TECHNICAL REPORT STANDARD PAGE

1. Report No. FHWA/LA-91/238	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Feasibility of Applying Cathodic Protection to Underground Culverts	5. Report Date June 1991 6. Performing Organization Code
7. Author(s) J. D. Garber, J. H. Lin, L. G. Smith	8. Performing Organization Report No. 238
9. Performing Organization Name and Address University of Southwestern Louisiana College of Engineering USL Box 42251 Lafayette, LA 70504	10. Work Unit No. 11. Contract or Grant No. La.HPR Study #88-4P(B)
12. Sponsoring Agency Name and Address Louisiana Department of Transportation & Development P. O. box 94245 Baton Rouge, LA 70804-9245	13. Type of Report and Period Covered Interim Report July 1988 - June 1991 14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The Louisiana Department of Transportation and Development uses metal culverts in various parts of the state. This study was undertaken to assess the feasibility of applying cathodic protection both externally and internally to metal culverts to prevent corrosion from occurring.

The methodology employed ranged from a variety of laboratory tests to an actual field study. The laboratory tests were conducted: (1) to determine the best coating system to use in conjunction with cathodic protection and (2) to prove that internal cathodic protection would work inside 24-inch culverts using zinc anodes. The field work consisted of installing 10-foot sections of eight different types of culverts with and without cathodic protection. Current and potential measurements have been made during the first two years of this four-year study.

The results of the field study have proved that culverts can be protected from corrosion economically using cathodic protection. It has been found that the outside of the culvert requires significantly more current for protection than does the inside. All of the unprotected culverts are experiencing corrosion, and the culvert requiring the least amount of current is the polymeric galvanized steel.

The only laboratory test that was able to predict the best coating system on galvanized steel was the 13-gallon water tank test using magnesium anodes. The more sophisticated tests, potentiostat and impedance, were unable to make good predictions.

It is recommended that cathodic protection be applied to culvert systems that are in low resistivity environments. Culverts being installed in new locations should be electrically connected so that cathodic protection can be more easily applied later.

17. Key Words Culvert, Cathodic Protection, Corrosion, Coatings, Potential, Current, Economic	18. Distribution Statement Unrestricted. This document is available to the public through the National Technical Information Service, Springfield, Virginia 21161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 168	22. Price

Form DOT F 1700.7 (8-69)

FEASIBILITY OF APPLYING CATHODIC PROTECTION TO UNDERGROUND CULVERTS

INTERIM REPORT

by

J. D. Garber, Ph.D., P.E.
Acting Dean of Engineering

J. H. Lin
Instructor

University of Southwestern Louisiana
Lafayette, LA 70504

and

Mr. Larry G. Smith, P.E., President
Corrosion Control, Inc.

CONDUCTED FOR

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
LOUISIANA TRANSPORTATION RESEARCH CENTER
in cooperation with
U.S. Department of Transportation
FEDERAL HIGHWAY ADMINISTRATION

JUNE 1991

ACKNOWLEDGMENT

We sincerely appreciate the contribution of the following people at LTRC who have made helpful suggestions during the project: Steve Cumbaa, William Temple, and Kirk Clement. Also, a special thanks to Mr. Eugene Waguespack of DOT for providing the staff needed to bury the test culverts at the Pecan Island site.

ABSTRACT

The Louisiana Department of Transportation and Development uses metal culverts in various parts of the state. This study was undertaken to assess the feasibility of applying cathodic protection both externally and internally to metal culverts to prevent corrosion from occurring.

The methodology employed ranged from a variety of laboratory tests to an actual field study. The laboratory tests were conducted: (1) to determine the best coating system to use in conjunction with cathodic protection and (2) to prove that internal cathodic protection would work inside 24-inch culverts using zinc anodes. The field work consisted of installing 10-foot sections of eight different types of culverts with and without cathodic protection. Current and potential measurements have been made during the first two years of this four-year study.

The results of the field study have proved that culverts can be protected from corrosion economically using cathodic protection. It has been found that the outside of the culvert requires significantly more current for protection than does the inside. The culvert requiring the least amount of current is the polymeric galvanized steel. All of the unprotected culverts are experiencing corrosion.

The only laboratory test that was able to predict the best coating system on galvanized steel was the 13-gallon water

tank test using magnesium anodes. The more sophisticated tests, potentiostat and impedance, were unable to make good predictions.

It is recommended that cathodic protection be applied to culvert systems that are in low resistivity environments. Culverts being installed in new locations should be electrically connected so that cathodic protection can be more easily applied later.

IMPLEMENTATION STATEMENT

The results of this study have verified that metal culverts can be cathodically protected in low resistivity soil and water using zinc anodes. The protection can be applied both internally and externally on new culvert installations. Since the test culverts have been in place for two years at this time, it is important to continue the monitoring process to see if some coatings will begin to deteriorate after long periods of field exposure.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Field studies conducted previously by the Louisiana Department of Transportation (1) verified that most underground metal culverts experience severe attack in low resistivity soils after exposure times of ten years or less. The nature of the corrosion attack is primarily caused by oxygen in the soil and water. At the same time, the Highway Department is being asked to install culverts that can provide a life expectancy of 50 to 70 years. From the previously mentioned study, it is obvious that coatings alone will never provide the time required, and therefore, an alternative system must be considered. Coated culverts in conjunction with cathodic protection appear to be a viable alternative.

The application of cathodic protection to the outside of pipes has been extensively studied and standards (2) have been established. One company in California, Farwest Corrosion Control Co., actually presents the design by which one can apply external cathodic protection to culverts. However, to completely protect the buried culvert from corrosion, cathodic protection must be installed internally as well as externally. It is the primary interest of this study to determine the current required to completely cathodically protect metal culverts having different types of coatings. Another consideration is the practical aspect of providing internal cathodic protection to culverts with 24-inch or larger diameters.

A careful survey of the available literature on the application of cathodic protection to culverts has revealed that only external anodes have been applied. There has also not been any previous work done to determine the effectiveness of various coatings in culverts when cathodic protection is being used. Researchers at Mobil (3) have applied internal cathodic protection in cement-lined piping and have found that the larger diameter pipes gave the best current distribution. A zinc spool anode gave sufficient cathodic protection at a distance of more than 50 times the diameter of the pipe. Similar results were found by Groover and Peterson (4) who showed that low carbon steel pipes in stagnant sea water would be completely protected only when the diameters were larger than two inches. Cathodic protection was most effective in systems where there was a slow flow rate of corrosive fluid.

MacKay and Grace (5) designed a zinc anode assembly and tested it inside tanker pipelines containing stagnant sea water. The anode used inside a 14-inch steel pipe produced a current density of 14.5 ma/m^2 and provided cathodic protection over a length of 520 pipe diameters.

A paper by Simpson and Robinson (6) examined which coatings on steel pipes work best in conjunction with cathodic protection. It was found that the worst blistering occurred at the highest protective potentials. The best coatings proved to be epoxy and coal tar epoxy systems. These coating systems showed no deterioration after four years of exposure.

The above papers represent the limited amount of literature that is available on the application of internal anodes to corroding systems. It is clear that this project can provide information that is very important to a better understanding of applying cathodic protection to metal culvert systems that have different types of coatings.

OBJECTIVES

The objectives of this study include:

1) To develop laboratory and bench scale tests to evaluate various coating systems for use in conjunction with cathodic protection.
2) To prove that cathodic protection can be applied internally to 24-inch culverts before going to the field.
3) To install eight different types of coated culverts in the field with and without anodes. Installation is to be in a harsh corrosive environment.
4) To monitor the potentials and current requirements of the field-installed culverts as a function of time to get design data for later field installations.
5) After four years in the field, the culverts will be removed and visually examined to see how effective cathodic protection was in this particular application.

SCOPE

This project addresses the effectiveness of providing cathodic protection to new metal culverts installed in the field. It does not suggest that the information obtained will be directly translated into existing systems in the field. For example, systems in less corrosive environments may require magnesium anodes rather than zinc.

Eight culvert systems are examined in this project, which is only a small sample of the number of culverts from which the state can choose. Because of this limitation, a laboratory test method must be developed to see if future culvert systems can be evaluated in the laboratory.

METHODOLOGY

This project can be divided into three different areas: (1) evaluating various coatings in the laboratory to ascertain which ones should perform best under cathodic protection, (2) proving in the laboratory that it is possible to apply anodes inside of culverts, and (3) installing cathodically protected and unprotected culverts in the field. Methods have been developed by which each of these areas could be studied.

(1) EFFECTIVENESS OF COATINGS FOR CATHODIC PROTECTION

Two electochemical methods were developed in this project in an attempt to determine in the laboratory which coatings should perform best in conjunction with cathodic protection. These two tests which are described below are (A) the potentiostat test and (B) the AC impedance test.

In both of these tests, it was necessary to prepare a 2-inch by 2-inch test electrode and make a salt bridge to connect the two beakers holding the test electrode and counter electrode. The procedures used are listed below.

Test Electrode Preparation

A 2-inch by 2-inch coupon is cut from the coated culvert and is used in this test. The sample culverts are prepared using the following procedure:

1) A hole is drilled about 1/4 inch from one of the edges.

2) The coating around the hole is removed to provide electrical contact.

3) The edges of the sample and the area around the hole are cleaned with an organic solvent.

4) A copper wire is cut and attached to the sample using a plastic bolt. The bolt passes through the hole of the sample and the copper loop.

5) The connection is coated with silicon rubber.

Procedure Used to Make a Salt Bridge

1) A piece of glass tubing is cut.

2) A bunsen burner is used to bend the glass tube into a U-shape.

3) A sea salt solution is heated and agar is added and mixed with this salt solution.

4) The mixture of agar and salt solution is poured into the U-shape glass tube while the mixture is hot.

5) The mixture of agar in the U-shape glass tube cools for several minutes and becomes solidified.

6) The salt bridge is stored in water so that it will not become dry.

After making a sea salt solution containing 0.75 percent Cl^-, 4000 ml of this solution is added to each beaker. At this point, either of the two electrochemical test methods could be conducted.

A. Potentiostat Test

This test method uses a potentiostat to lower the potential of a metal 300 millivolts below its open circuit potential value and measures the current required to do this as a function of time. Since the test coupons are all 2 inches by 2 inches in size, the amount of current required is directly related to coating effectiveness. For example, a poor coating on a piece of glavanized, aluminized, or plain carbon steel will require more current than a good coating would require. The 300 millivolt level was selected since this is a criteria by which cathodic protection is normally provided. The detailed procedure to perform this test follows:

1) The test electrode is immersed in 0.75 percent sea salt solution and oxygen is bubbled into the solution. A silver-silver chloride reference electrode is immersed very close to the cathode (the test electrode to be protected). The counter electrode used to complete the circuit (normally galvanized steel) is immersed in the electrolyte in the second beaker.
2) A salt bridge connects the two beakers.
3) The leads from the potentiostat are connected to the cathode, anode (counter electrode), and reference electrode.
4) The AC power switch of the potentiostat is turned on.
5) The initial potentiostat control is set to the desired potential.
6) The push button is set to the "on" position and an independent voltage meter reads the set potential to verify that the instrument is working.

7) After potentiostat control is verified, the meter push button is released and the current range is selected.

8) Current readings are made at various time intervals.

B. AC Impedance Test

This is the newest techology used to evaluate coatings. The major parameters that can be determined for this test method are the pore resistance, charge transfer resistance, and double-layer capacitance of the circuit being tested. The higher the resistance of the circuit, the better the coating, and the smaller the capacitance, the better the coating. Since this information appears to be useful, a detailed procedure was developed for making AC impedance measurements. This electrochemical impedance test has two techniques. One is the lock-in amplifier technique, and the other is the Fast Fourier Transform (FFT) technique.

The lock-in amplifier uses analog electronics to measure the phase and amplitude characteristics of an AC signal. This technique makes measurements in the 5 herz to 100 kilo-herz range.

The Fast Fourier Transform technique makes measurements from 0.1 milliherz to 10 herz. FFT is used for measurements at low frequencies, while the lock-in technique makes measurements at high frequencies.

The cell used in this test is the same as the one used in the potentiostat test. The electrolyte concentration, air agitation, electrodes, temperature, reference electrode, and arrangement of the cell are identical.

The following procedure is used for the AC impedance test:

1) The leads from the AC impedance system are connected to the working electrode (the test electrode), the counter electrode and the reference electrode.
2) The IBM PC computer, potentiostat/galvanostat and lock-in amplifier are turned on.
3) The computer is programmed to run the experiment.
4) The cell is switched into the experimental circuit.
5) The impedance plots are measured.
6) The data is stored on a disk.
7) The impedance measurements are made after one hour and repeated after 25 and 49 hours, respectively, following steps 1-7.

A third laboratory method used a 13-gallon water tank to help evaluate the various culverts and their coatings. The water tank contained 0.75 percent sea salt solution and was continuously purged with air. The test culvert pieces having dimensions of 2 inches by 8 inches were coupled with zinc and magnesium anodes using coated copper wire. A 0.01 Ω resistant shunt was placed between the anode and cathode to allow current flows to be measured. Figure 1 shows the cathodic protection setup. Pieces of uncoupled zinc and magnesium were also placed in the test tank to determine their normal weight loss in the aerated sea water. The pH of the water in the tank was monitored on a daily basis and adjusted with diluted hydrochloric acid.

At the end of the first week, the test coupons were removed for weighing and visual examination. They were then reconnected

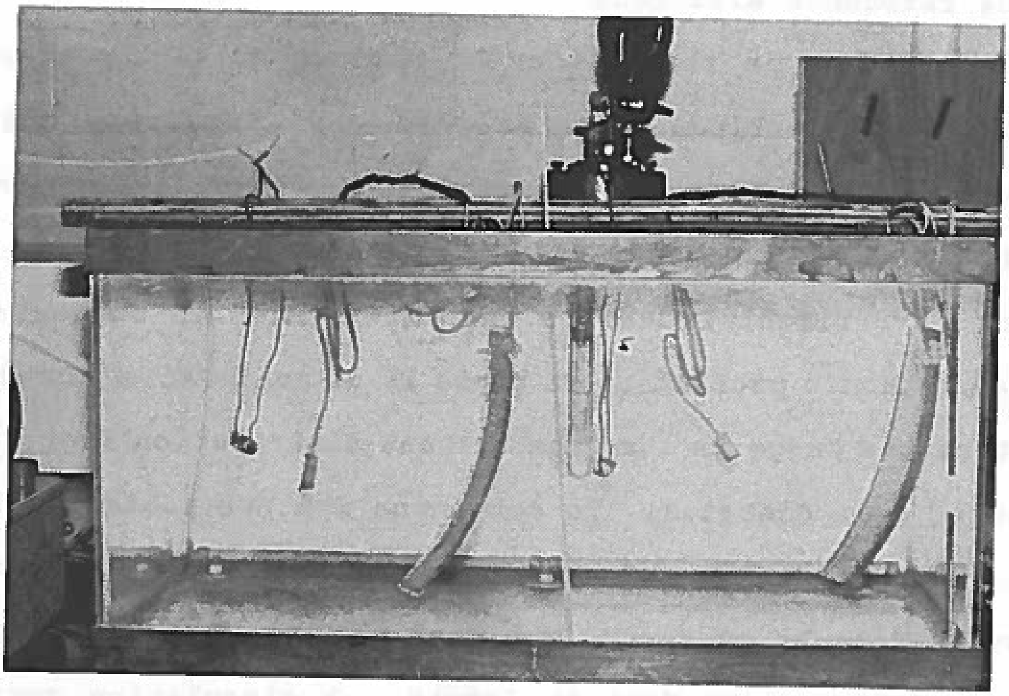

Figure 1. Water tank used in the experiment.

and returned to the tank for a second week of testing. During the test, the current flow between the coupons and their anodes and the pH of the solution were measured daily. Potential measurements made on the various pieces were performed using a silver-silver chloride reference electrode.

The strategy is that since the various culvert pieces to be protected are identical in size, the ones requiring the least amount of current should be the easiest to cathodically protect.

(2) LABORATORY STUDY USING INTERNAL ANODES

Some experimental data in the literature has suggested that internal cathodic protection on pipes is an achievable possibility. The literature suggests that the current distribution improves with increasing pipe diameter. To determine whether anodes would work inside culverts, a test tank was constructed with dimensions of 2.5 feet by 24 feet by 12 feet. The tank was capable of holding five culverts that were 10 feet in length. A circulation system was designed to pump water through each culvert on a continuous basis. The flow rate through each culvert was set at 7 gallons per minute, which corresponds to a residence time of 35 minutes. The water contained 0.75 percent sea salt which maintained the resistivity at 90 Ω-cm. The culverts used in this study were 2 feet in diameter. Figure 2 shows the tank loaded with five of the galvanized steel culverts being tested together. Figure 3 shows the zinc anode placed in the center of the culvert on a rubber mat. The electrical connections were made on each of the 5-foot culvert sections and the connecting metal band. The leads from the anode

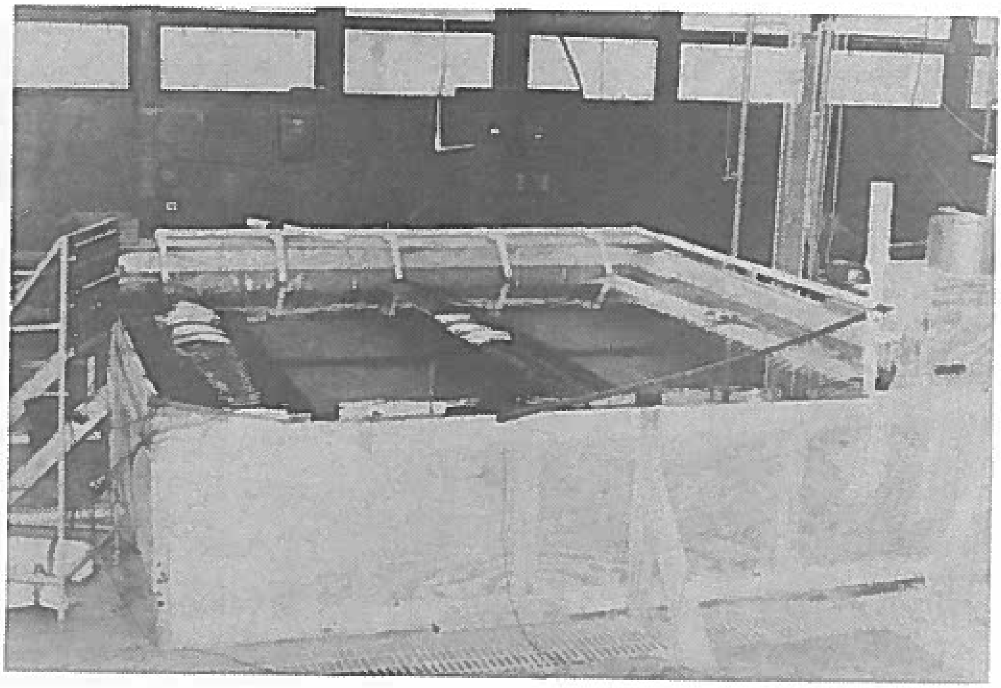

Figure 2. Large water tank with water circulating.

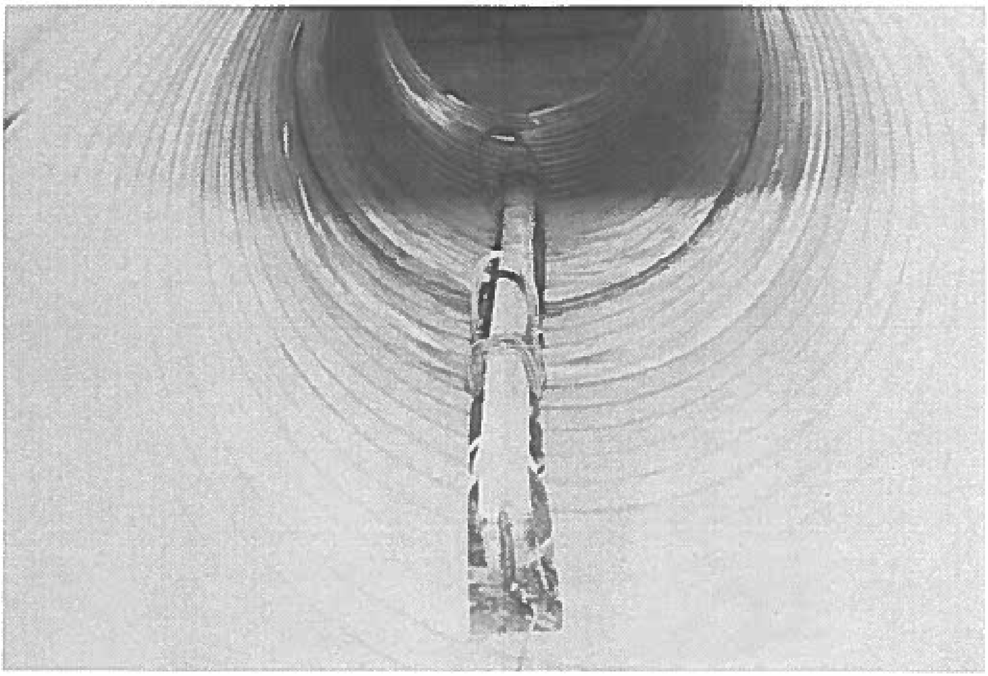

Figure 3. Zinc anode inside the galvanized culvert.

and culverts were connected across a 0.01Ω shunt so that current flow versus time could be determined. Potential measurements were made using a copper-copper sulfate reference electrode. The current was measured each day, and the potential was measured at the mouth of each culvert at four positions: 12, 3, 6 and 9 o'clock with the anode connected. At the same time each day, the anode was disconnected and after approximately two hours, the potentials were measured again. The open circuit potential of the zinc anode could be determined at that time.

After 30 days of this type of measurement, the tank was drained and the culverts were removed for examination. After this, the tank was reloaded with water and the three aluminized steel culverts were tested. The final test was on the polymeric cold-rolled steel culvert, which was tested alone.

The test was designed to determine if the culvert could be internally cathodically protected. The potential measurements verified that fact. Also, the current measurements throughout the 30-day period showed which culvert system required the minimum amount of current from the anode. The coatings that are incompatible with cathodic protection show increased current output from the anode with time.

(3) FIELD INSTALLATION OF CULVERTS

On June 13 and 14, 1989, eight sets of culverts were installed at Pecan Island (near the Fresh Water Bayou pontoon bridge). The Louisiana Department of Transportation installed eight 10-foot sections of culverts parallel to Hwy. 3147 at two different sites. Site 1, closest to the pontoon bridge, is where eight 10-foot sections of culverts were installed with zinc anodes on the inside and outside of each culvert. Site 2 is where eight 10-foot sections of the same culverts were installed without anodes. At each site, there was a drainage ditch and the eight culverts were placed on the north side of the drainage ditch. The culverts are listed as follows with culvert A being closest to the ditch at each site:

Culvert No.	Culvert Type
A	Polymeric Cold-Rolled Steel
B	Polymeric Aluminized Type II Steel
C	Polymeric Aluminized Type I Steel
D	Polymeric Galvanized Steel (Supplier 2)
E	Polymeric Galvanized Steel (Supplier 1)
F	Bituminous Galvanized Steel
G	Galvanized Steel
H	Fiber-Bonded Bituminous Galvanized Steel

The intention of this experiment was to check the potential of the protected and unprotected section of culverts and to measure the current output of the zinc anodes.

