

Compound A performed best under this aging condition exhibiting initially low values of radial resistance and a declining radial resistance characteristic for the three to six month aging period. Its performance, based on calculated values of radial resistance, was comparable to its performance under air oven aging. It retained 75 percent of its original tensile strength, 120 percent of its original tensile strength after six months air oven aging.

<u>Soil Burial Aging</u>

(Figures 4-17 - 4-40 and 4-41 - 4-46; Tables 5 - 10).

Fluctuations in the data between one month and three months aging were caused by evaporation of water from the soil with the method of conditioning of the cables that was initially employed. The test set-up was subsequently changed whereby the polyethylene-covered soil-filled containers were placed in a humidity and temperature controlled room. This facilitated more accurate control of temperature and moisture content of the soil and thereby corrected the problem.

There was no significant difference in the performance of the six semiconducting jacket compounds in the three soils in which they were aged. Based on calculated values of radial resistance, all compounds exhibited a positive thermal coefficient of resistivity. Compounds A, C and H exhibited moderate increases in calculated radial resistances for the first three months of soil aging which were generally more pronounced at 80°C. For the same period, the radial resistance of Compound B was essentially stable at room temperature and 50°C and increased significantly at 80°C. Compounds C, D and H exhibited essentially stable or decreases in calculated radial resistances between three and six months soil burial aging. Compounds A, B and E exhibited gradual increases in calculated radial resistances in this time period which were more pronounced at the elevated temperatures. Soil burial aging under controlled moisture content at 50°C temperature affected the radial resistances of the semiconducting compounds to a significantly lesser extent than water immersion aging at 75°C and to essentially an equal or lesser extent than air oven aging at 100°C.

In the case of soil burial aging, contact resistance between the concentric tinned copper wires and the inner surface of the semiconducting jacket of the cable, evident as the difference between measured and calculated values, was more pronounced than for air oven aging and was less than, but approached that of water immersion aging. This is attributed to the lesser amount of moisture that penetrated to the interface of the tinned copper concentric wires and the inner surface of the semiconducting jacket as compared to water immersion aging and therefore the less intensive affect on the extent and thickness of the coating formed on the surface of the copper wires. In practically all cases, the contact resistance decreased with increase in the temperature at which the radial resistance was measured. This same condition existed in the Water Immersion Test and was explained previously.

Compound B again exhibited higher calculated radial resistances at 80°C than the measured values. For all other compounds, the calculated values of radial resistance were significantly lower than the measured values at all temperatures.

The contact resistance at room temperature ranged from approximately ten to one humdred ohms and was generally less than fifty ohms at 80°C for the two inch active section of the test section.

There were no significant differences in room temperature measured values of radial resistances of the six semiconducting compounds in the three soils conditioned with and without voltage applied between the concentric copper wires and ground.

There was no significant difference in retention of physical properties of the six semiconducting compounds aged in the three soils. The retention of elongation of the six semiconducting compounds after six months aging of the full size cables in the three soils at 50°C was in the range of 80 to 100 percent. Tensile strength values remained stable or increased moderately.

Compound D performed best, closely followed by Compounds A, C and H, under this aging condition. The compounds exhibited initially low values of radial resistance. Compound D exhibited low and essentially stable or declining measured and calculated radial resistance values in the three to six months aging period. Compounds A, C and H exhibited low and essentially stable or declining calculated radial resistance values in the three to six months aging period. However, the measured values of radial resistance for the three compounds in this time period increased moderately or remained stable at higher levels than the calculated values.

Capacitance Measurements

Since the capacitive reactance of a semiconducting thermoplastic compound is generally at least ten times higher than its radial resistance, this characteristic does not significantly influence the transient voltage gradient in the earth under fault conditions.

The capacitance of the semiconducting jackets was initially small and remained essentially unchanged for all compounds during the air oven aging test at 100°C of the full size cables. Compounds A and H exhibited the smallest increases in capacitance for the various aging conditions. Compounds B and D exhibited the greatest increases in capacitance for the various aging conditions. Generally, the greatest increases in capacitance with aging were experienced with the 75°C water immersion test and in the earth burial test at 50°C in Wisconsin soil with applied voltage.

Investigation of Rectification Effects

The purpose of this investigation was to determine the magnitude of the d-c component of the current flowing through the semiconducting jacket. No previous data of this nature were available. It was anticipated that the density of the current flowing through the jacket during the aging period might have an effect on the rectification properties of the six jackets under evaluation. Therefore, five sets of samples were prepared for testing using different current densities from zero to 5 amperes per test set. One set of samples (No. 5) was placed in soil rather than in hot water in an attempt to more closely simulate service conditions.