The actual culvert installation took two days and used equipment and a crew of five men from Louisiana DOTD. A view of Site 1 before any construction work is seen in Figure 4. Figure 5 shows a culvert being prepared for installation. The final hook-

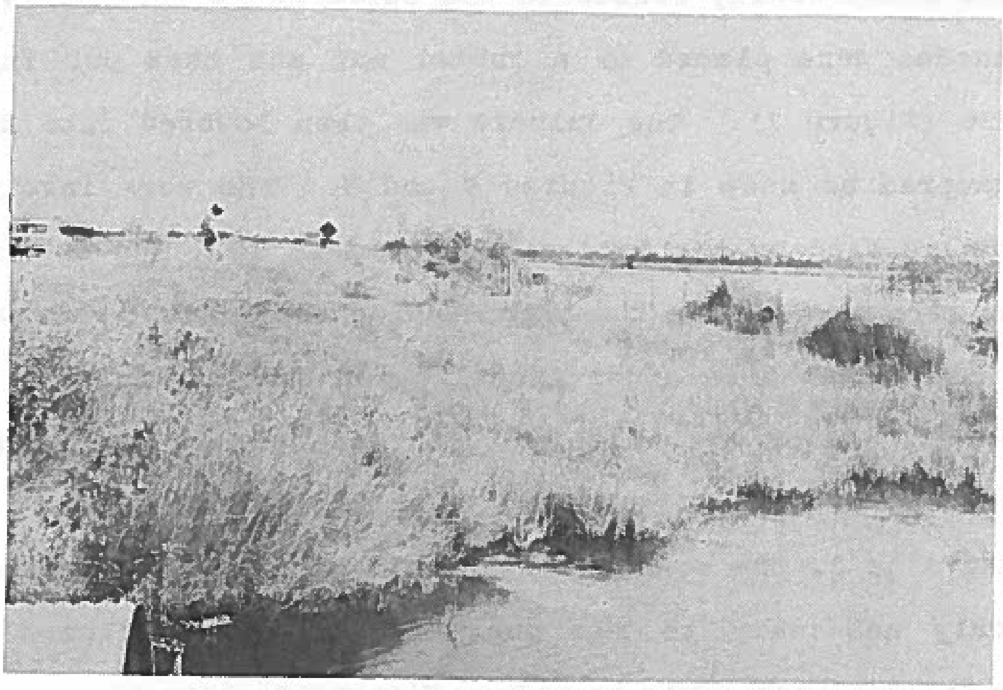

Figure 4. This is the protected site before any construction.

Figure 5. This is a culvert being prepared for installation.

up that electrically connected the culverts is shown in Figure 6. The anodes were placed on a rubber mat and then put inside the culvert (Figure 7). The culvert was then lowered into the ditch and covered as seen in Figures 8 and 9. The work involved some hazards as seen by the alligator in Figure 10. The external zinc anodes were pushed into the ground using the Gradall shovel (Figure 11). The final site after installation was completed is seen in Figure 12. Note the white polyethylene pipe that contains the electrical wires.

At Site 2, the process of installation was much simpler. It was only necessary to run one wire from the culvert so that potential readings could be made. Figure 13 shows the test site at the beginning of the day. Figure 14 shows the electrical connection that was made. Since anodes were not involved at this site, it was easier to install the culverts as seen in Figure 15. The final site after the culverts were installed is seen in Figure 16. The polyethlene pipe houses the electrical wire connected to the culvert.

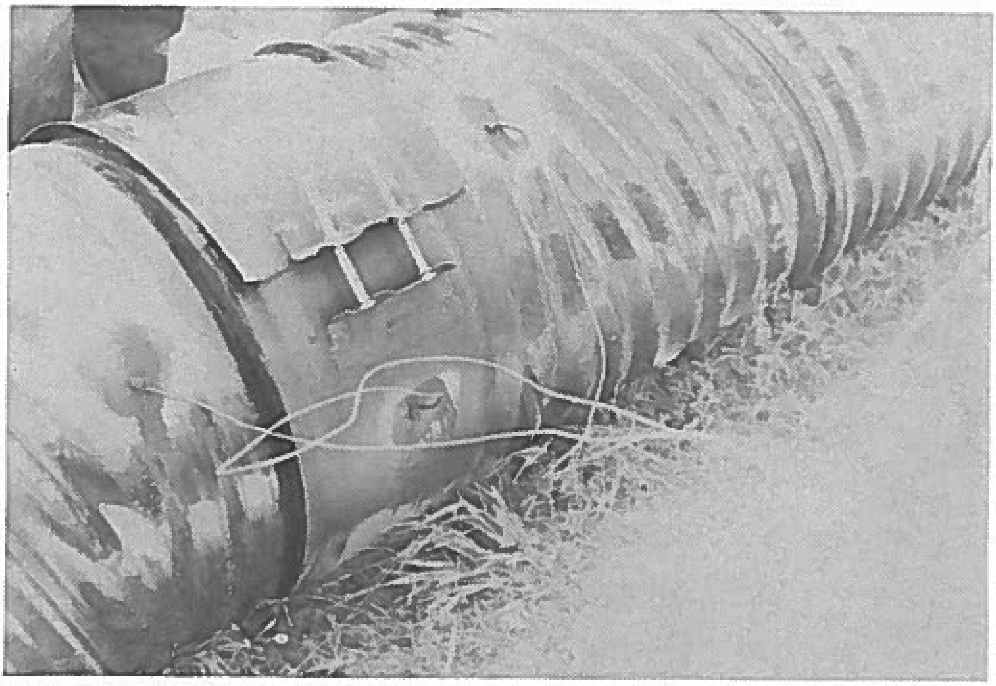

Figure 6. The final electrical hookup is shown in the photograph.

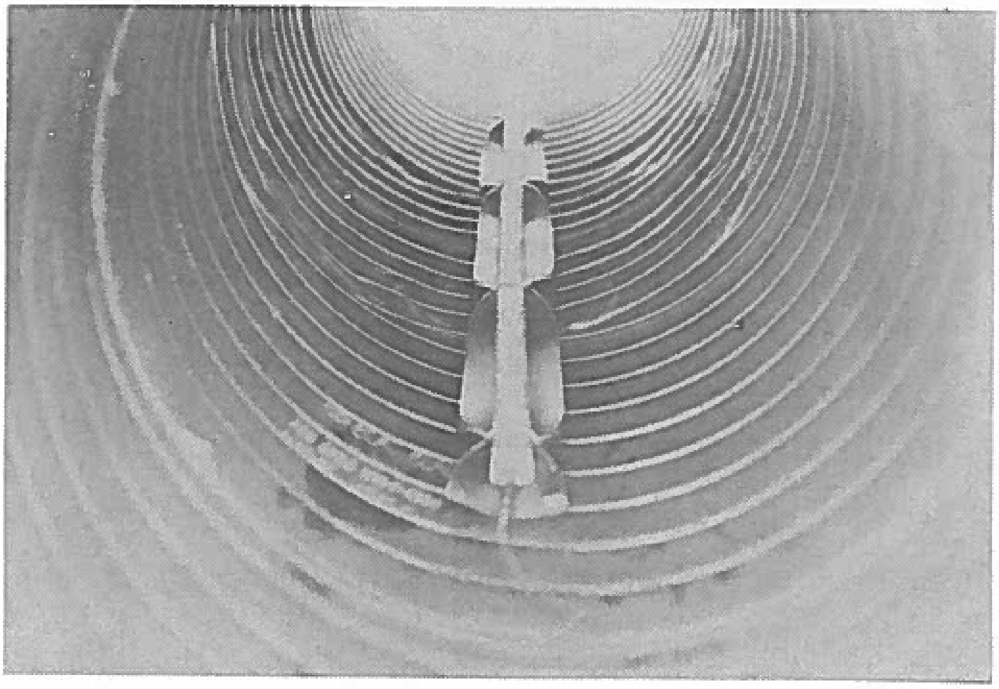

Figure 7. The anodes were placed on rubber mats so that they would be insulated from the culvert.

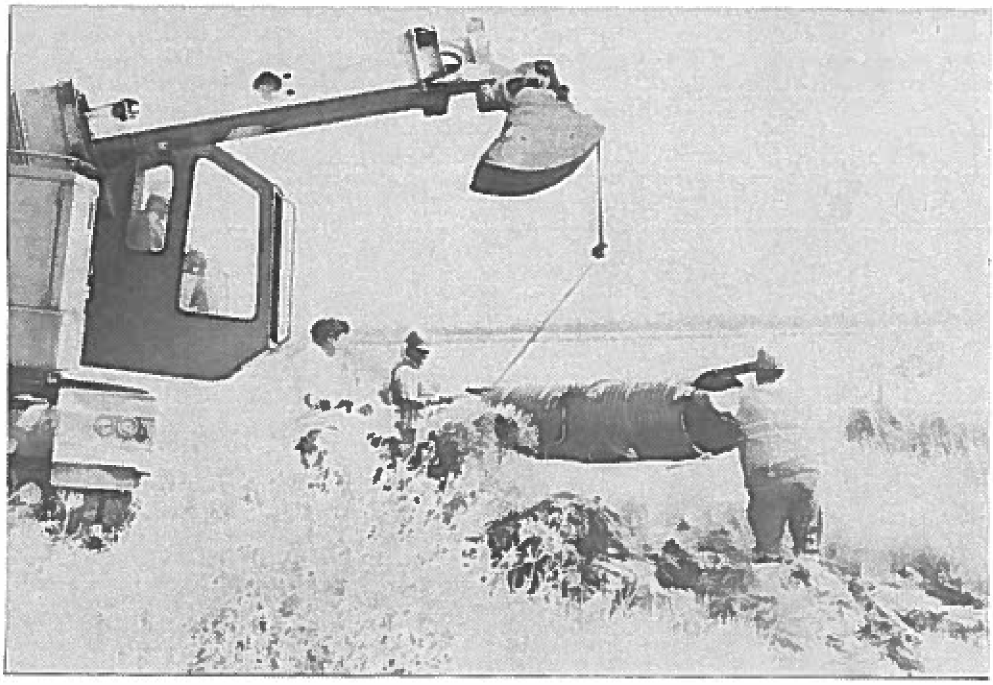

Figure 8. One of the culverts is being lowered into the ditch.

Figure 9. The culvert is being covered with the removed soil.

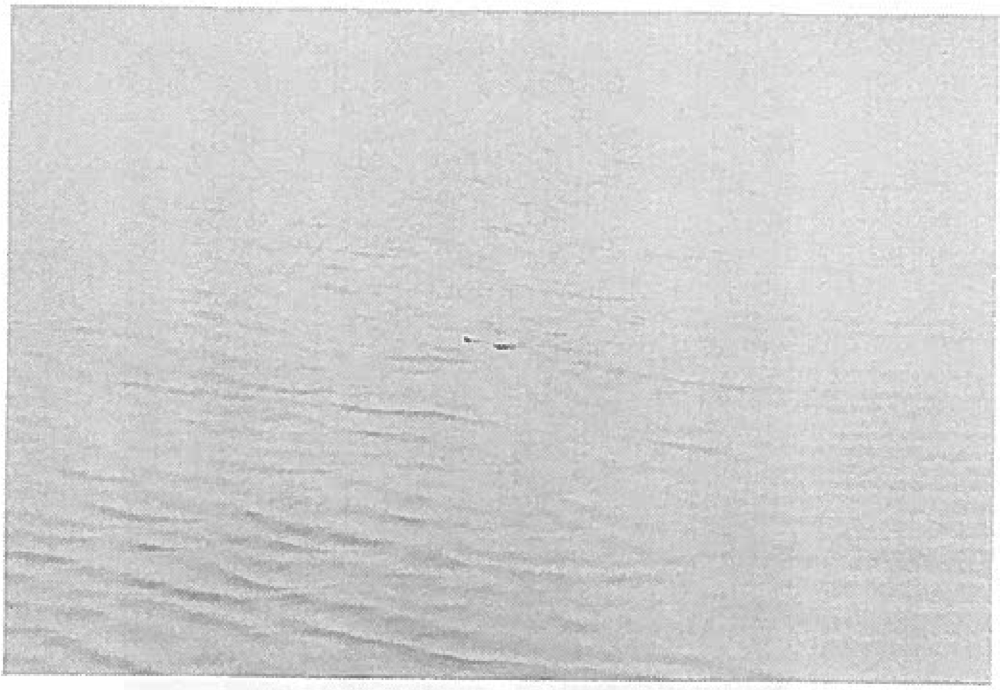

Figure 10. This work was not without its hazards as seen in this photograph.

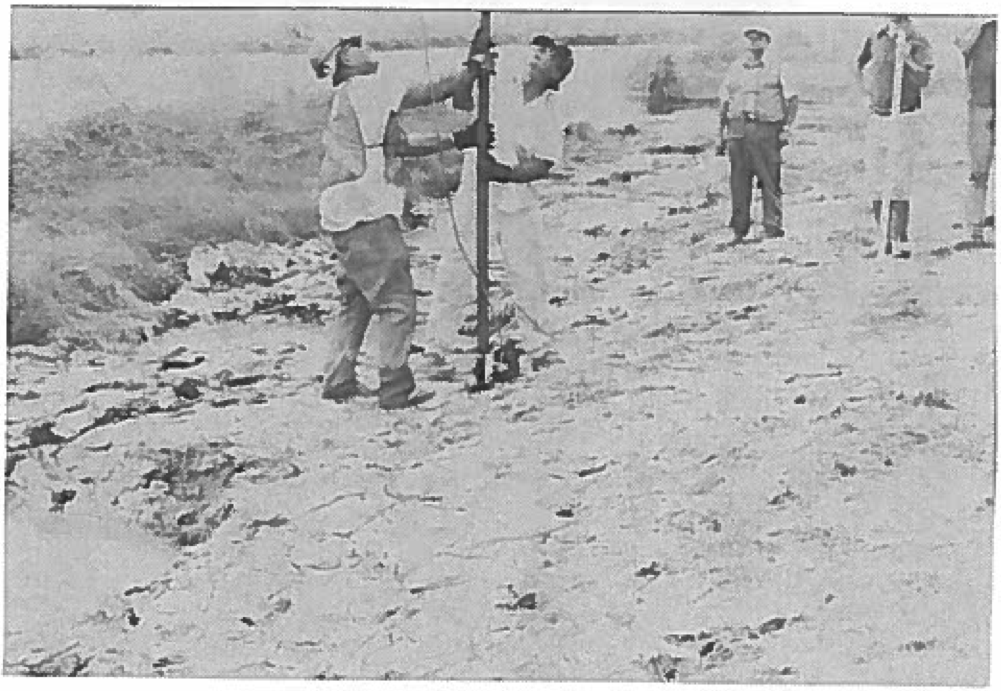

Figure 11. The external anodes were pushed into the ground using the Gradall shovel.

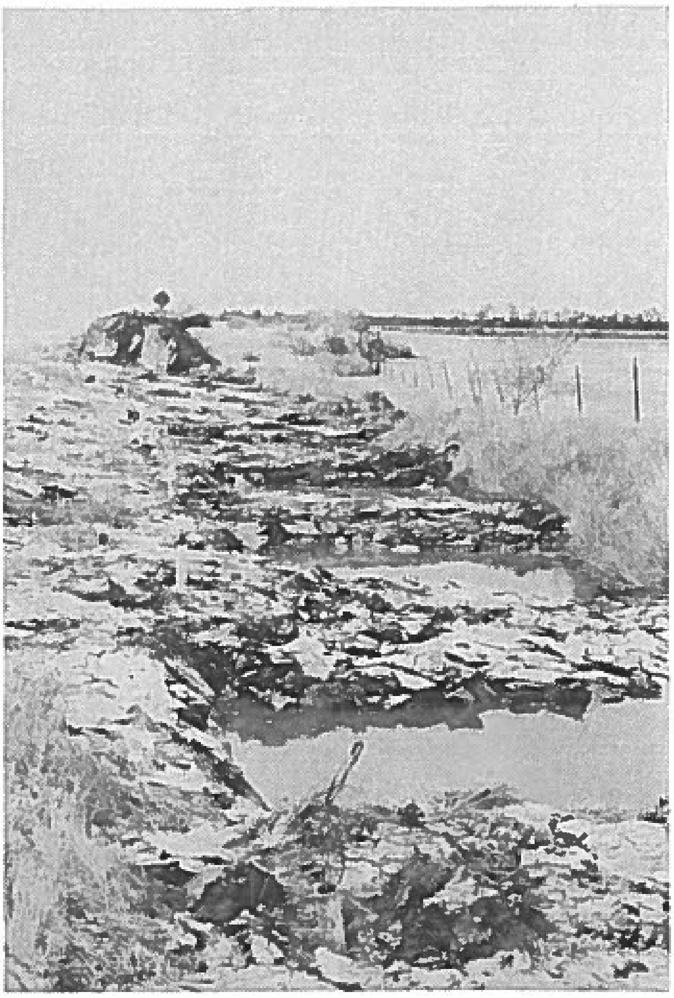

Figure 12. This is what the site looked like after the installation was completed.

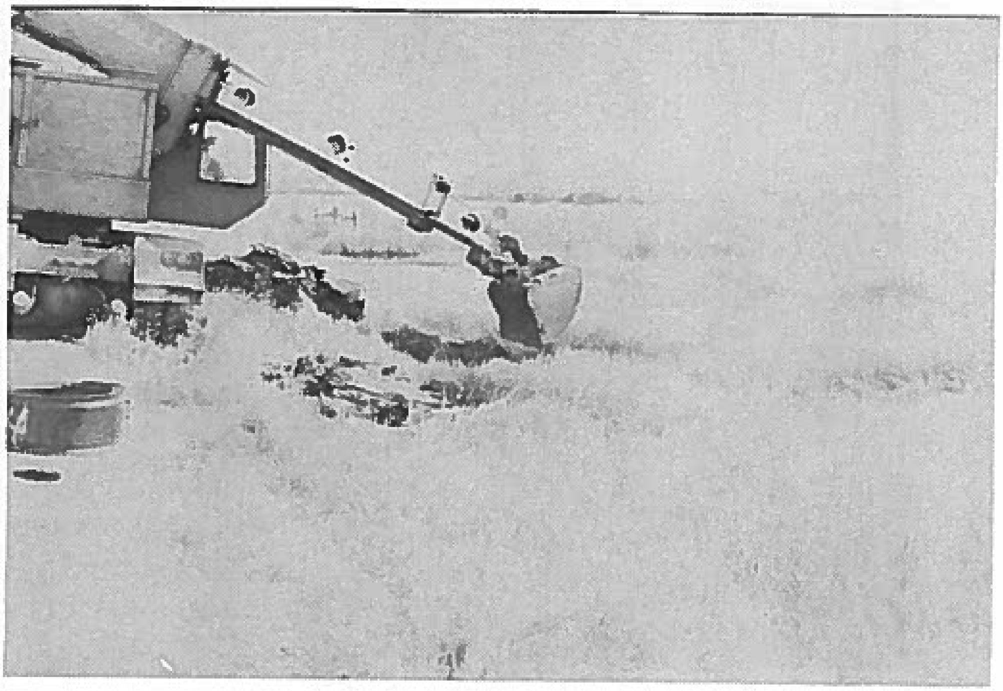

Figure 13. This is the unprotected site at the beginning of construction.

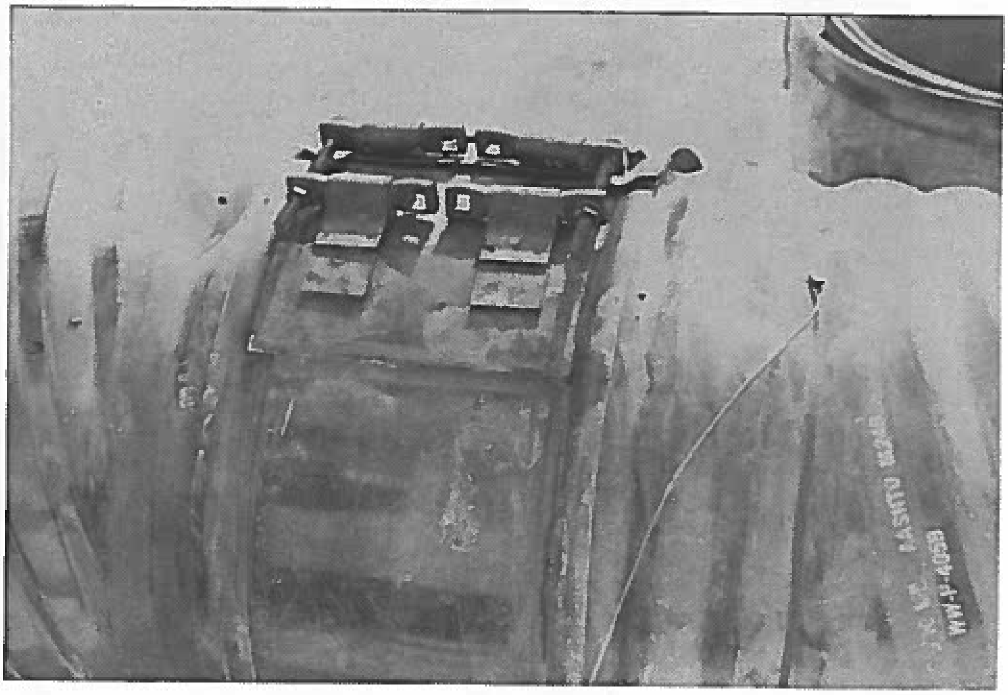

Figure 14. This shows the electrical connection made on the unprotected culvert.

Figure 15. The unprotected culvert is lowered into the ditch.

Figure 16. This is what the unprotected site looked like after the installation was completed.

DISCUSSION OF RESULTS

In the previous section of this report, three different methods of testing on culverts were described. The tests checked the effectiveness of coatings for use in cathodic protection and determined if culverts could be cathodically protected internally. The results of these tests are given below.

(1) EFFECTIVENESS OF COATINGS FOR CATHODIC PROTECTION

The two electrochemical tests described in the methodology section were run on pieces of culvert material to evaluate which is the best to use in conjunction with cathodic protection.

A. <u>Potentiostat Test</u>

This test reduced the potential on the 2-inch by 2-inch culvert test section by 300 mv below its open circuit value. The current required to do this was measured over a period of about six days. The resultant plot of current density versus time for the coated and non-coated culverts are shown in Appendix A. The average current density was determined by measuring the area under the curve and the coating effectiveness was determined by comparing the current density of the uncoated to the coated material. Table 1 gives these results for the 10 pieces of culvert material that were examined. It is believed that the percentage of coating effectiveness is a direct indication of which coatings would work best in the field.

It is evident from Table 1 that the aluminized culverts

TABLE 1

RESULTS OF THE POTENTIOSTAT TEST

Culvert Type	Ending Current Density (ma/ft^2)	Average Current Density (ma/ft^2)	% Coating* Effectiveness
Galvanized	57.7	53.0	0
Bituminous Galvanized	17.7	16.2	69
Polymeric Galvanized (Supplier 1)	15.6	17.2	68
Fiber-Bonded Bituminous	13.5	14.6	72
Asbestos-Bonded Bituminous	11.2	11.9	78
Aluminized Type II	6.8	7.5	0
Polymeric Aluminized Type II	0.9	1.7	77
Polymeric Aluminized Type I	1.4	1.9	75
Cold-Rolled Carbon Steel	10.0	17.0	0
Polymeric Cold-Rolled Steel	2.3	3.3	81

*% Coating Effectiveness is defined as

$$\frac{\text{Average Current Uncoated} - \text{Average Current Coated}}{\text{Average Current Uncoated}} \quad (100)$$

perform better than the galvanized materials. Also, the polymeric cold-rolled steel had the highest percentage of coating effectiveness showing a value of 81 percent. Among the galvanized group of culverts, the asbestos-bonded bituminous culvert performed best with the fiber-bonded bituminous coming in second.

B. <u>AC Impedance Test</u>

The AC impedance technique is useful in that it determines the overall resistance of the material to the corrosion process. The better the coating, the higher the resistance of the circuit. Since the resistance can be measured at any time during the run, it was decided to make an impedance run on each culvert one hour, 25 hours and 49 hours into the run. The impedance plots generated after 49 hours of testing are shown in Appendix B. The horizontal axis is where the value of the resistance (pore and charge transfer resistances) of these coatings can be obtained. Table 2 gives these resistance values for 10 different culverts.

The resistance of some of these coatings increased with time. For example, the resistance of fiber-bonded bituminous increased from 159 to 431 ohms within 48 hours. Also, the resistance of a polymeric aluminized Type I increased from 279 to 615 ohms within 48 hours. The polymeric cold-rolled steel showed a decrease in the resistance between 25 and 49 hours.