Test data summarized in Table 11 revealed that:

a) the rectification effect did not change significantly with the time of aging carried out to 7-1/2 months,

b) the recitifcation effect of samples immersed in water was strongly influenced by the density of the current flowing through the jacket in the aging period. The average d-c components of the six samples for the 4 sets immersed in water in the final measurements were:

Set No.	1	2	3	4
Rectification Effect (DC Component), %	4.62	2.08	0.64	0.21

This shows that Set No. 1 with no current flowing through the jacket exhibited the highest d-c component, while Sets No. 2 through 4 which had currents flowing through the jacket, exhibited lower d-c components decreasing with increasing current density.

c) The proportions of the d-c components of the samples with different jacket compounds were not consistent throughout the test and they also varied from one set to the other. Therefore, it is not possible to compare and evaluate the jacketing compounds with respect to their rectification properties.

d) The samples tested while buried in the Wisconsin soil showed the most consistent results with a total average rectification effect of 0.63% throughout the test.

It is postulated at this time that partial rectification of the a-c current flowing radially through the semiconducting jacket is initially caused by contact of the carbon particles in the jacket with the copper concentric wires. Rectification effect is later influenced by the oxide coating which develops on the surface of the copper wires under normal operating conditions.

It is difficult to assess the significance of the above test results and the effect that the rectification properties of the semiconducting jackets may have on concentric neutral corrosion in actual service. From the visual examination of concentric neutral wires on samples aged in three soils, where no difference in the degree of corrosion was observed between samples aged with and without voltage, a conclusion could be drawn that the rectification properties of the semiconducting jacket are negligible. However, in our opinion, the rectification phenomemon of semiconducting jackets deserves an in-depth investigation to learn more about the mechanism of this rectification, conditions and compound properties that affect the rectification, and the practical impact of this phenomenon on corrosion of the concentric neutral.

Section 6

EXAMINATION OF CONCENTRIC NEUTRAL WIRES AFTER AGING

GENERAL

Although the study of the corrosion of copper concentric neutral wires was not a part of this project, examination of wires removed from cable samples aged in 100°C oven, 75°C water and 50°C soil was included in the test program to obtain information on the behaviour of the tinned copper concentric neutral wires embedded in semiconducting jackets.

The concentric neutral of the 15kV XLP insulated cable with six semiconducting jackets evaluated under this project consisted of 10 #14 AWG tin coated copper wires. The tin coating had an approximate average thickness of 0.1 mil and was applied by hot dip process. Tin coated rather than uncoated copper wires were selected because tin coated concentric neutral copper wires are preferred by the majority of utilities for URD cables.

In the early stages of aging different degrees of discoloration of the concentric neutral wires were observed. The discoloration was due to the formation of a black substance on the surface of the wires and was much more pronounced on samples aged in 75°C water and 50°C soils than on samples aged in 100°C oven. Therefore, all water and soil aged samples at each test period were carefully examined for corrosion of the concentric neutral wires by the laboratory metallurgist. The results of this examination are summarized as follows:

Samples Aged in 75°C Tap Water

The concentric neutral wires jacketed with semiconducting Compounds A, B, C, E and H showed similar behaviour. Black discoloration of the wires gradually increased with time and was more evident on the side facing the semiconducting jacket. The corrosion product causing the discoloration was initially identified as metallic oxide, not of organic nature, such as cupric and/or stannous oxide, which are both black compounds. After approximately 3 months of aging, the blackened tin coating lost its adhesion to the copper. Upon bending the wires around their own diameter, the tin coating flaked off exposing the copper wire which was also oxidized. No significant change in the wire diameter was detected.

The concentric neutral wires embedded in the semiconducting jacketing Compound D exhibited the most severe discoloration evident after the first month of aging. Slight signs of discoloration were also noted on the unaged samples. Loss of adhesion of the tin coating occurred after 2 months of aging. The corrosion was more evident on the sides of the wires facing the semiconducting jacket. Investigation of the corrosion product on the wires using a scanning electron microscope and X-ray spectroscopy (see Figures 6-1 and 6-2 below) revealed the presence of sulphur which had migrated from the jacketing compound.