In general, a resistance increase was most likely caused by the calcareous deposits and magnesium compounds formed on the edges of the test sample, since these deposits block the pores in the coatings. These deposits serve as a semi-permeable membrane which

TABLE 2

RESISTANCE (Ω) AFTER 1, 25 AND 49 HOURS

Culvert	1 Hour Resistance	25 Hours Resistance	49 Hours Resistance
Galvanized	49	19	29
Bituminous Galvanized	116	160	221
Polymeric Galvanized (Supplier 1)	63	163	111
Fiber-Bonded Bituminous	159	356	431
Asbestos-Bonded Bituminous	306	430	438
Aluminized Type II	284	643	600
Polymeric Aluminized Type II	400	560	500
Polymeric Aluminized Type I	279	482	615
Cold-Rolled Carbon Steel	65	5	4
Polymeric Cold-Rolled Steel	60	162	136

stops oxygen and ions from getting to the substrate from the electrolyte. Initially, the edges of the test sample are exposed directly to the electrolyte. As a result, the edges contribute very little to the resistance; however, when the deposits start to accumulate on the edges, the current passing through the edges is reduced because of increasing resistance, and with time the edges contribute more resistance. In addition, the zinc coating on the steel forms an oxide (zinc oxide). The aluminum coating on the steel likewise forms aluminum oxide. These oxides provide additional resistances to the culverts.

The polymeric cold-rolled steel shows a resistance increase of 60 to 162 ohms within a 24-hour period, but later, it decreased from 162 to 136 ohms during the same time period. This decrease in resistance occurs because corrosion products of the iron do not provide any resistance compared with zinc and aluminum oxides. The AC impedance of the bare carbon steel without any coating was measured and the resistance decreased rapidly from 65 to 3.9 ohms within 49 hours after the sample was immersed in the electrolyte. By visual observation, the electrolyte in which the plain carbon steel was treated turned red indicating that the corrosion product was low resistance ferric oxide. As a result, the resistance of the carbon steel drops rapidly as it corrodes.

Based on this work, one would predict that the polymeric aluminized Type I should perform well, as should the other two aluminized products. Within the galvanized group, the asbestos-bonded bituminous is the best with the fiber-bonded coming in second.

The third laboratory method used to evaluate various coatings in conjunction with cathodic protection was the 13-gallon water tank test. In this test, seven different culvert materials were tested in 0.75 percent sea salt solution at 75° F. Three different tests were conducted on each of the culvert coupons and the results are given below.

a. Weight Loss Measurements of the Anode & Culvert Materials

During this two-week test, the anodes and cathodes were removed from the tank and weighed after the first and second week. Table 3 shows the percent weight loss of the magnesium anodes attached to seven culverts as well as the weight loss of the uncoupled magnesium.

The uncoupled magnesium lost 2.08 percent of its original weight after two weeks of testing. The magnesium connected to the aluminized steel lost 24.75 percent of its original weight, and the polymeric aluminized Type I and Type II culverts caused the magnesium to lose 11.42 percent and 12.21 percent, respectively. The galvanized steel produced an 11.8 percent weight loss of the magnesium, and the polymeric galvanized produced the lowest magnesium weight loss of only 5.24 percent. The fiber-bonded bituminous galvanized produced a 6.49 percent loss in the magnesium and the polymerized cold-rolled steel gave a 10 percent loss in magnesium. This test produced

TABLE 3

PERCENT WEIGHT LOSS OF MAGNESIUM ANODE IN 13-GALLON WATER TANK TEST

Coupled Material	Mg Anode, % Weight Loss 1st Week (%)	 2nd Week (%)	 Total (%)
1) Galvanized	6.21	5.59	11.80
2) Fiber-Bonded Bituminous	3.66	2.83	6.49
3) Polymeric Galvanized (Supplier 1)	2.40	2.84	5.24
4) Aluminized Type II	10.09	14.48	24.57
5) Polymeric Aluminized Type II	5.98	6.23	12.21
6) Polymeric Aluminized Type I	5.04	6.38	11.42
7) Polymeric Cold-Rolled	4.76	5.24	10.00
Mg Anode (Uncoupled)	1.10	0.98	2.08

good discrimination between coatings, and its results suggest that the polymeric galvanized is the best.

This same test was conducted using zinc as the anode material. The zinc weight loss has been determined in the same manner as the magnesium. Since it has a much smaller driving potential, the percentage of weight loss was much less. Table 4 shows what happened to the zinc during the two-week test period. The uncoupled zinc anode lost 0.15 percent of its weight after two weeks of testing. Two polymeric-coated aluminized steel samples, Type I and Type II, have lower zinc weight losses than that. This suggests that these materials may be protecting the zinc.

The actual percentage of weight loss of various culvert materials when coupled with magnesium and zinc are given in Table 5. Most of the coupons, coupled with the magnesium anode, have gained some weight as a result of precipitation of white scale on the edge of the coupon. The aluminized polymeric Types I and II showed a net weight loss.

The coupons coupled with zinc generally showed little weight loss or a gain in weight. The galvanized steel was the only coupon which was definitely not sufficiently protected by the zinc anode. The polymeric galvanized is seen to have gained some weight while Table 4 shows that it required very little zinc anode weight loss.

TABLE 4

PERCENT WEIGHT LOSS OF ZINC ANODE IN 13-GALLON WATER TANK TEST

Coupled Material	Zn Anode, % Weight Loss 1st Week (%)	2nd Week (%)	Total (%)
1) Galvanized	0.22	0.09	0.31
2) Fiber-Bonded Bituminous	0.08	0.08	0.16
3) Polymeric Galvanized (Supplier 1)	0.09	0.08	0.17
4) Aluminized Type II	0.16	0.13	0.29
5) Polymeric Aluminized Type II	0.06	0.01	0.07
6) Polymeric Aluminized Type I	0.01	0.08	0.09
7) Polymeric Cold-Rolled	0.08	0.12	0.20
Zn Anode (Uncoupled)	0.08	0.07	0.15

TABLE 5

COUPON WEIGHT LOSS COUPLED TO MAGNESIUM OR ZINC

Culvert Material	Coupon % Weight Loss		
	1st Week (%)	2nd Week (%)	Total (%)
A. With Mg			
1) Galvanized	0.0004	gain 0.05	gain 0.04
2) Fiber-Bonded Bituminous	0.04	gain 0.026	gain 0.16
3) Polymeric Galvanized (Supplier 1)	gain 0.005	gain 0.157	gain 0.16
4) Aluminized Type II	0.004	gain 0.240	gain 0.235
5) Polymeric Aluminized Type II	0.045	0.037	0.08
6) Polymeric Aluminized Type I	0.027	0.025	0.052
7) Polymeric Cold-Rolled Steel	0.004	gain 0.006	gain 0.002
B. With Zn			
1) Galvanized	0.24	0.23	0.50
2) Fiber-Bonded Bituminous	0.08	gain 0.05	0.025
3) Polymeric Galvanized (Supplier 1)	0.06	gain 0.12	gain 0.06
4) Aluminized Type II	0.01	gain 0.016	gain 0.006
5) Polymeric Aluminized Type II	gain 0.013	gain 0.006	0.018
6) Polymeric Aluminized Type I	0.016	gain 0.008	0.008
7) Polymeric Cold-Rolled Steel	0.008	0.007	0.016

b) Current Measurement

The current flowing between the culvert coupon and the magnesium anode was measured each day and is plotted on figures in Appendix C. There was no measurable current flow between the culvert coupon and zinc anode. Current flow is an indicator of the effectiveness of a coating, or the corrosivity of the culvert. An average culvert value over the 14-day test period is given below for each culvert coupled to magnesium.

Protected Culvert	Average Current (MA)	Current Density (MA/ft^2)
1) Galvanized	30	135
2) Polymeric Galvanized	15	68
3) Fiber-Bonded Bituminous	14	63
4) Aluminized Type II	62	279
5) Polymeric Aluminized Type II	27	122
6) Polymeric Aluminized Type I	24	108
7) Polymeric Cold-Rolled Steel	25	113

Coupon area = 0.222 ft^2

This table reveals that the two best coatings for cathodic protection are the polymeric galvanized or the fiber-bonded bituminous since they required the least amount of current. The aluminumized coupons are not protected by magnesium since local pH changes cause rapid attack of the aluminum coating.

c) Potential Measurements

The potentials of the culverts connected to magnesium and to zinc anodes are plotted versus time on figures located in Appendix D.

In all cases, the magnesium anode has produced a much lower potential than zinc. In general, the difference in potential has been around 300 mv.

Protected Culvert	Coupled with Zinc (V)	Coupled with Magnesium (V)
1) Galvanized	-1.010	-1.350
2) Polymeric Galvanized	-1.000	-1.410
3) Fiber-Bonded Bituminous	-1.020	-1.400
4) Aluminized Type II	-1.010	-1.310
5) Polymeric Aluminized Type II	-1.010	-1.350
6) Polymeric Aluminized Type I	-1.030	-1.400
7) Polymeric Cold-Rolled Steel	-1.000	-1.420

An interesting observation from the above data is that the metals which show the greatest negative potential shift should represent the best coated material. Of those coupled with the zinc anode, the polymeric aluminized Type I shows the most negative potential and the fiber-bonded bituminous came out second. Of the material protected with magnesium, and polymeric cold-rolled steel shows the most negative potential value and the polymeric galvanized steel came out second.

(2) RESULTS OF LABORATORY STUDY USING INTERNAL ANODES

The large water tank test was very important to prove that zinc anodes would provide cathodic protection inside of a 2-foot diameter culvert. The circulation system pumped water through each culvert so that its volume was displaced 45 times during a 24-hour period.

In all, there were nine culverts tested in this manner. The following testing order was used in this part of the study.

Culvert No.	Culvert Type
1	Fiber-Bonded Bituminous Galvanized Steel
2	Bituminous Galvanized Steel
3	Polymeric Galvanized Steel (Supplier 1)
4	Polymeric Galvanized Steel (Supplier 2)
5	Galvanized Steel
6	Polymeric Aluminized Type I Steel
7	Polymeric Aluminized Type II Steel
8	Aluminized Type II Steel
9	Polymeric Cold-Rolled Steel

A. Test Results

Internal potential measurements were made on the culverts each 24-hour period. The results of these one-month tests are presented in figures in Appendix E. The potential of the culvert while connected to the anode was measured as well as its potential two hours after being disconnected from the anode. The amount of current required to shift the potential of each culvert is given in figures in Appendix F. Table 6 shows the ending voltage and current values of these culverts tested in the large tank. The fiber-bonded bituminous galvanized steel showed the largest potential difference of 0.245V while drawing 10 ma of current from the anode. The galvanized culvert only shifted 0.002V and drew 1 ma of current. All of the polymeric materials showed relatively low current draw, always less than 4 ma. The worst material appears to be the bituminous since it drew 44 ma and showed a potential difference of 0.152V.

The potential difference between the closed-circuit value and the open-circuit value (after two hours) is very important since it shows which culverts depolarize fastest. Rapid depolarization is generally an indication of a poor coating. The results in

TABLE 6

ENDING POTENTIAL AND CURRENT VALUES FOR THE LARGE WATER TANK TEST

Culvert	Open Circuit* Potential, V	Closed Circuit Potential, V	Potential Difference, V	Current ma
Fiber-Bonded Bituminous	-0.760	-1.005	0.245	10
Bituminous Galvanized	-0.808	-0.960	0.152	44
Polymeric Galvanized (Supplier 1)	-1.008	-1.055	0.047	4
Polymeric Galvanized (Supplier 2)	-0.962	-1.032	0.070	4
Galvanized	-1.064	-1.066	0.002	1
Polymeric Aluminized Type I	-0.885	-1.060	0.175	3
Polymeric Aluminized Type II	-0.900	-1.063	0.163	3
Aluminized Type II	-0.852	-1.008	0.156	17
Polymeric Cold-Rolled Steel	-0.913	-1.034	0.121	4

*Open circuit potential values were measured two hours after being disconnected from the zinc anode.

Table 6 suggest that the two polymeric galvanized culverts should provide the best coating system to be used in conjunction with cathodic protection. In general, all of the closed-circuit potential values are well below the -0.85V value required to protect the steel beneath the coating. The average open circuit potential of the zinc anodes used in this study was -1.093V versus a copper-copper sulfate reference electrode.

B. <u>Culvert Condition After Testing</u>

Upon removal from the water tank, each culvert was photographed and visually examined for its overall condition. the following discussion describes each culvert.

1) <u>Fiber-Bonded Bituminous Galvanized Steel</u>. Figures 1-4 in Appendix G show the condition of this culvert immediately after the test. White deposits can be seen on the exposed areas and some rust deposits were noted on the bottom of the culvert. There is evidence of some disbondment occurring at the end of the culvert. The fibers appear to hold the bituminous material to the culvert fairly well.

Generally, it was found that the culvert is in good condition. The only disbondment occurred on the edge and was limited. There was white powder on about 2 percent of the surface at the bolts, bands, and damaged areas. Using the criteria of 1 being the worst and 10 being the best condition possible, this culvert received a rating of 8.0.

2) Bituminous Galvanized Steel. Figures 5-9 in Appendix G show the condition of this culvert after testing. An overall view of the outside of the culvert shows a very substantial amount of white powder deposits on the outside and the inside of the culvert. No rust spots are visible on the culvert.

Generally, it appears that the culvert was well protected since no visual attack can be seen. White scale covered about 10 percent of the culvert surface area. There are localized signs of the bituminous peeling off after being saturated with water. The overall rating of the culvert is 5.5.

3) Polymeric Galvanized Steel (Supplier 1). Figures 10-13 in Appendix G show the condition of this culvert immediately after testing. There is only a small amount of white scale which suggests that the polymer coating was effective. A close-up view of the inside of this culvert shows some rust at the bottom of the ridges. The rust appears to be superficial, perhaps from steel particles on the surface.

There appears to be some corrosion occurring under the coating, especially around the edges. In general, the coating is held tightly. The outside of the culvert is in very good condition. Overall rating on this coating is 7.0.

4) Polymeric Galvanized Steel (Supplier 2). Figures 14-17 in Appendix G show the condition of this culvert after testing. In general, the outside of the culvert showed some rust, but not as much as was seen in culvert No. 3. Most of the inside

deposits appear to be sediments on the surface, but there are obvious corrosion products inside the ridges.

The overall conditions of the culvert was good. The coating is seen to be very adherent. The overall rating is 7.5.

5) Galvanized Steel. Figures 18-20 in Appendix G show the condition of this culvert after testing. A close-up of the outside of culvert shows some attack of the bare zinc. It is obvious that some scales have formed on the inside of the culvert, and there is evidence of light attack of the zinc on the inside.

About 10 percent of the galvanizing on the main body of the culvert is gone. At the ends of the culvert, more galvanizing is gone. Generally, the corroding areas are covered with white scale. Overall rating of the culvert is 5.0.

6) Polymeric Aluminized Type I. Figures 21-23 in Appendix G show this culvert after one month of testing. In general, the culvert looks good with very little corrosion on the outside. The inside of the culvert is in good condition, with some specks of rust. The rust spots washed off easily with no evidence of corrosion.

In general, this culvert is in very good condition. There is some rust on one of the cut edges and white powder has formed on the outside. The overall condition is a 9.5.

7) Polymeric Aluminized Type II. Figures 24-28 in Appendix G show this culvert after testing. A close-up of the outside shows the culvert to be generally in good condition.

The inside of the culvert is seen to contain a large number of rust spots.

Generally, there is some rusting, especially where the culvert has been cut. Overall the culvert condition is a 7.0.

8) <u>Aluminized Type II</u>. Figures 29-32 in Appendix G show this culvert after the one month of testing. There is some external attack. An inside view of the culvert shows that there is a small amount of attack.

From an overall view, there is a small amount of peeling that occurred on the culvert, inside and out. However, it is generally in good condition. The overall rating is a 7.0.

9) <u>Polymeric Cold-Rolled Steel</u>. Figures 33-36 in Appendix G show this culvert after testing. Corrosion can be noted on the upper edge that was not in the water and did not receive any protection. In general, the outside of this culvert looks good. There is white powder wherever the coating is damaged. The inside of the culvert is in good shape and some white scale has formed.

The overall condition of the culvert is good, and it receives a rating of 8.5. This shows that steel without galvanizing can be well protected with zinc.

Based on these visual examinations after testing, it is possible to rank the culverts. Table 7 gives the assigned rating values, and it appears that the culvert in the best condition after

TABLE 7

CULVERT VISUAL RATING AFTER THE LARGE WATER TANK TEST

Culvert	Visual Rating *
Fiber-Bonded Bituminous Galvanized	8.0
Bituminous Galvanized	5.5
Polymeric Galvanized (Supplier 1)	7.0
Polymeric Galvanized (Supplier 2)	7.5
Galvanized	5.0
Polymeric Aluminized Type I	9.5
Polymeric Aluminized Type II	7.0
Aluminized Type II	7.0
Polymeric Cold-Rolled Steel	8.5

*The ratings are 1 to 10 with 1 being the worst and 10 the best.

testing was the polymeric aluminized Type I with the polymeric cold-rolled steel coming in second. The two culverts that were in the worst condition after testing were the galvanized steel and the bituminous galvanized steel.

Although the white powder on the culverts was not analyzed, it is obvious that its existence at points of exposure is proof that the culvert is being cathodically protected. It is also believed that the rust seen in the bottom of some protected culverts is from steel particles removed during cutting of the culverts. A jigsaw was used and the specks of steel on the surface of the polymer coating were not cathodically protected because they were insulated from the zinc anode due to the coating.

(3) RESULTS OF FIELD STUDY

Since installation on June 13 and 14, 1989, the test site has been visited on 15 different occasions. Measurements of the resistivity of the water has been made on ten of these occasions and a tabulation of these data is in Table 8. It can be seen that the values appear somewhat cyclic and range between 140 and 1170 Ω-cm. In general, the resistivities of the two sites tend to follow each other. The soil resistivities were 428 Ω-cm for the protected site and 370 Ω-cm for the unprotected site. These soil values are not expected to change with time. During installation, samples of water were also tested for chloride and pH, yielding 7.7 pH and 0.22 percent Cl^- at the protected site, and 7.3 pH and 0.22 percent Cl^- at the unprotected site.

Measurements of the potential of the protected and unprotected

TABLE 8

RESISTANCE READINGS AT FIELD TEST SITES

(Ω-cm)

		Site 1 (Protected)		Site 2 (Unprotected)	
Date	Day	Soil	Water	Soil	Water
June 13, 1989	0		140		160
June 30, 1989	17		220		190
September 30, 1989	109	428	432	370	585
November 30, 1989	170		655		945
March 30, 1990	290		825		790
May 30, 1990	351		488		475
August 31, 1990	444		280		310
November 31, 1990	535		140		180
February 28, 1991	625		613		1170
June 13, 1991	730		815		712
Average Resistivity		428	460	370	552

culverts have been made on both the inside and outside of the culvert during each visit. The figures that show these results are given in Appendix H. Tables 9 and 10 show the potential values of the protected and unprotected culverts and the voltage difference that existed between these two numbers on June 13, 1991. The larger this potential difference, the more the structure is protected. From this information, the polymeric galvanized steel appears to have experienced the greatest potential shift. In fact, all of the polymeric coatings appear to be very well protected. The fiber-bonded bituminous and and bituminous galvanized culverts show much less shift. This suggests that these culverts have few holidays (holes in the coating), and they are primarily being attacked on the ends where galvanizing is present.

It takes current from the internal and external anodes to maintain the potential differences shown in Tables 9 and 10. Appendix I shows a tabulation and graphs of the current measurements that were made during the 15 visits since the installation. Table 11 shows some recently obtained current values for the eight culverts in the field. The two polymeric galvanized culverts require the least amount of current and appear to be performing the best. The galvanized culvert requires substantially more current to be protected than any of the other culverts.

The average current values were calculated using data from during the past 15 visits. Table 12 lists these average values of current for the outside and inside of each culvert. The total current values show that the polymeric galvanized steel is

TABLE 9

INTERNAL POTENTIAL READINGS MADE ON JUNE 13, 1991

Culvert	Protected Potential, Volts	Unprotected Potential, Volts	Difference Volts
Polymeric Cold-Rolled Steel	-1.052	-0.651	0.401
Polymeric Aluminized Type II	-1.057	-0.662	0.395
Polymeric Aluminized Type I	-1.067	-0.690	0.377
Polymeric Galvanized Steel (Supplier 1)	-1.077	-0.661	0.416
Polymeric Galvanized Steel (Supplier 2)	-1.069	-0.731	0.338
Bituminous Galvanized Steel	-1.063	-0.965	0.098
Galvanized Steel	-1.027	-0.931	0.096
Fiber-Bonded Bituminous Galvanized Steel	-1.052	-0.775	0.276

TABLE 10

EXTERNAL POTENTIAL READINGS MADE ON JUNE 13, 1991

Culvert	Protected Potential, Volts	Unprotected Potential, Volts	Difference Volts
Polymeric Cold-Rolled Steel	-1.055	-0.662	0.393
Polymeric Aluminized Type II	-1.066	-0.662	0.404
Polymeric Aluminized Type I	-1.075	-0.689	0.386
Polymeric Galvanized Steel (Supplier 1)	-1.076	-0.666	0.410
Polymeric Galvanized Steel (Supplier 2)	-1.076	-0.734	0.342
Bituminous Galvanized Steel	-1.059	-0.945	0.114
Galvanized Steel	-1.001	-0.909	0.092
Fiber-Bonded Bituminous Galvanized Steel	-1.045	-0.766	0.279

TABLE 11

CURRENT MEASUREMENTS MADE ON JUNE 13, 1991

Culvert	Outside Current ma	Inside Current ma	Total Current ma
Polymeric Cold-Rolled Steel	60	11	72
Polymeric Aluminized Type II	48	15	63
Polymeric Aluminized Type I	38	12	50
Polymeric Galvanized Steel (Supplier 2)	20	8.5	28.5
Polymeric Galvanized Steel (Supplier 1)	30	16	46
Bituminous Galvanized Steel	41	17	58
Galvanized Steel	100	28	128
Fiber-Bonded Bituminous Galvanized Steel	49	10	59

TABLE 12

AVERAGE CURRENT VALUES ON CULVERTS*

Culvert	Outside Current ma	Inside Current ma	Total Current ma
Polymeric Cold-Rolled Steel	84	21	105
Polymeric Aluminized Type II	66	17	83
Polymeric Aluminized Type I	38	14	52
Polymeric Galvanized Steel (Supplier 2)	22	10	32
Polymeric Galvanized Steel (Supplier 1)	31	16	47
Bituminous Galvanized Steel	38	12	50
Galvanized Steel	42	13	55
Fiber-Bonded Bituminous Galvanized Steel	66	16	82

*This is the average of 15 readings.

performing the best. The internal current requirements of all the culverts are fairly close in magnitude. They range from 10 to 21 ma. The outside current requirements are much larger values and they range from 22 to 84 ma. These high external corrosion currents are somewhat of a surprise since at the start of the project, it was unclear where the major corrosion action on a culvert was occurring.

These preliminary results show that in general the current requirements to protect any of the culverts is reasonable. To prove this point, the following calculation has been performed.

Calculate the pounds of zinc required to protect a 24-inch, 10-foot bituminous galvanized culvert, inside and outside, for 25 years. From Table 12 the average current requirement for a bituminous culvert is 50 ma. Therefore,

Zinc required = (0.050 amps) (25 yrs) (25# zinc/amp yr) = 31#

A 30-foot culvert would require three times this amount or 93 pounds of zinc, and if you wanted to protect this 30-foot culvert for 50 years instead of 25 years, it would require twice as much zinc or 186 pounds. If the polymeric galvanized culvert would be used, this requirement would be reduced by about one-third because of the lower current requirement. One estimate of the materials cost of installing a culvert in the Pecan Island area is $85/foot and the culverts in that region have historically lasted for 25 years. Installation of the anodes required to protect these culverts for 50 years would cost approximately $1000 and the culverts would be in like-new condition. This compares to two replacements of the culvert by DOTD at an estimated present value cost of $2,600 This calculation assumes a 6% inflation rate and 8% interest rate over that time period and illustrates that cathodic protection on culverts appears economically feasible.

CONCLUSIONS

- All culverts in the field have successfully responded to both internal and external cathodic protection.
- All coated culverts can be economically protected by cathodic protection. A calculation made on bituminous coatings shows that it would require 186 pounds of zinc to completely protect a 24-inch diameter by 30-foot length culvert for 50 years. This can be done at an estimated installed cost of $1,000. After the project is completed, more conclusive economics can be obtained.
- Based on measurements made after two years of exposure, it can be said that the polymeric galvanized coated culvert is requiring the least amount of current for protection. The bituminous culverts require more current than the polymeric galvanized culvert, but only one-half as much as the bare galvanized culvert.
- The unprotected culverts in the field are losing whatever protection they may have had from their galvanized or aluminized coatings, and they are experiencing corrosion. This is known to be true since the potentials of the culverts are more positive than the -0.85V potential value required for protection.
- Internal current requirements are lower than external values because there was less coating damage to the inside during installation and the natural soil stresses are causing coating damage on the outside of the culverts.

- Even though the resistivity of the water at the protected culvert site varied from 140 to 825Ω-cm, it was still easy for the zinc anodes to protect the culverts.
- The field study has showed that a culvert disconnected from the anode can be readily identified. After reconnection to the anode, the potential and current values return to normal almost immediately.
- The 30-day water tank test demonstrated that the culverts could be cathodically protected in the laboratory. All of the closed circuit potentials were more negative than the -0.85V potential required for protection.
- The large water tank proved that the polymeric galvanized culverts would not very readily depolarize and would have a low current draw.
- Visual examination of the culverts after the 30-day test showed that the fiber-bonded bituminous culvert and the polymeric cold-rolled steel showed the least effect of corrosion. The galvanized steel culvert and bituminous galvanized culvert suffered the worst corrosion attack.
- The 13-gallon water tank that used magnesium and zinc anodes to determine coating effectiveness appears to hold some promise for evaluating galvanized coatings.
- Aluminum type culverts should not be used in conjunction with magnesium anodes since the generated alkali causes increased corrosion.
- The potentiostat test and AC impedance test do not appear to

properly predict which coating would perform best in the field. The tests did predict the polymeric aluminized Type I as a good prospect, but rated the polymeric galvanized very low.

RECOMMENDATIONS

- This project has shown that new 24-inch diameter culverts can be cathodically protected in Pecan Island at a reasonable cost.
- It is necessary to know how many culverts in Louisiana are candidates for cathodic protection and what effect the variable soil and water resistivities have on the economics of its installation.
- It would be beneficial to have a survey on metal culverts under state highways that are south of I-10. The survey should include the culvert dimensions, the resistivity of the soil and water in the area and if electrical conductivity exists across the entire length of the culvert.
- Based on this survey, representative culverts can be selected for retrofit to determine the economical feasibility of installing cathodic protection on existing systems. These results will provide the basis for installation throughout the state.
- Because of the positive nature of the results of this report, it is recommended that the Department of Transportation begin to electrically connect culvert sections in new installations. This inexpensive procedure will facilitate the installation of cathodic protection when it is needed.

REFERENCES

1. Temple, W. H., Cumbaa, S. L. and Gueho, B. J., "Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation," Report No. FHWA/LA-85/174, Louisiana Transportation Research Center, March 1985.

2. "Control of External Corrosion on Underground or Submerged Metallic Piping Systems," National Association of Corrosion Engineers (NACE), Standard RP-01-69, Houston, Texas.

3. Jensen, F. Q. and Tems, R. D., "Internal Cathodic Protection of Cement-Lined Steel Pipes," NACE Corrosion 88, Paper 25, St. Louis, Missouri, 1988.

4. Groover, R. E. and Peterson, M. H., "Cathodic Protection of Internal Surfaces of Pipes Containing Sea Water," Materials Performance, November 1984, pp. 24-29.

5. MacKay, W. B. and Grace, L. R., "Cathodic Protection of Pipeline Internals," Proceedings of the 4th International Congress on Marine Corrosion and Fouling, Antibes, 1976, p. 345.

6. Simpson, V. P. and Robinson, R. C., "Experimental Studies Relate Effect of Cathodic Protection with Certain Generic Coating Systems," Offshore Technology Conference, Paper 3857, 1980.

Appendix A

Potentiostat Test Current Versus Time

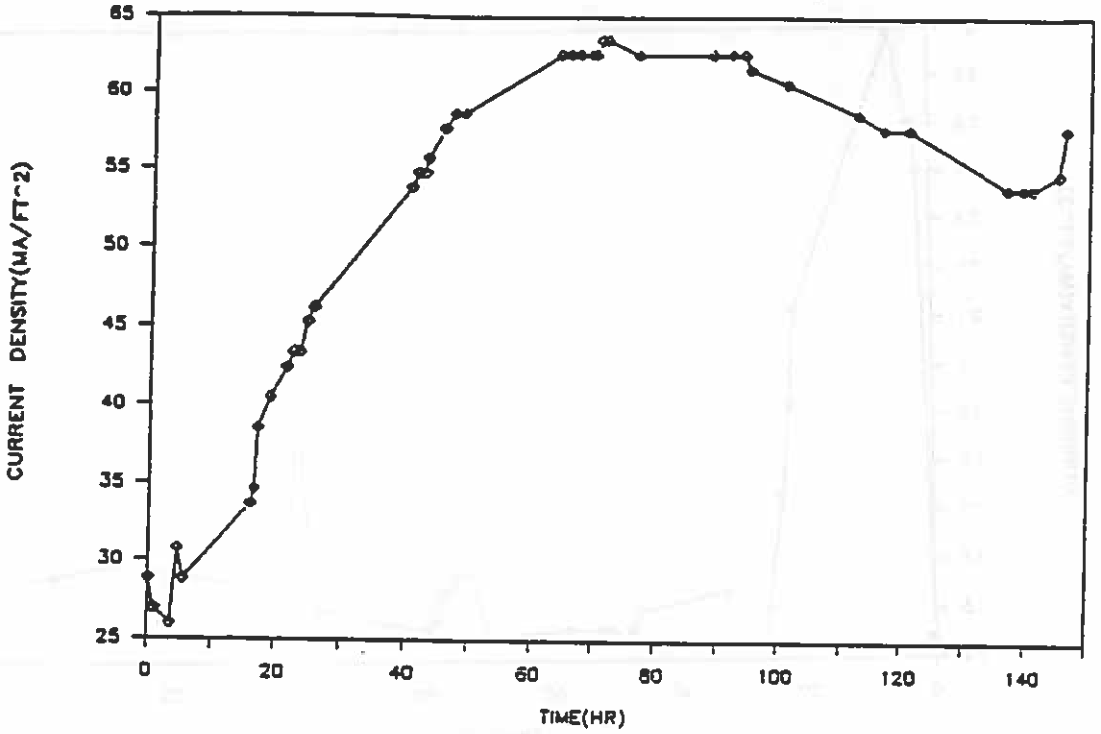

Figure A-1. Potentiostat test results on galvanized steel.

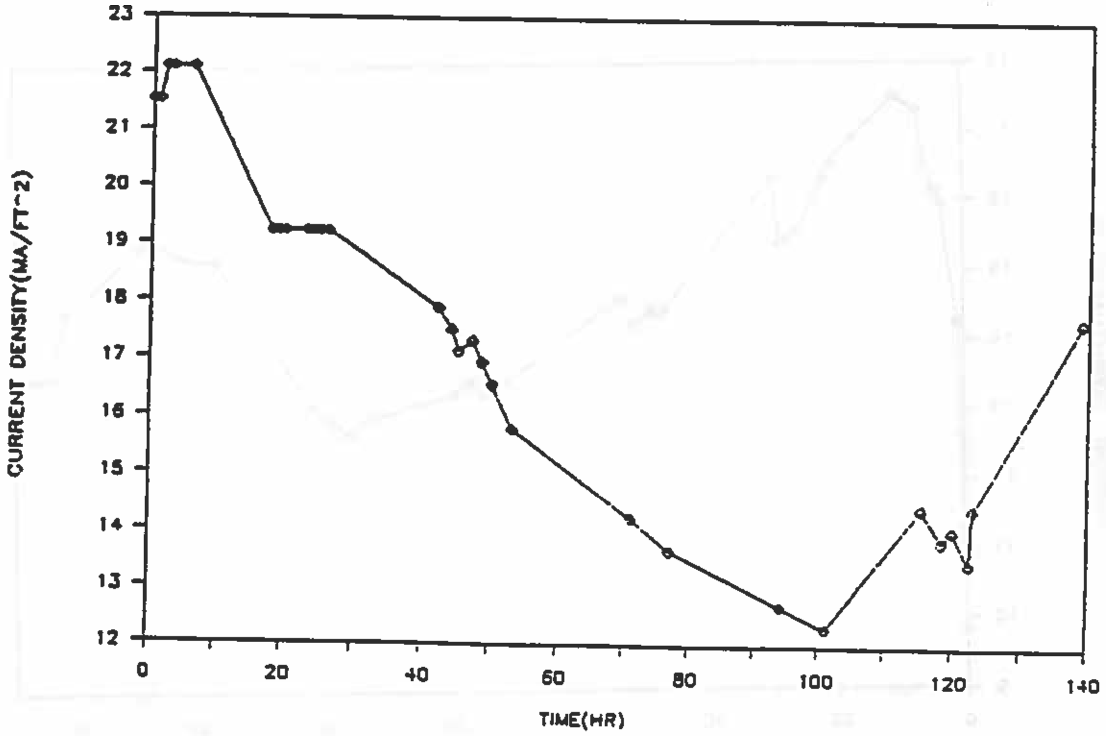

Figure A-2. Potentiostat test results on bituminous galvanized steel.

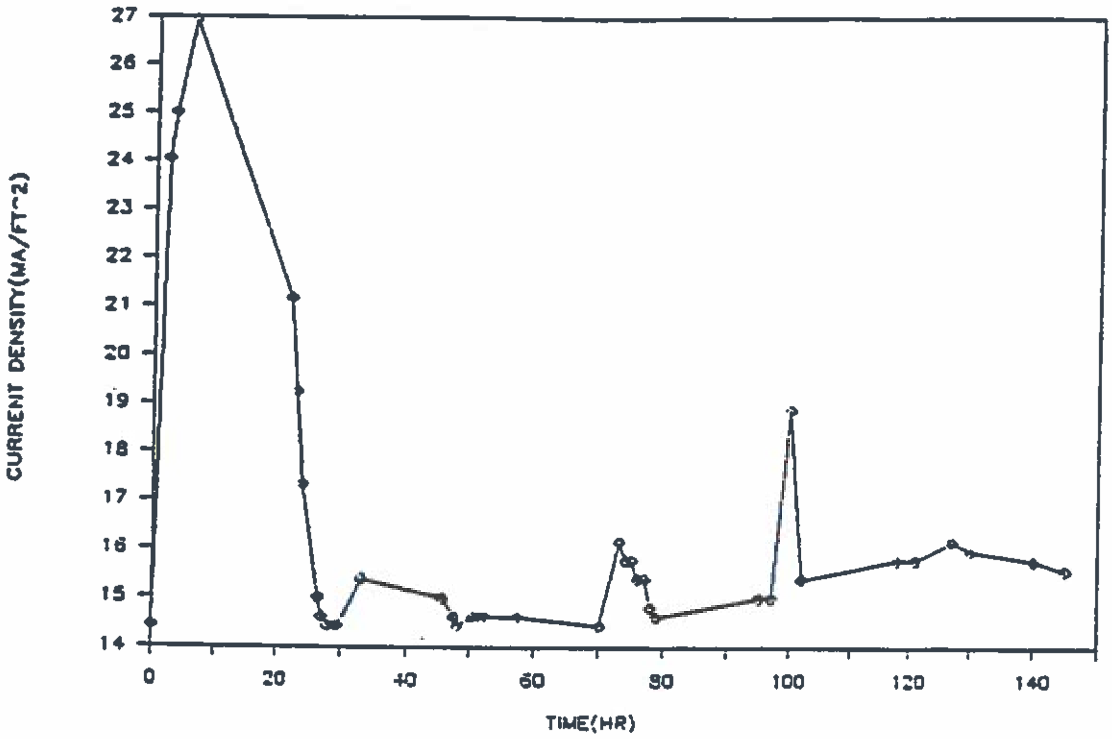

Figure A-3. Potentiostat test results on polymeric galvanized steel.

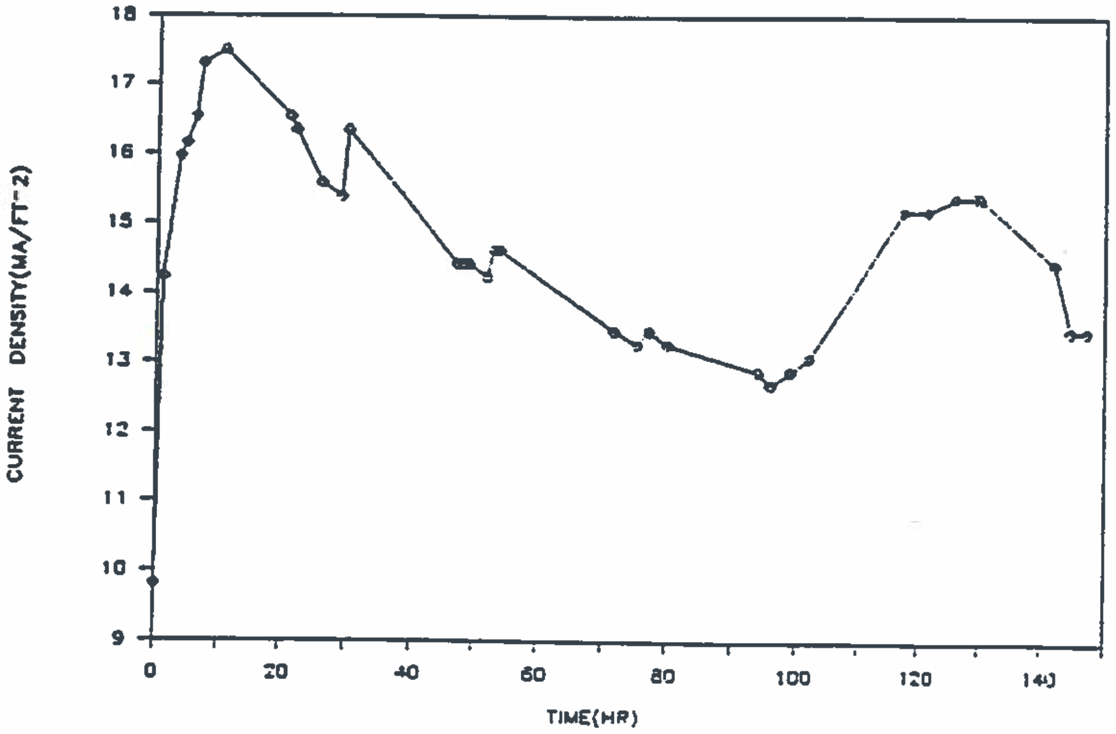

Figure A-4. Potentiostat test results on fiber-bonded bituminous galvanized steel.

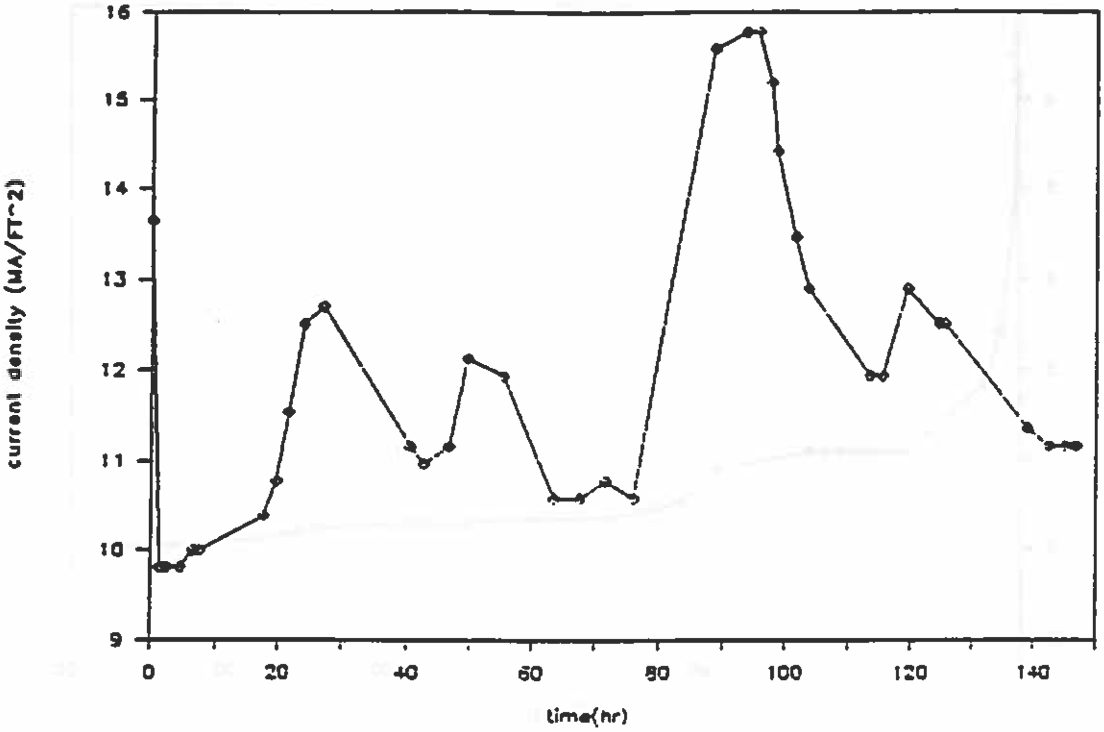

Figure A-5. Potentiostat test results on bituminous asbestos-bonded galvanized steel.

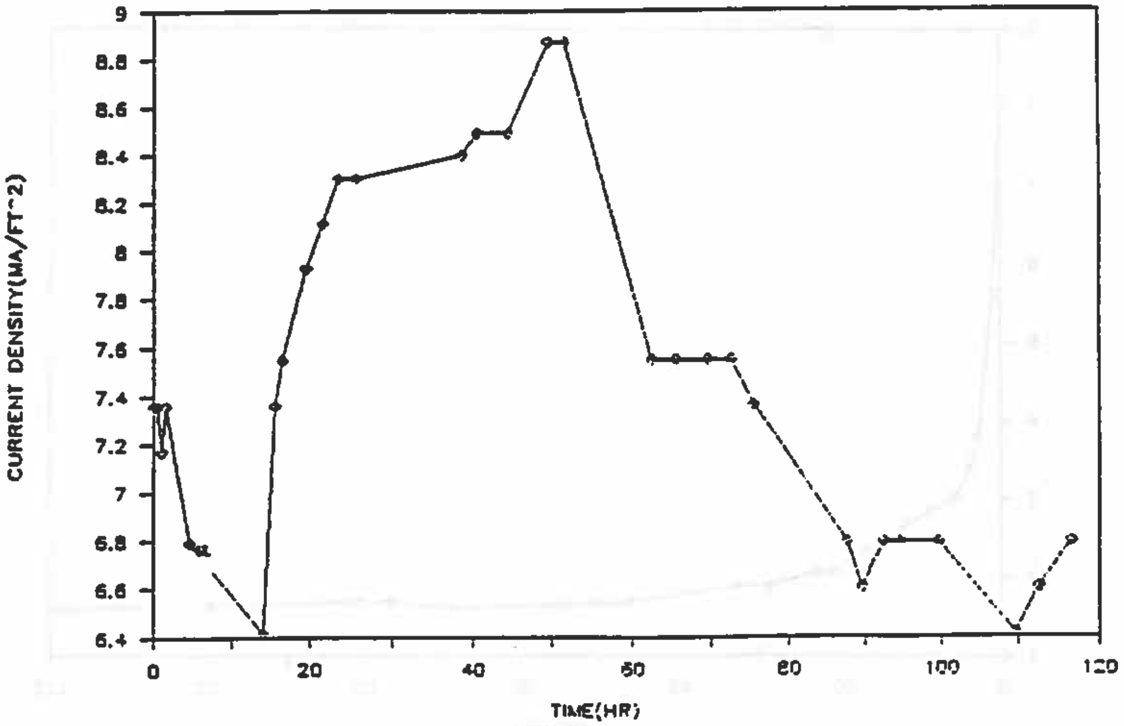

Figure A-6. Potentiostat test results on aluminized Type II.

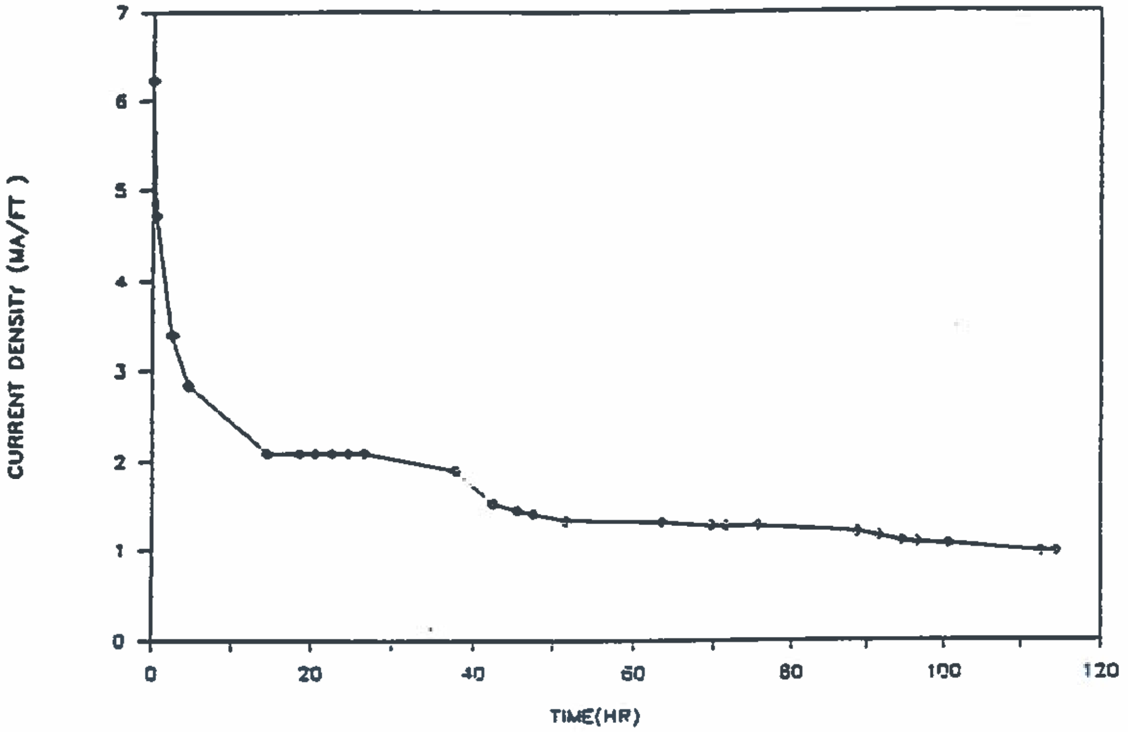

Figure A-7. Potentiostat test results on polymeric aluminized Type II.

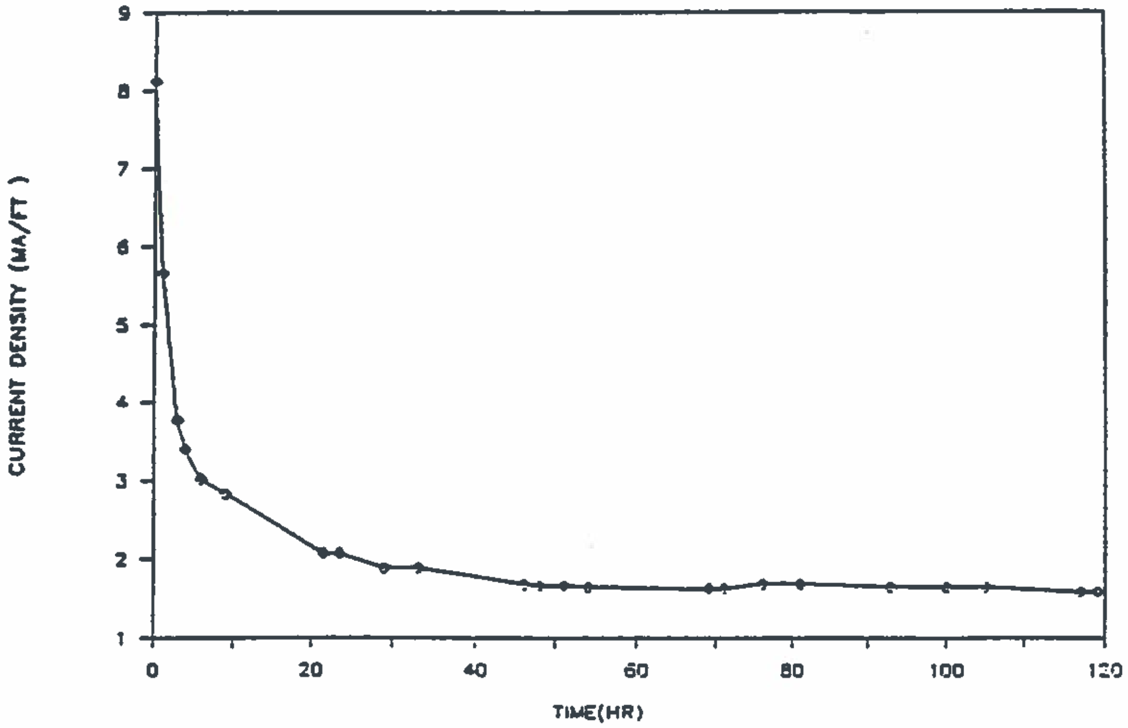

Figure A-8. Potentiostat test results on polymeric aluminized Type I.