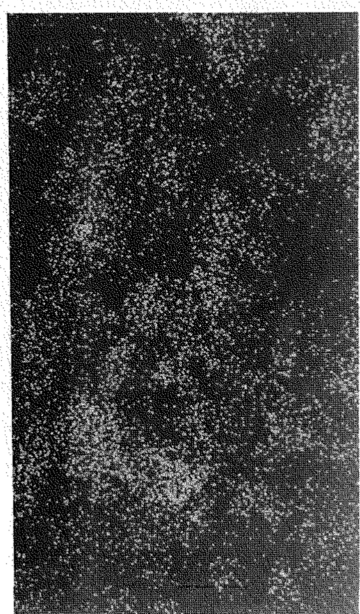


Figure 6-1. X-ray mapping for sulphur.

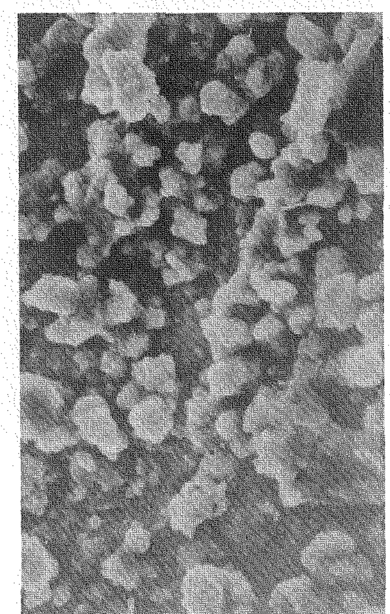


Figure 6-2. Crystals of the black corrosion product on the wire, 20,000 X.

The corrosion products are probably tin sulphides, and/or copper sulphides in addition to tin or copper oxides.

Samples Aged in 50°C Soil

Examination of samples aged in 50°C Florida, Georgia and Wisconsin soils showed no practical difference in the discoloration of the concentric neutral wires due to the type of soil or due to the application of an electrical potential to the concentric neutral (test with and without voltage). The concentric neutral wires jacketed with semiconducting Compounds A, B, C, E and H all showed similar behaviour. After the first month, the side facing the jacket showed a matted pattern of discoloration. This discoloration progressed very slowly in the first three months, then became more evident in the fourth and sixth month but to a much lesser degree than that of the samples immersed in water. The adhesion of the tin coating was not affected.

The concentric neutral wires embedded in the semiconducting jacketing Compound D showed severe discoloration combined with the loss of adhesion of the tin coating-similar to the samples with semiconducting jacket Compounds A, B, C, E and H aged in 75°C water.

General Observations

Various degrees of discoloration of the concentric neutral wires observed on all samples after aging is the result of a direct chemical attack due to the presence of certain chemicals in the semiconducting jacketing compounds. In the case of Compound D where the wires exhibited the most severe discoloration, the chemical was identified as sulphur. The sulphur severely attacked the tin coating and caused it to flake and disintegrate. Sulphur reacts with copper to form copper sulphide. Copper sulphide can form a protective film on the copper and protect it from further corrosion.

The discoloration was more severe in the water immersion test than in the soil test. This is probably due to the higher temperature and higher moisture content of the samples aged in water. The oven aged samples showed only a very slight discoloration because of the lack of moisture.

Measurements of point to point contact resistance of the discolored copper wires after six months of aging in 75°C water yielded values ranging from 12 MΩ to 5 MΩ. The wide spread in values is attributed to the non-uniformity of the discoloration of the copper wires. The discoloration of the copper wires is considered to be a major factor in the contact resistance between the concentric copper wires and the semiconducting jacket. Since the discoloration is a very thin, physically weak non-uniform coating on the surface of the copper wires, it is not expected to influence the performance of the cable insofar as transient voltage gradients in the earth are concerned. However, it would appear desirable to further investigate this phenomenom on both coated and bare copper wires.

APPENDIX 1

DETERMINATION OF THE MOISTURE PERMEABILITY CONSTANT OF CARBON BLACK FILLED COMPOUNDS SELECTED FOR FUNDED PROJECT RP 671-1

ABSTRACT

The moisture permeability constant of nine commercial conductive thermoplastic compounds and two commercial polyethylene jacketing compounds were determined by the Research Laboratory according to ASTM E 96-66 procedure A at 23°C and 50% relative humidity.

PURPOSE

Determine the moisture permeability constant of commercial thermoplastic semi-conductive shielding compounds and thermoplastic jacketing compounds.