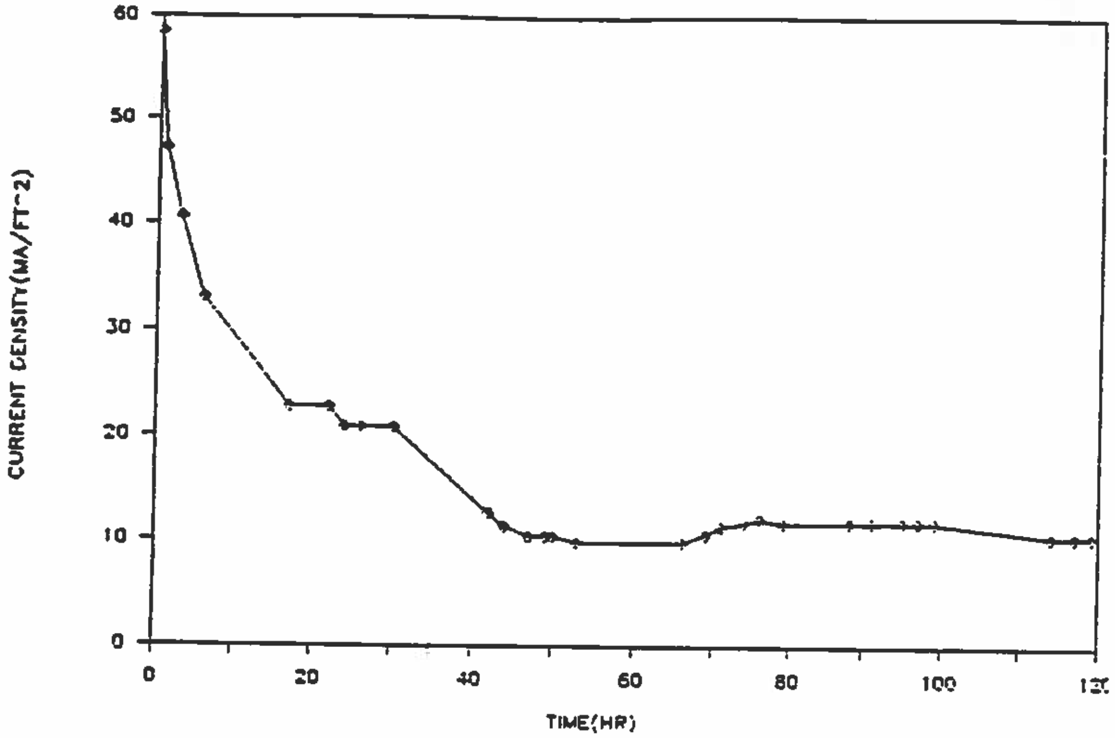

Figure A-9. Potentiostat test results on uncoated carbon steel.

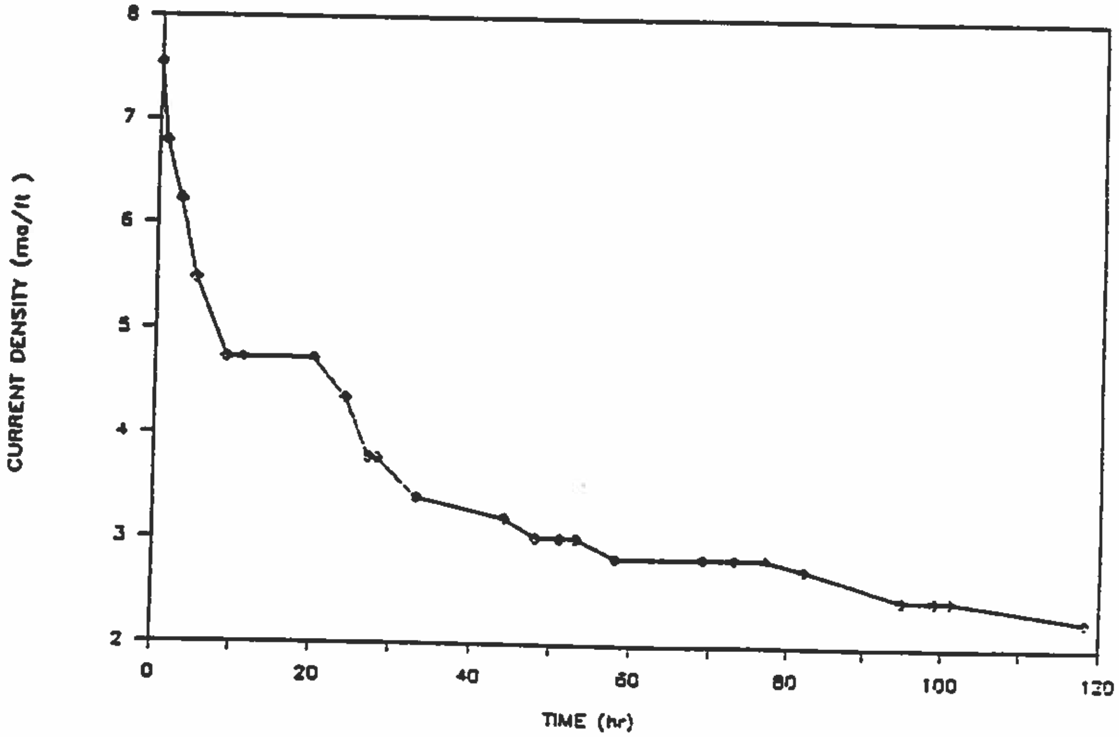

Figure A-10. Potentiostat test results on polymeric cold-rolled steel.

Appendix B

AC Impedance Test Results After 48-Hours

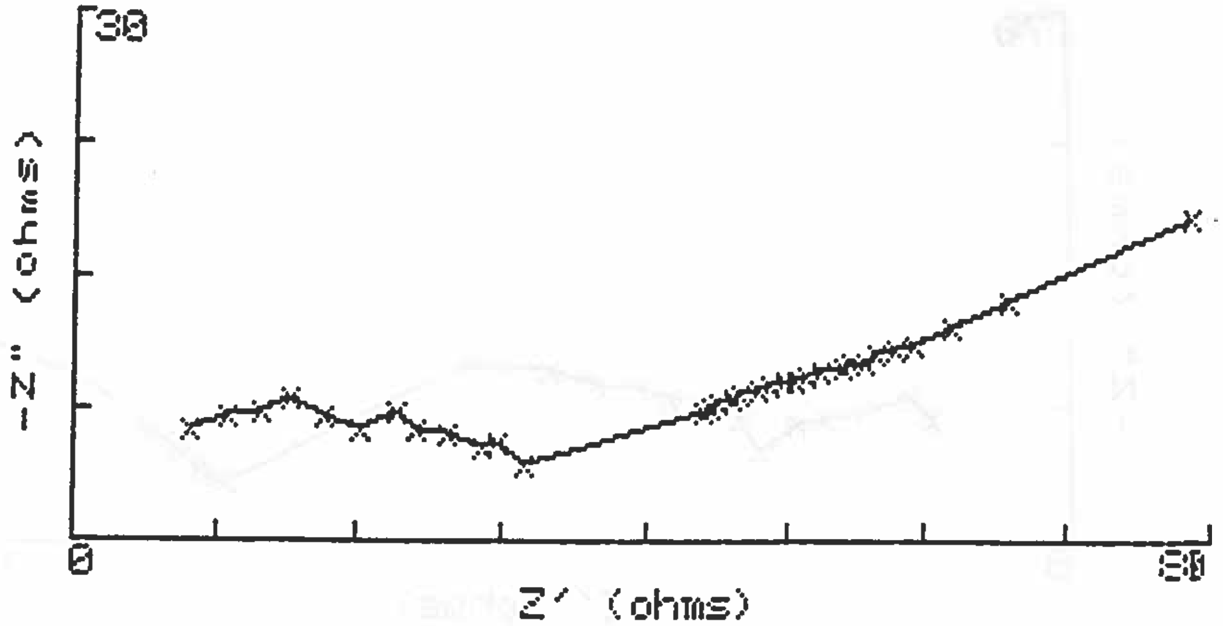

Figure B-1. Galvanized steel impedance plot.

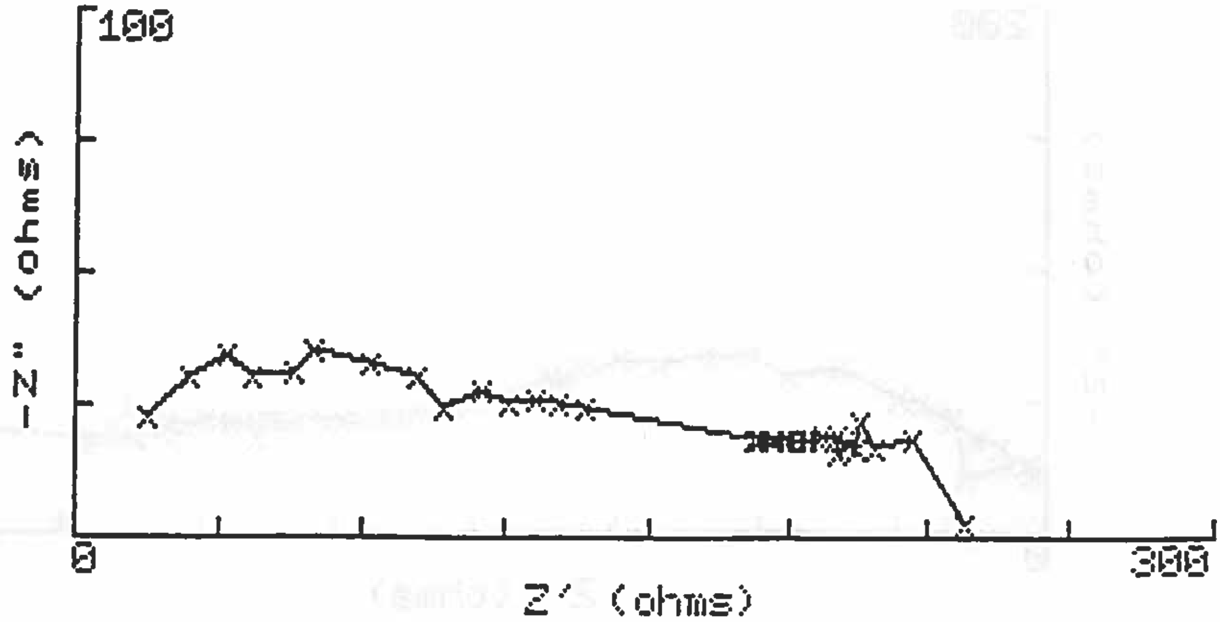

Figure B-2. Bituminous galvanized steel impedance plot.

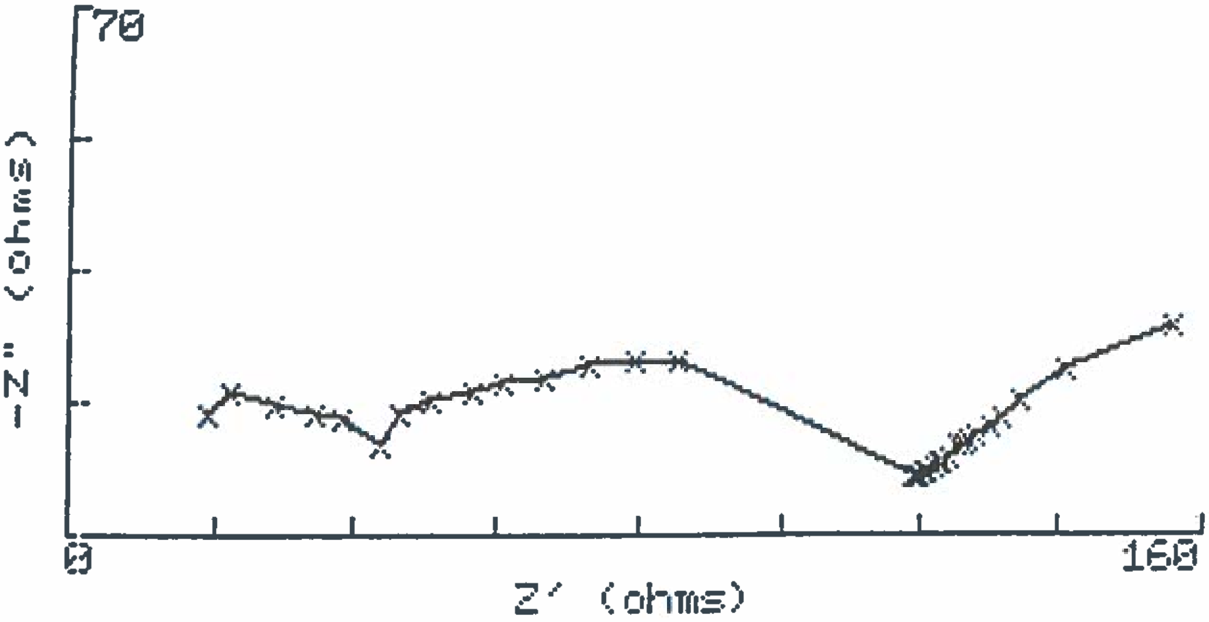

Figure B-3. Polymeric galvanized steel (Supplier 1) impedance plot.

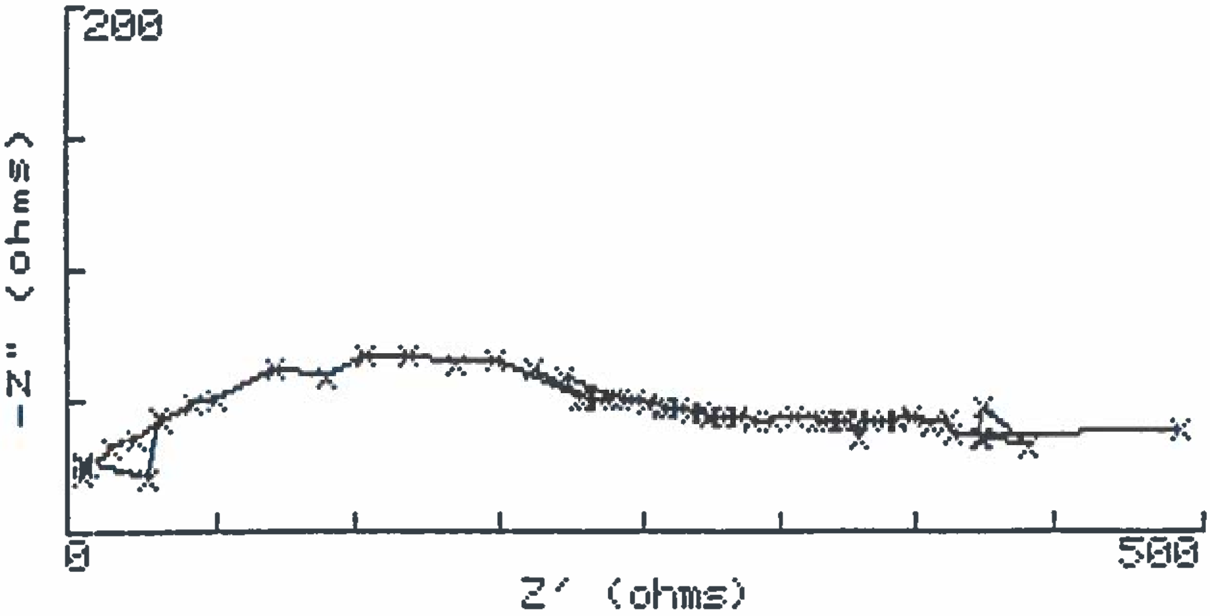

Figure B-4. Fiber-bonded bituminous galvanized steel impedance plot.

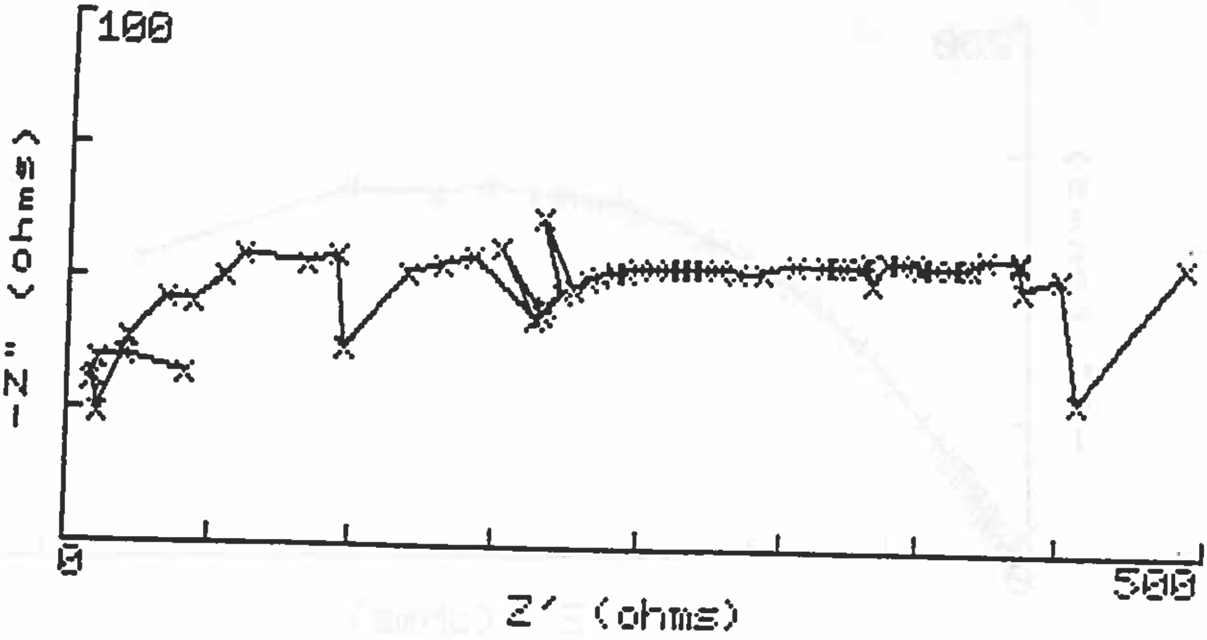

Figure B-5. Asbestos-bonded bituminous galvanized steel impedance plot.

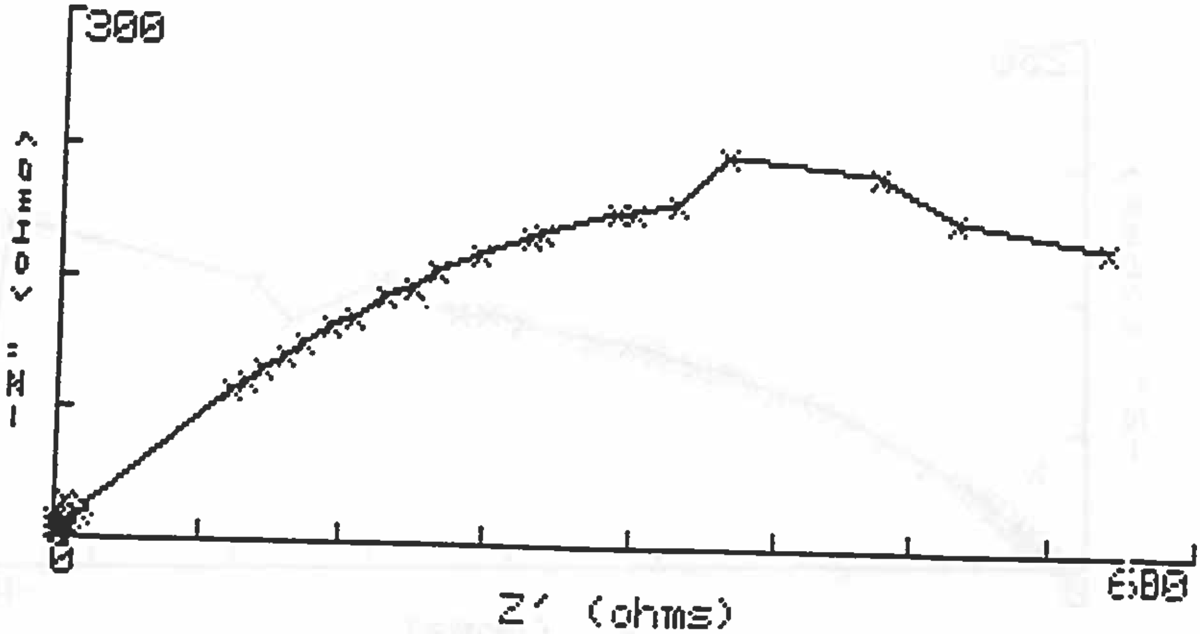

Figure B-6. Aluminized Type II impedance plot.

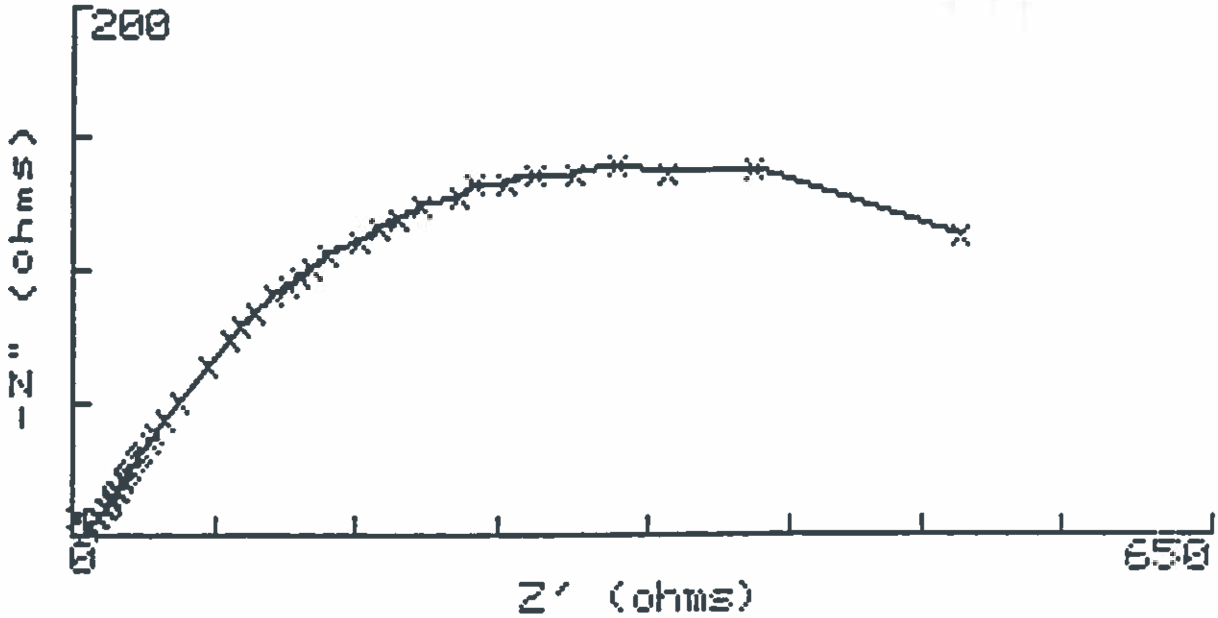

Figure B-7. Polymeric aluminized Type II impedance plot.

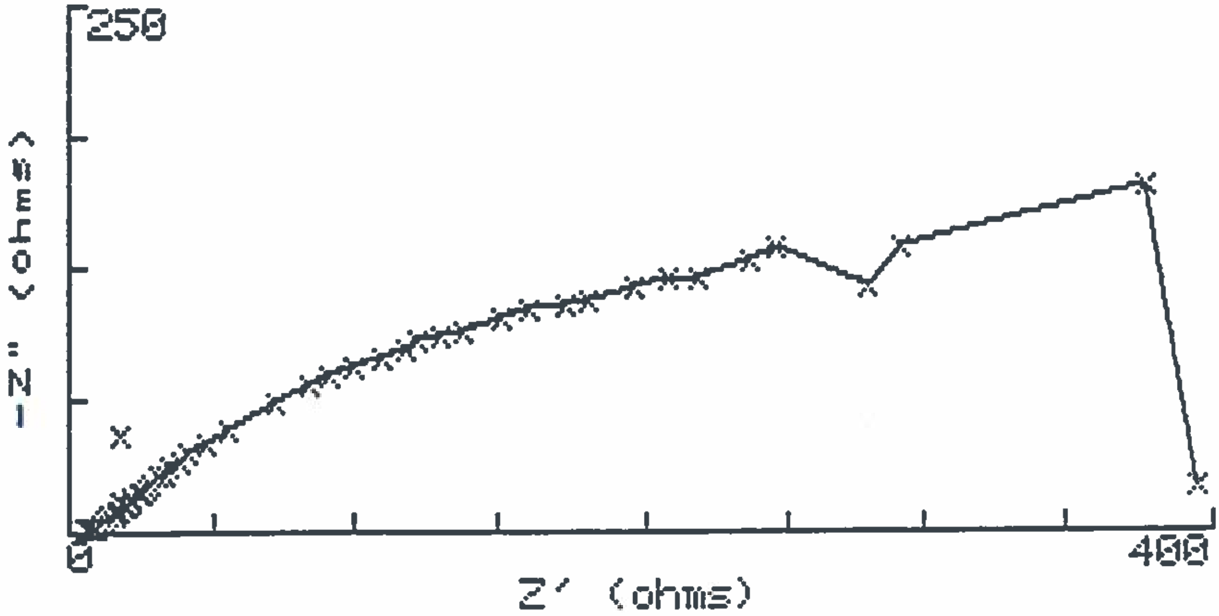

Figure B-8. Polymeric aluminized Type I impedance plot.

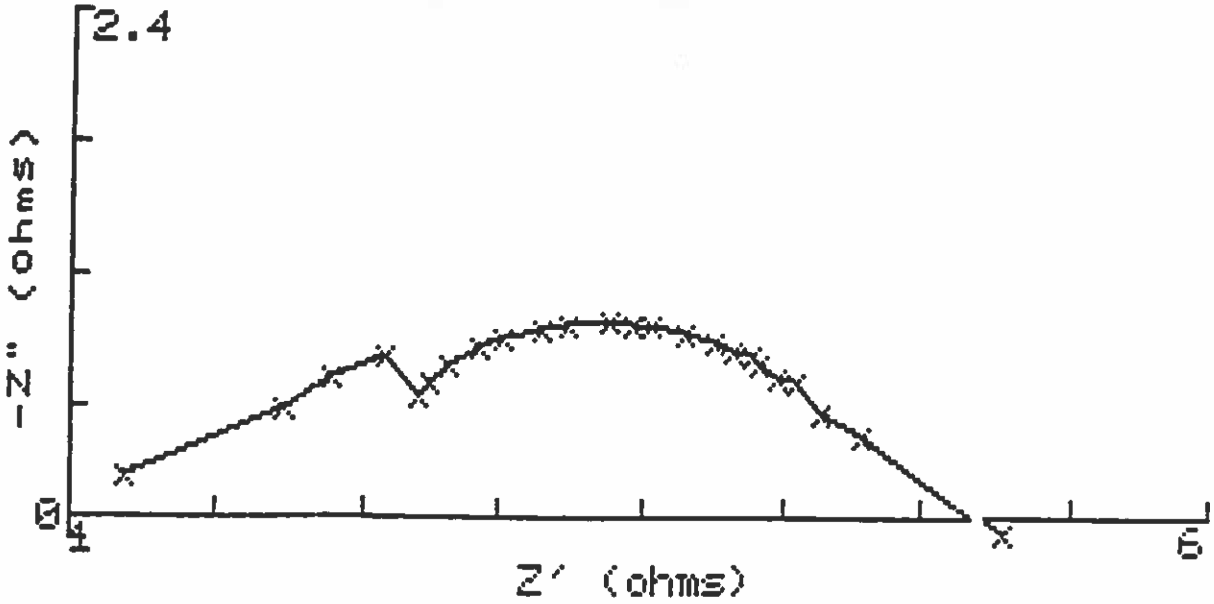

Figure B-9. Carbon steel impedance plot.

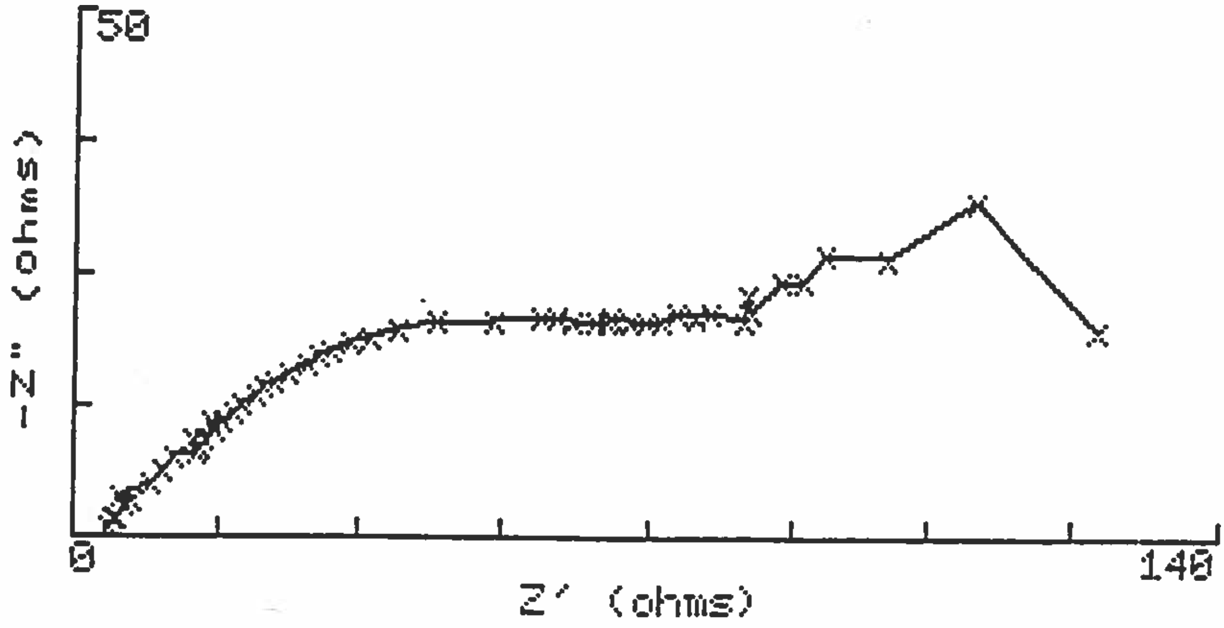

Figure B-10. Polymeric cold-rolled steel impedance plot.

Appendix C

Thirteen (13) Gallon Water Tank Test Current Versus Time

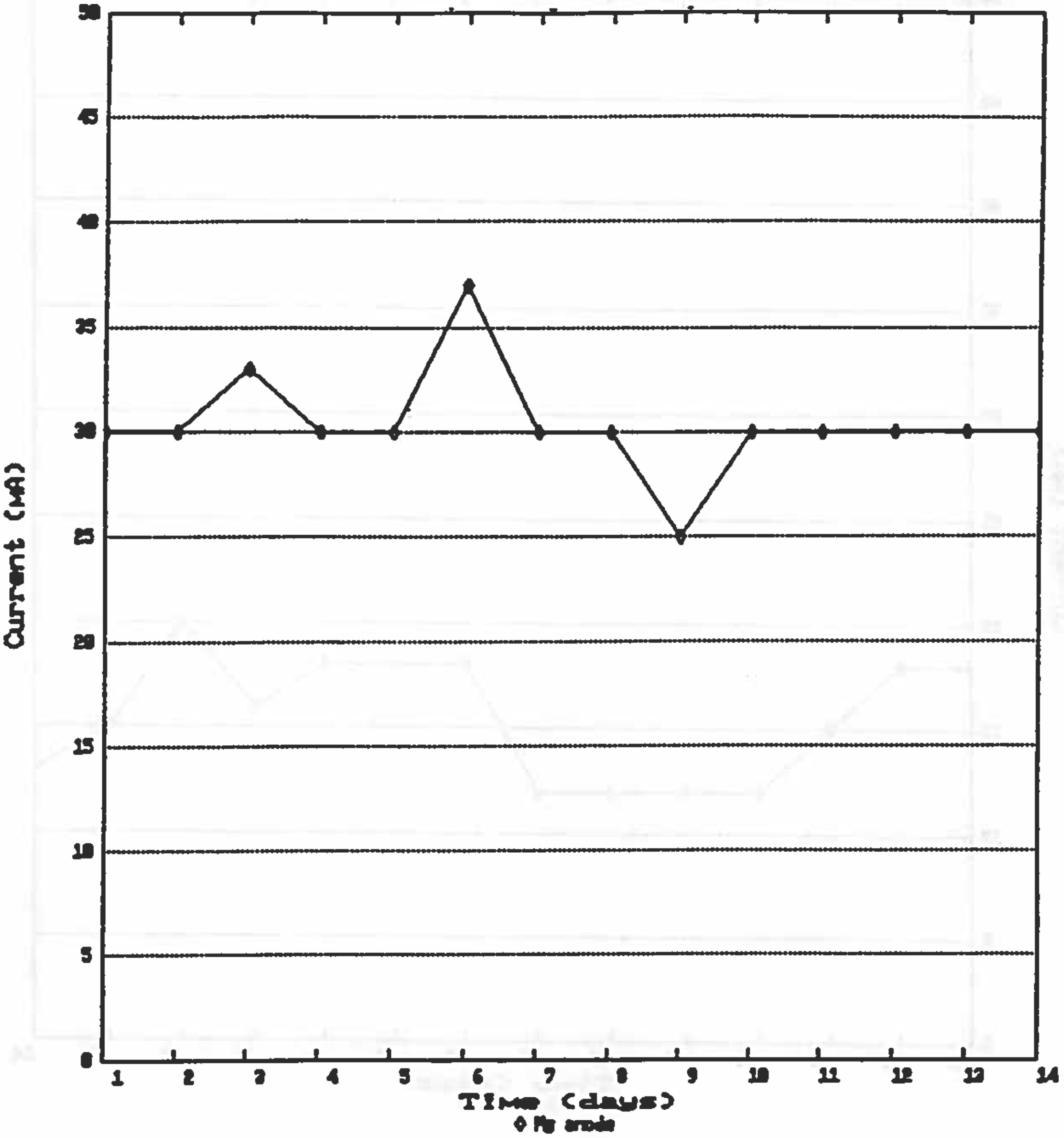

Figure C-1. Current requirement of galvanized steel in the 13-gallon water tank.

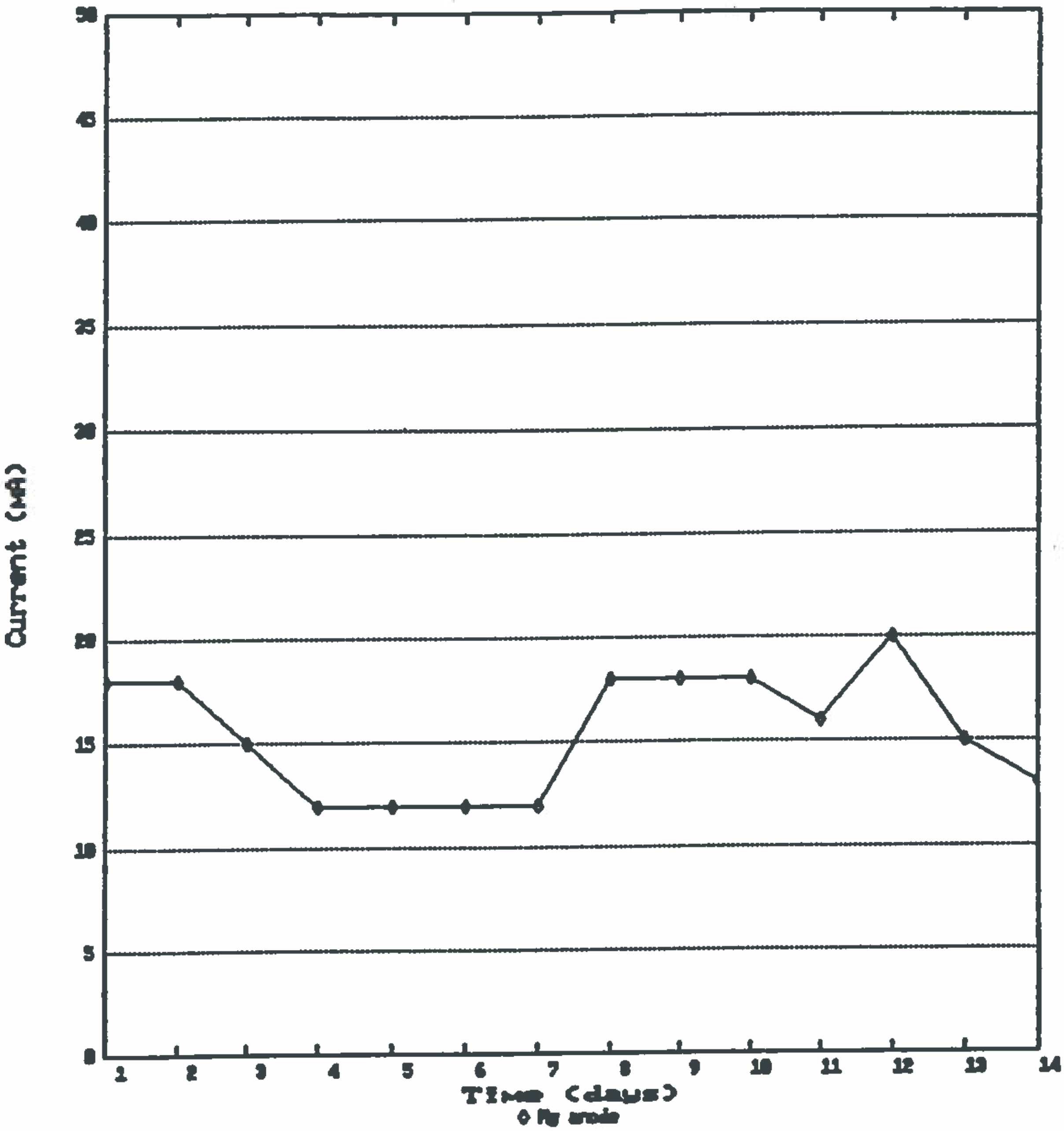

Figure C-2. Current requirement of polymeric galvanized steel in the 13-gallon water tank.

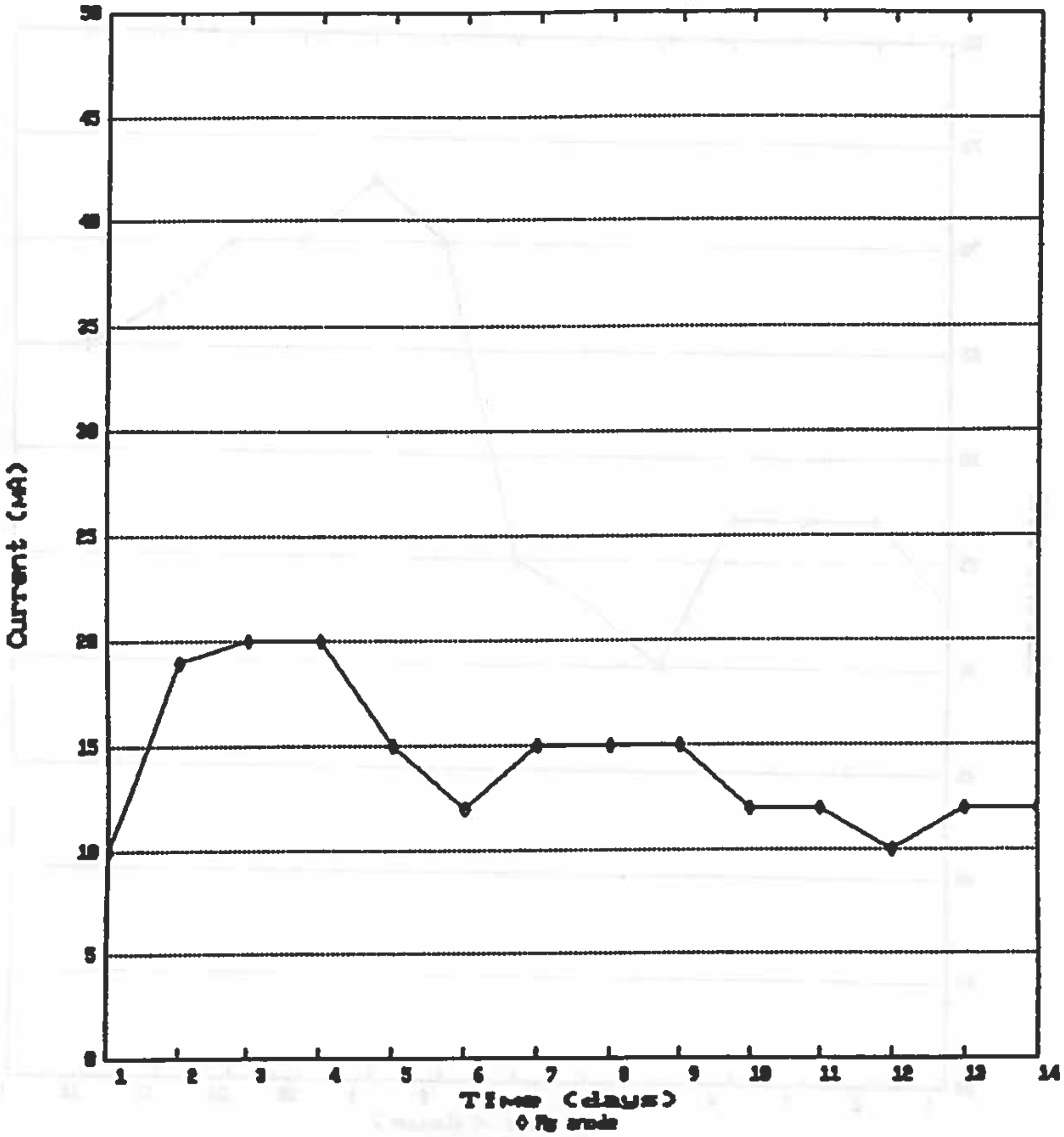

Figure C-3. Current requirement of fiber bituminous galvanized steel in the 13-gallon water tank.

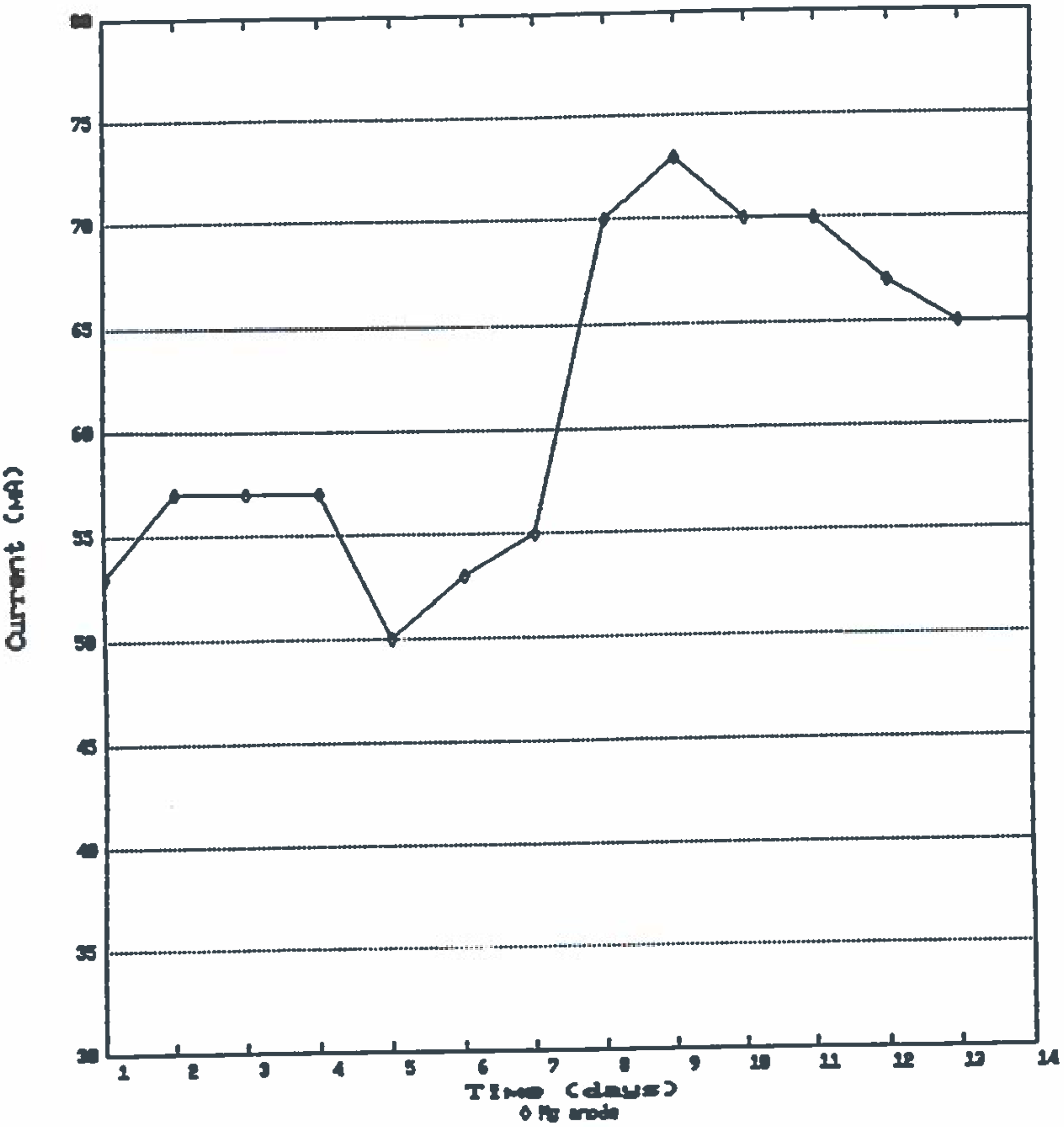

Figure C-4. Current requirement of aluminized Type II in the 13-gallon water tank.

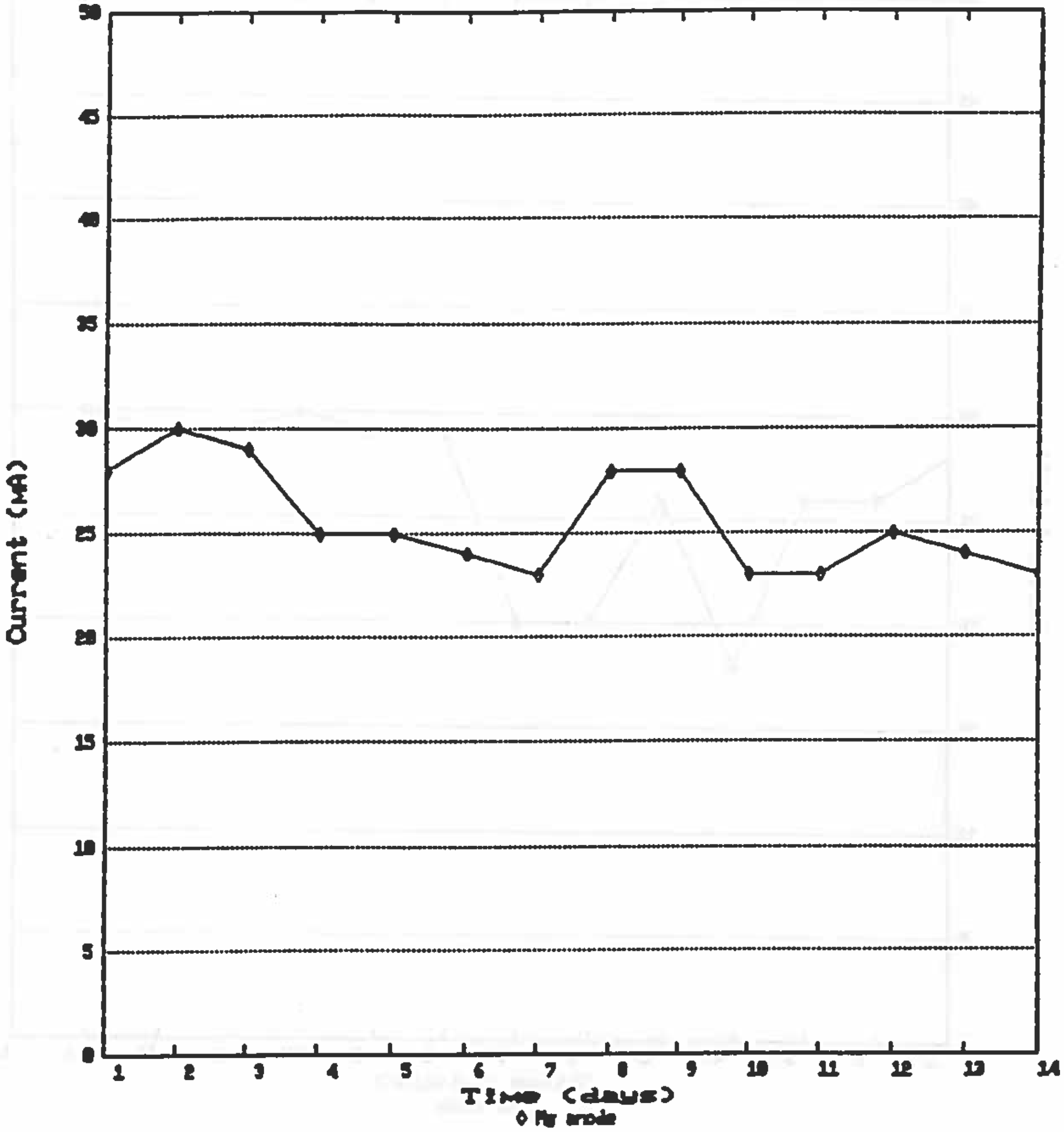

Figure C-5. Current requirement of polymeric cold-rolled steel in the 13-gallon water tank.