SAMPLES

Compound Identification

A

B

C

D

E

F

G

H

Medium Density Black Polyethylene Jacket Compound

Low Density High Molecular Weight Black Polyethylene Jacket Compound

PROCEDURE

Desiccant Procedure A conducted at 23°C and 50% relative humidity of ASTM E 96-66 was used to determine the moisture permeability constant of the compounds tested.

The procedure utilizes a desiccant which is placed in a dish and the sample sheet sealed with wax to the mouth of the dish. The assembly is placed in an atmosphere of constant temperature and humidity, and the weight gain of the assembly is used to calculate the rate of water vapor movement through the sheet.

SAMPLE PREPARATION

Thin test specimens approximately 15 mils thick were prepared from the molded slab samples and utilized for the moisture vapor transmission test. The molded slabs were vacuum dried at 65°C for 16 hours before being pressed at 175°C and 1000 psi for 1 minute and slowly cooled to room temperature. The films were pressed between chrome plated stainless steel plates having a mirror finish in order to prepare a uniform and defect-free surface.

The film samples were measured in each quadrant with a flat head thickness gauge and the average thickness recorded.

TEST PROCEDURE

Circular films 96mm in diameter were cut from the pressed samples, placed on a supporting ring in a petri dish, 100mm by 20mm, containing 25 grams of anhydrous calcium chloride, and sealed with molten wax while a circular template having a diameter of 72.6mm was placed on top of the film to define a surface area of $0.00414 m^2$. The assembly was placed in a controlled temperature and humidity atmosphere which was continuously recorded. The samples were weighed each day and the weight gain plotted vs. time. It was determined that a minimum of 7 days was necessary for the thin samples (10-15 mils) with low permeability constants to reach a steady state of transmission. The slope of the line from the next 5 consecutive days or the average transmission rate and the average temperature and humidity were used to calculate the water vapor transmission. At each weighing the assembly was <u>carefully</u> shaken to maintain a 0% relative humidity inside the petri dish and to avoid damage to the wax seal.

CALCULATION

1. Water Vapor Transmission (WVT) = (g x 24)/(t x a)

where: g = weight gain, grams
t = time, hours
a = exposed area, m^2
WVT = rate of water vapor transmission, grams/m^2.24 hours

2. Permeance = WVT/ΔP = WVT/[S(R_1-R_2)]

where: P = vapor pressure difference, mm Hg
S = saturation vapor pressure, at test temperature, mm Hg
S - 20.69 @ 73°F, 21.14 @ 73.5°F & 21.45 @ 74°F

R_1 = relative humidity at the source
R_2 = relative humidity at the sink (zero)

Permeance = WVT/mm Hg expressed in metric perms

3. Average Permeability = Permeance x thickness centimeters

4. Permeability constant given in metric units (cm^3 STP)(cm)/(cm^2)(SEC)(cm Hg) = Average permeability/1754

(cm^3STP)/cm/cm^2/SEC/cm Hg = cubic centimeters of water vapor at standard temperature and pressure per centimeters thickness per square centimeter per second per centimeter of mercury.

DISCUSSION

The transport of water vapor through polyethylene obeys Fick's and Henry laws. Fick's law relates mass transfer rate M to a concentration gradient and infinite difference form is

$$M = DA \frac{\Delta C}{\Delta X}$$

where D is the diffusion constant, A is the area, and ΔC is a concentration difference across an increment in length, ΔX. Henry's law is

$$C = SP$$

where S is solubility and P is the vapor pressure of penetrant. If Fick's and Henry's laws are combined

$$M = DSA \frac{\Delta P}{\Delta X}$$

and the permeability P = DS

The permeability constant is independent of film thickness, however, it has been found to be an exponential function of the reciprocal absolute temperature, therefore, the permeability constant increases with temperature (ref. 2 and 3).

Table I lists the moisture permeability constant determined by the laboratory tests.

The jacketing Compounds 1 and 2 containing 2.6% carbon black have a very low permeability constant as determined by the Research Laboratory and correlate with the published data for polyethylene containing 2.7% carbon black.

CONCLUSION

The permeability constants obtained by the Research Laboratory on samples 10 to 15 mils thick using the ASTM E 96-66 procedure agree quite well with published data for jacketing and conducting compounds.

The permeability constant is not only a function of the chemical structure of the polymer, but varies with the morphology of the polymer and depends on many physical factors such as density, degree of crystallinity, the amount and degree of dispersion of fillers. However, the chemical structure can be considered as the predominant factor which controls the magnitude of the permeability constant.

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