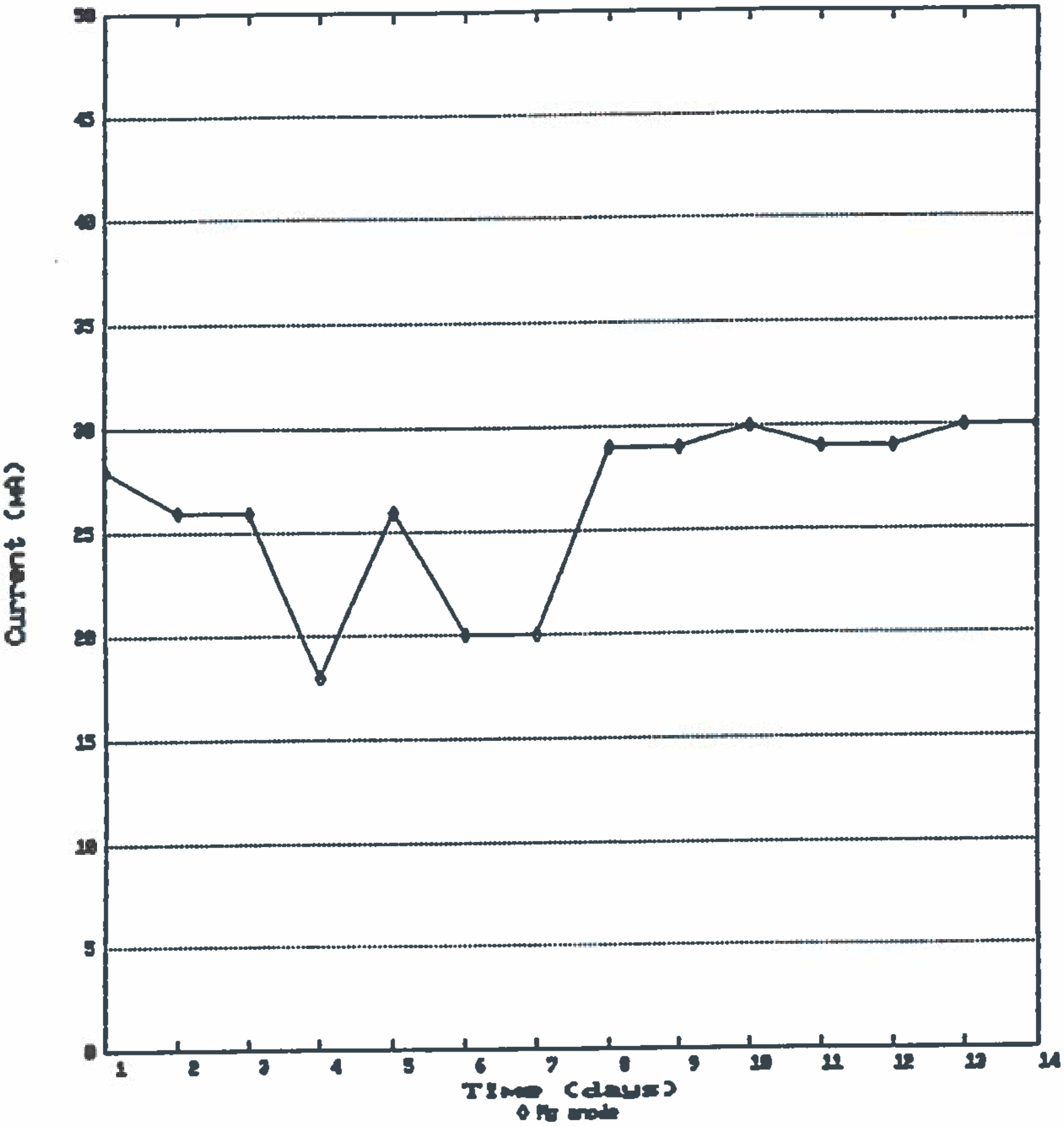

Figure C-6. Current requirement of polymeric aluminized Type II in the 13-gallon water tank.

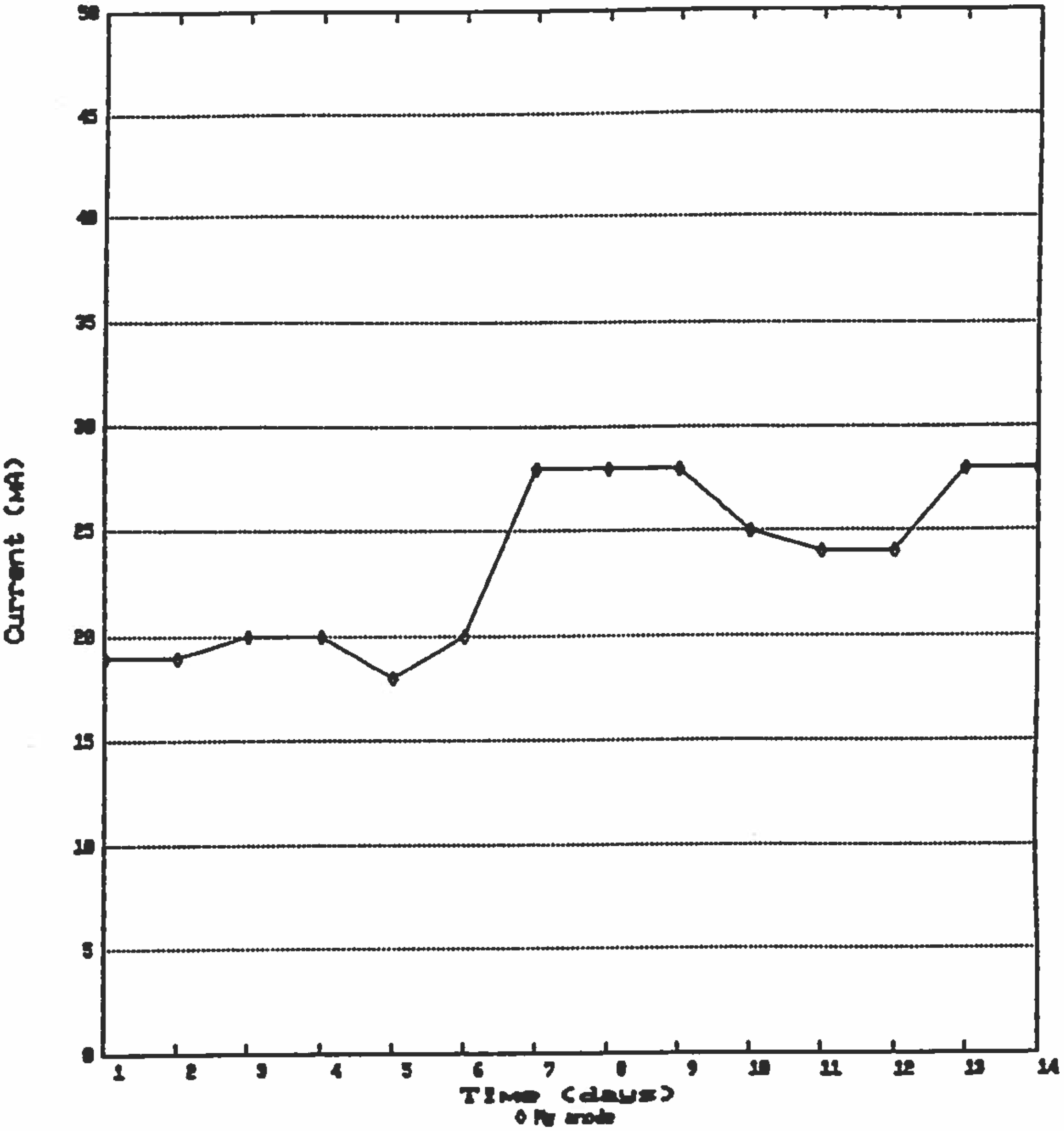

Figure C-7. Current requirement of polymeric aluminized Type I in the 13-gallon water tank.

Appendix D

Thirteen (13) Gallon Water Tank
Test Potential Versus Time

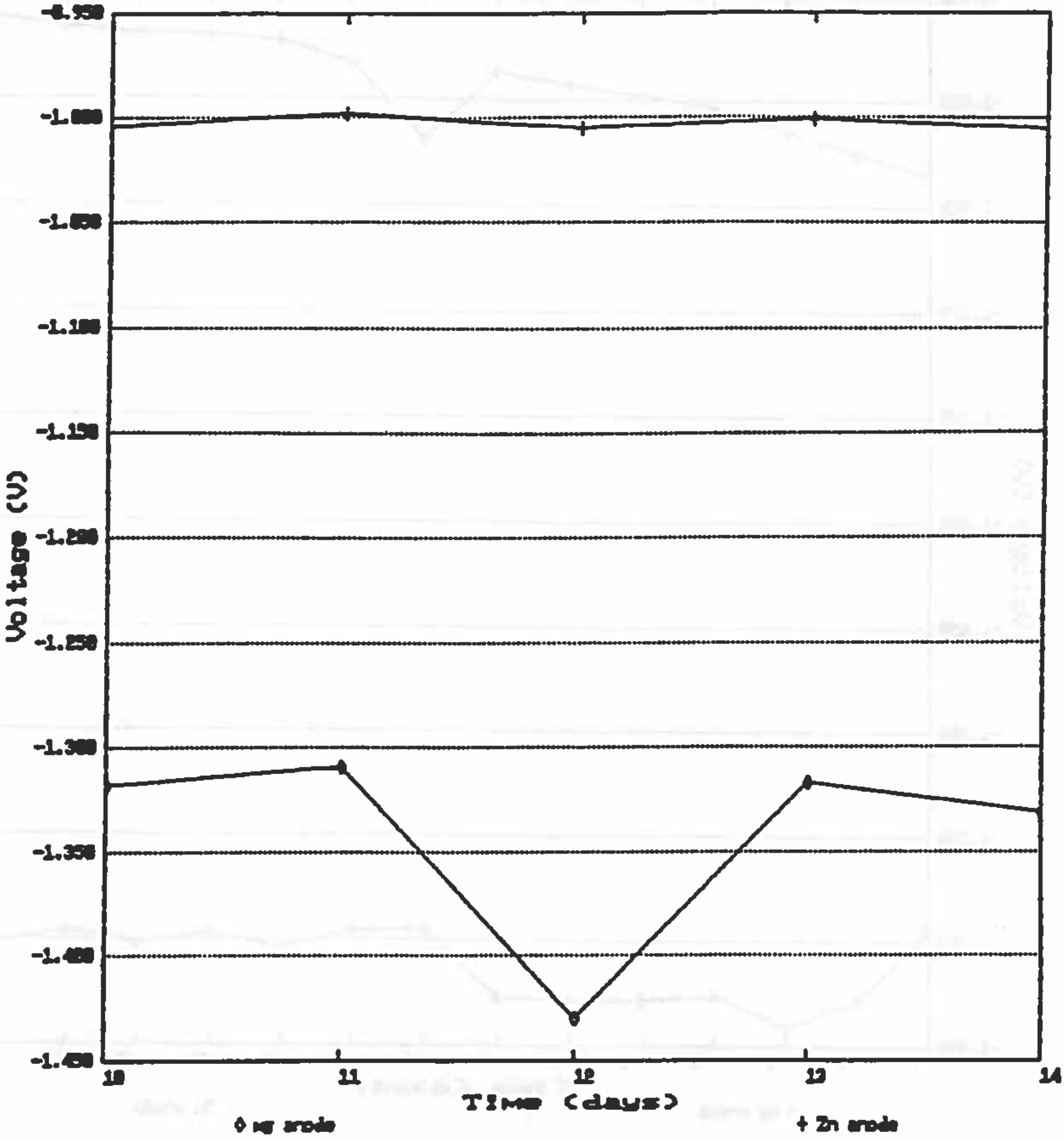

Figure D-1. Potential of galvanized steel hooked to magnesium and zinc anodes.

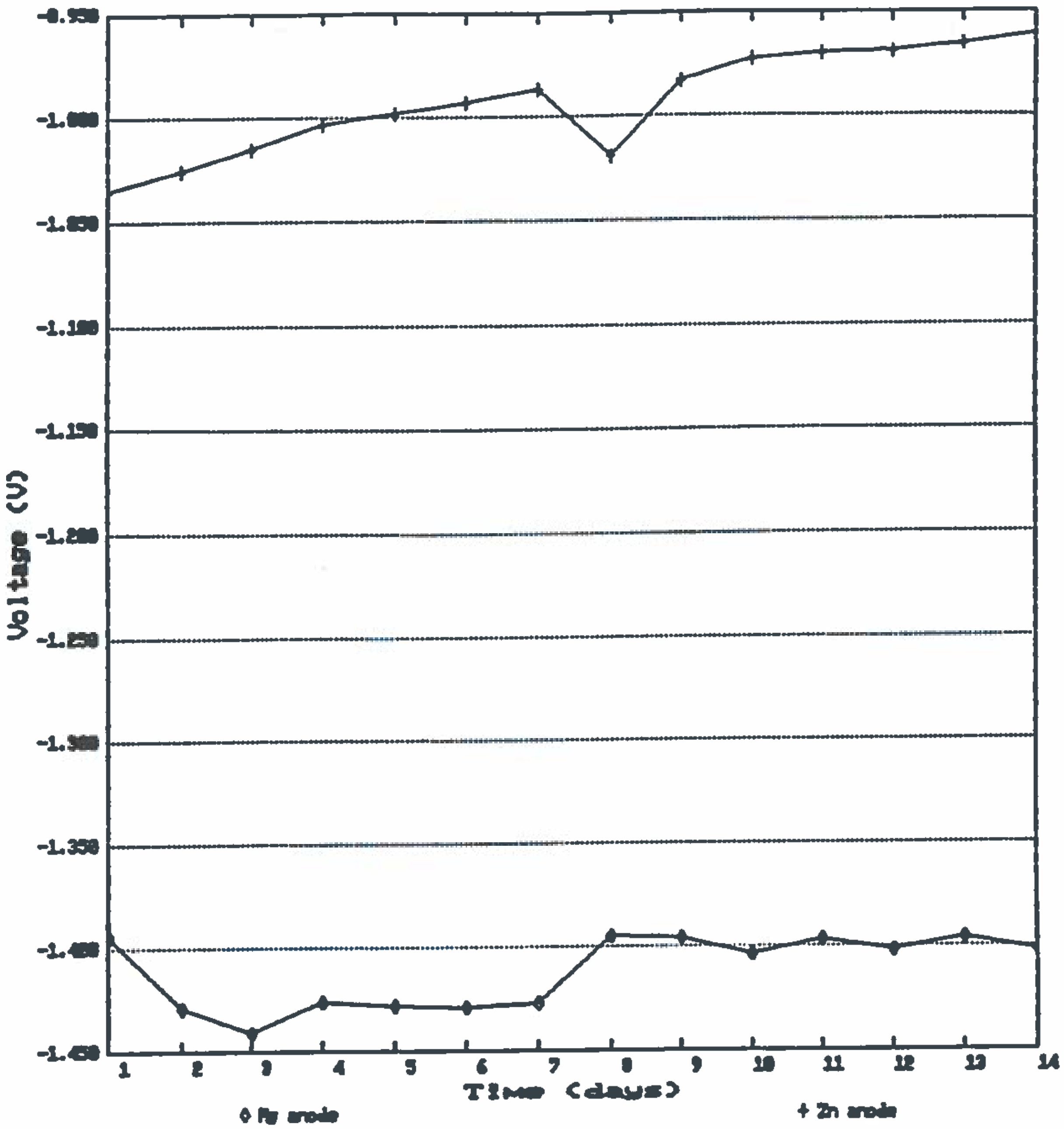

Figure D-2. Potential of polymeric galvanized steel hooked to magnesium and zinc anodes.

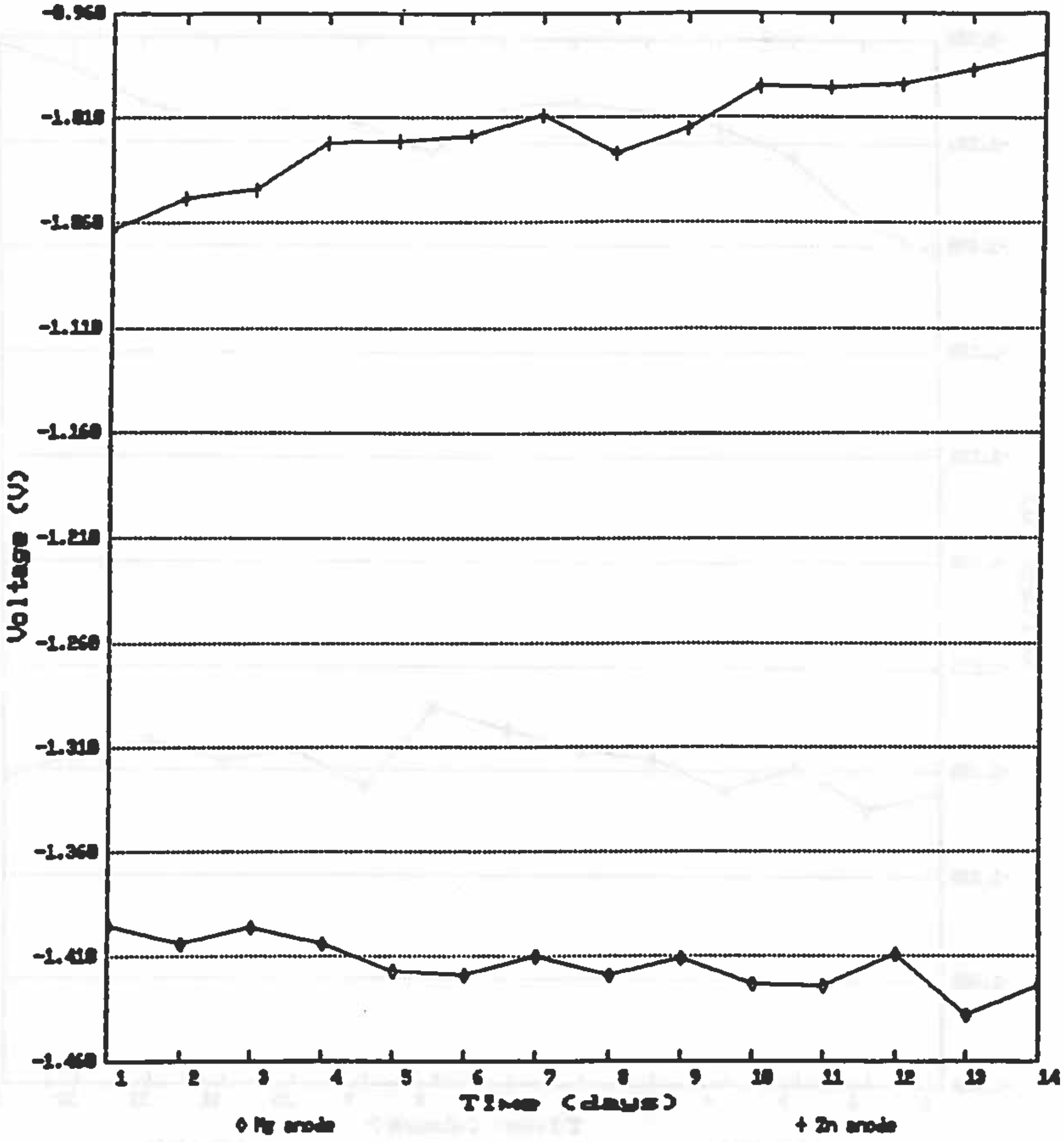

Figure D-3. Potential of fiber-bonded bituminous galvanized steel hooked to magnesium and zinc anodes.

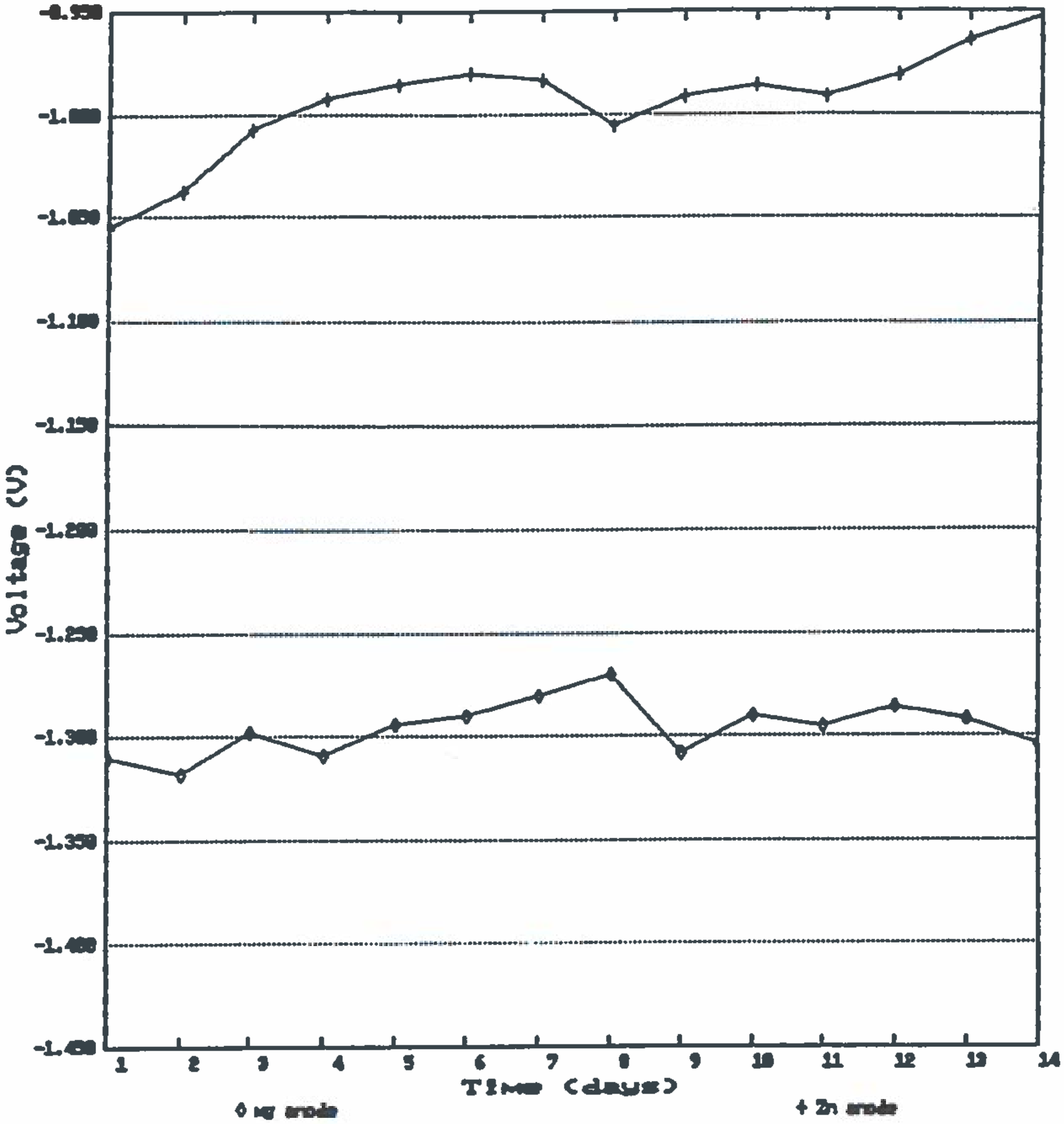

Figure D-4. Potential of aluminized Type II hooked to magnesium and zinc anodes.

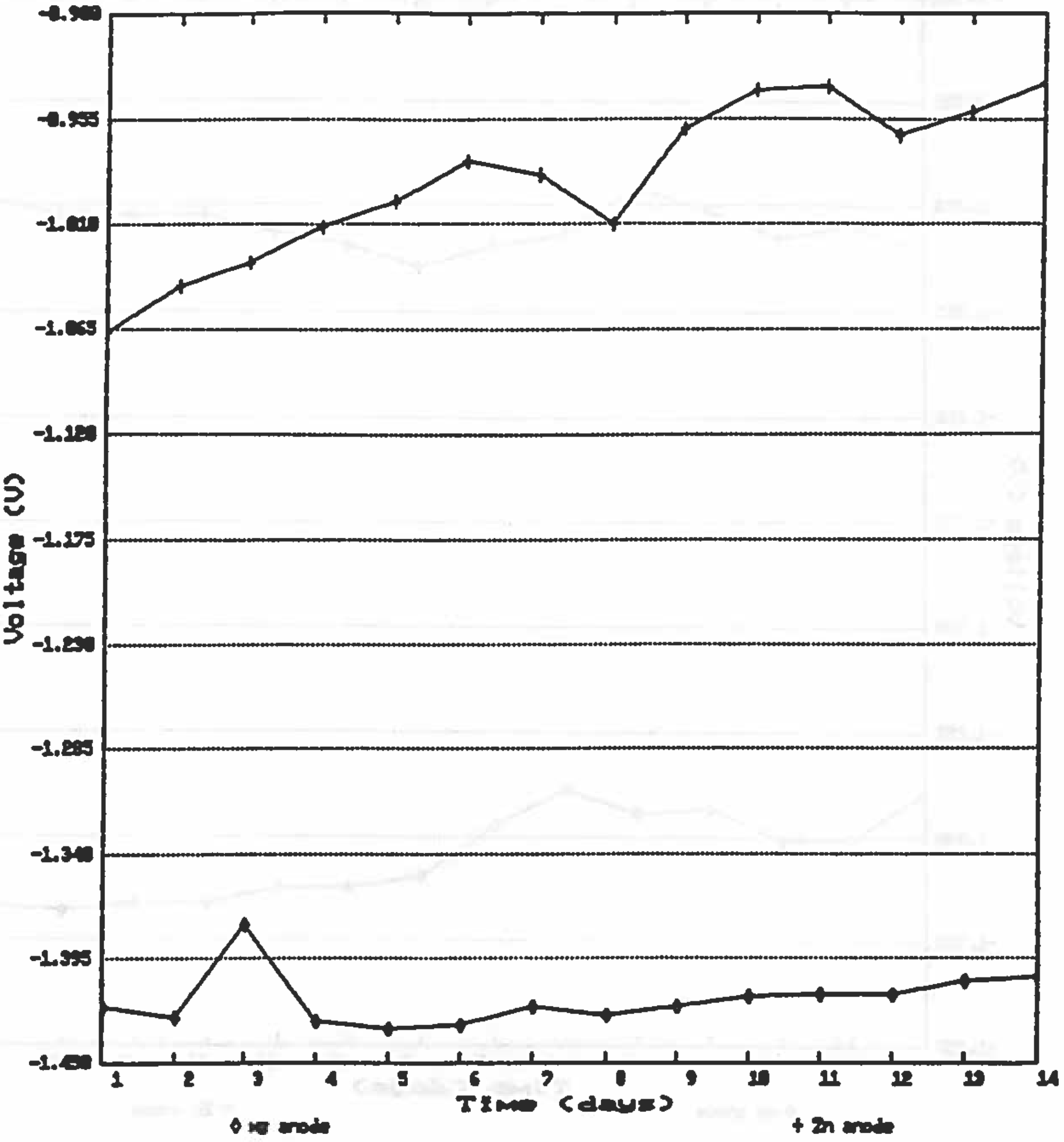

Figure D-5. Potential of polymeric cold-rolled steel hooked to magnesium and zinc anodes.

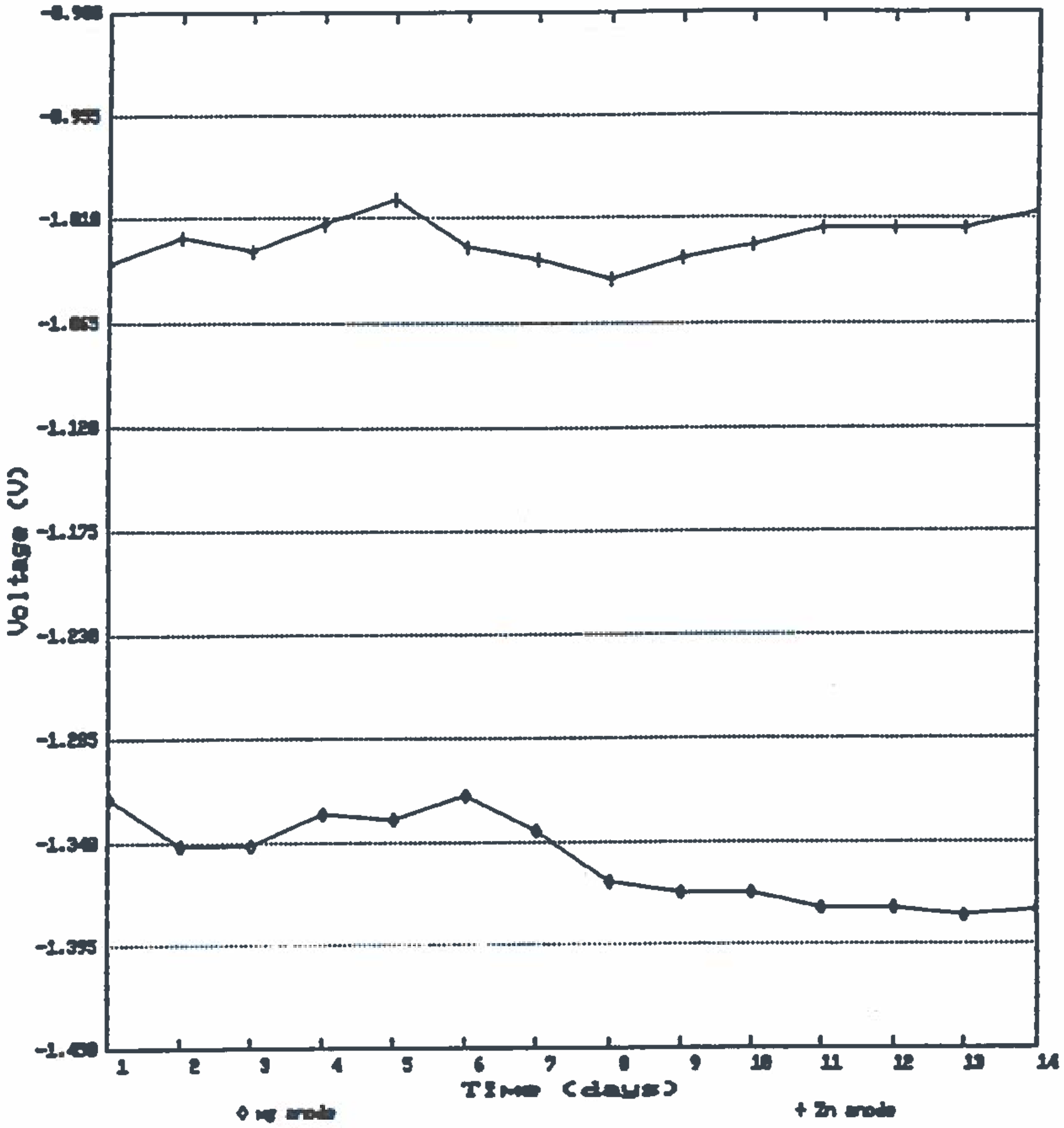

Figure D-6. Potential of polymeric aluminized Type II hooked to magnesium and zinc anodes.

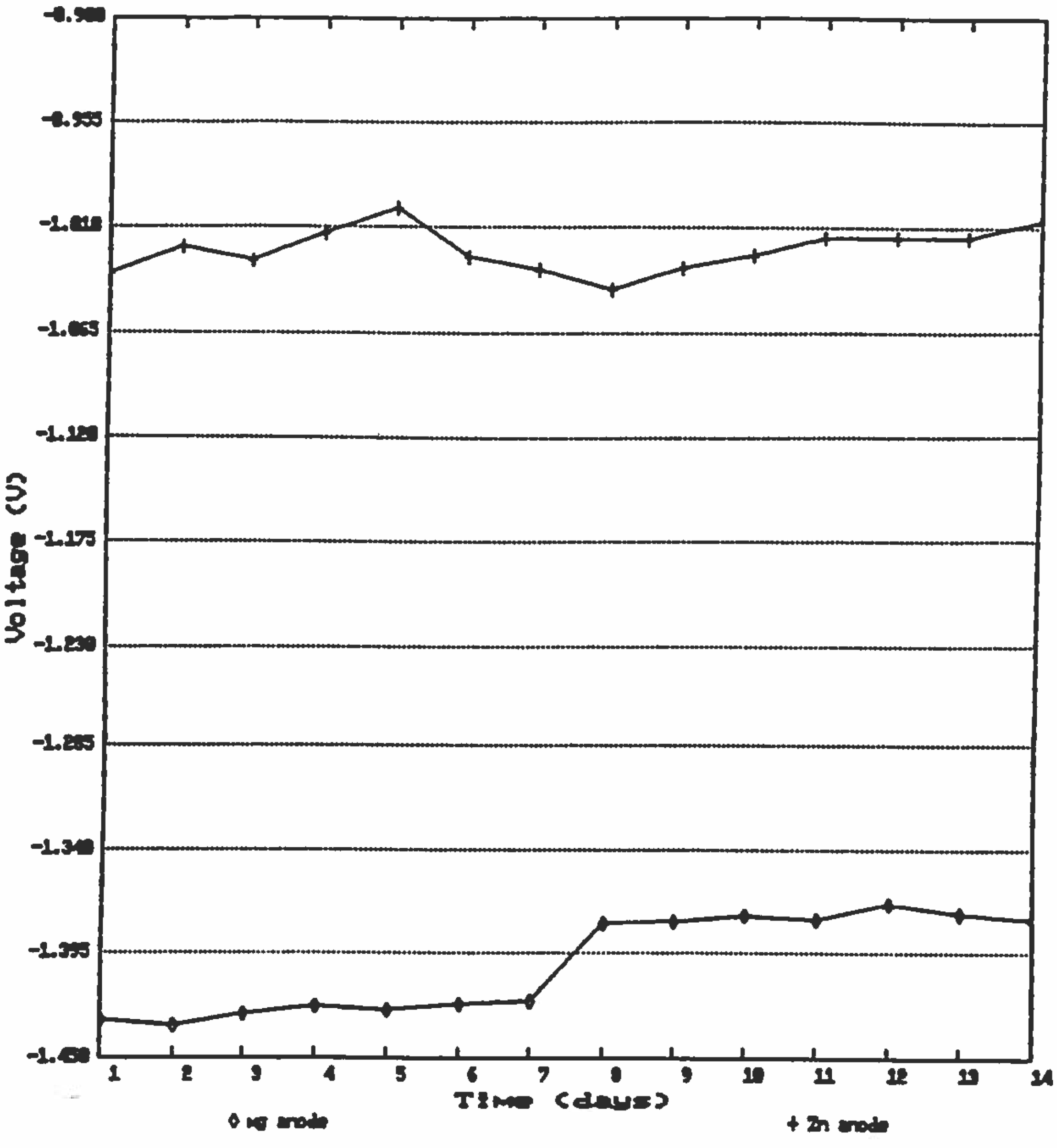

Figure D-7. Potential of polymeric aluminized Type I hooked to magnesium and zinc anodes.

Appendix E

Large Water Tank Test
Potential Versus Time

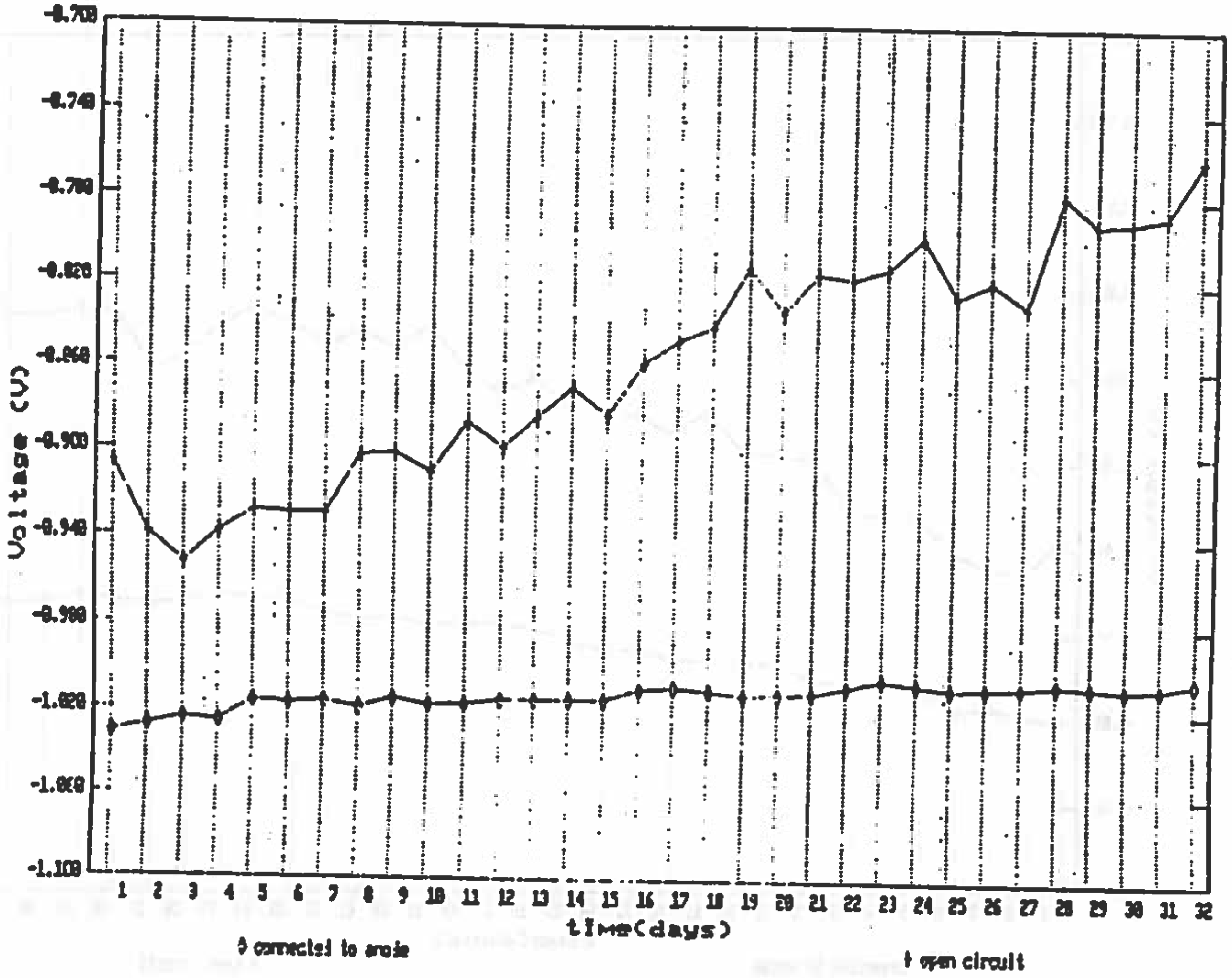

Figure E-1. Connected and open circuit potential of fiber-bonded bituminous galvanized steel in the large water tank.

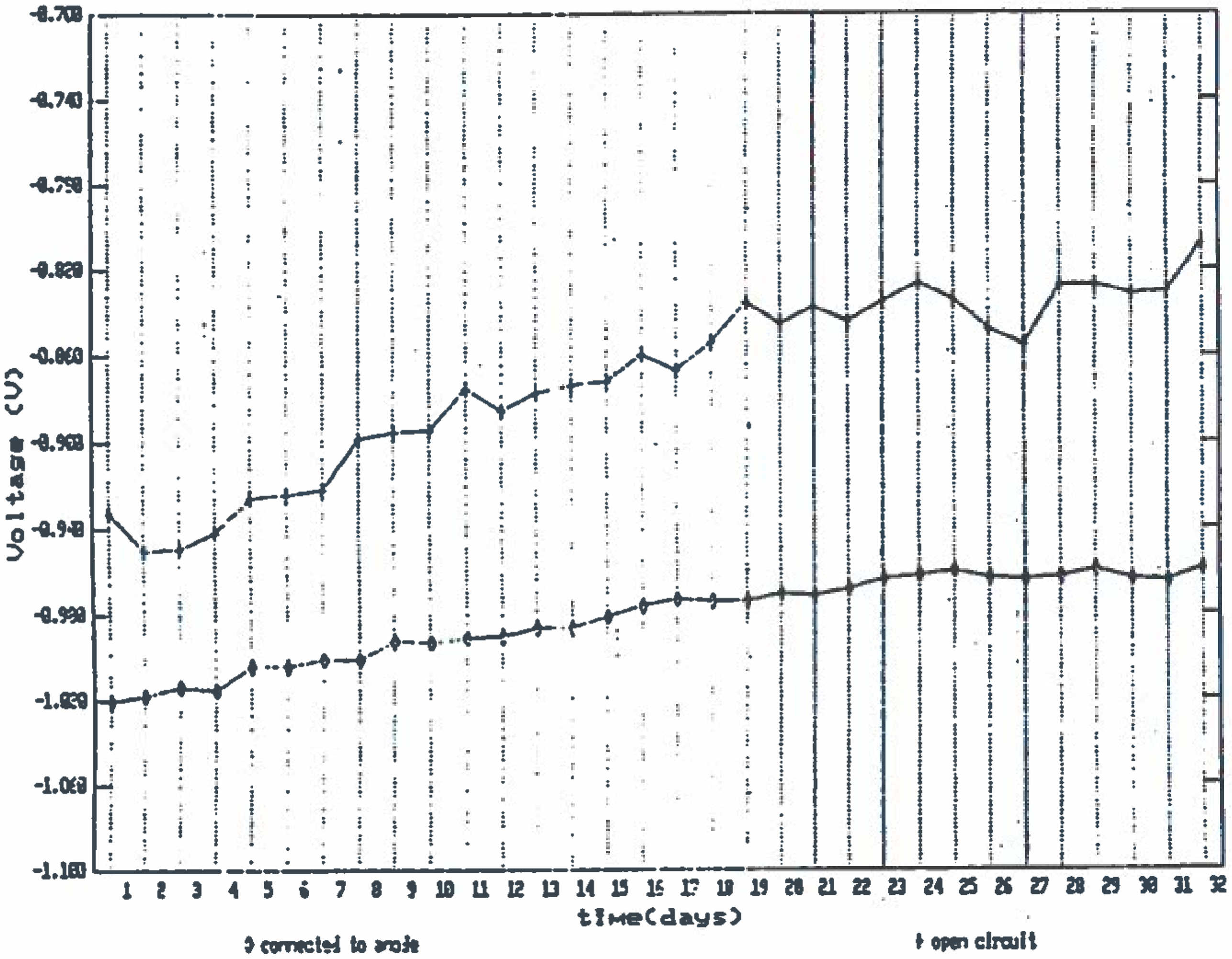

Figure E-2. Connected and open circuit potential of bituminous galvanized steel in the large water tank.

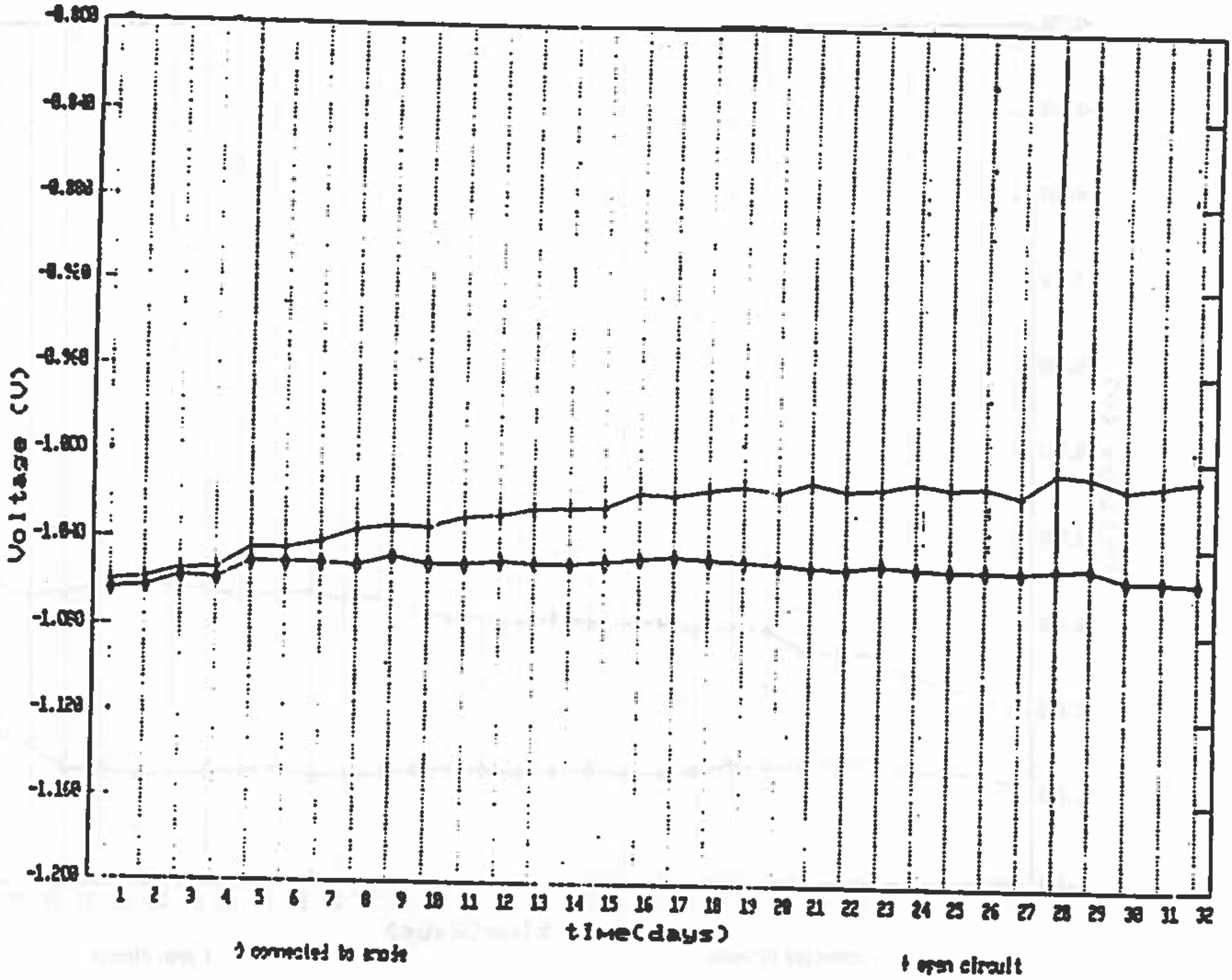

Figure E-3. Connected and open circuit potential of polymeric galvanized steel (Supplier 1) in the large water tank.

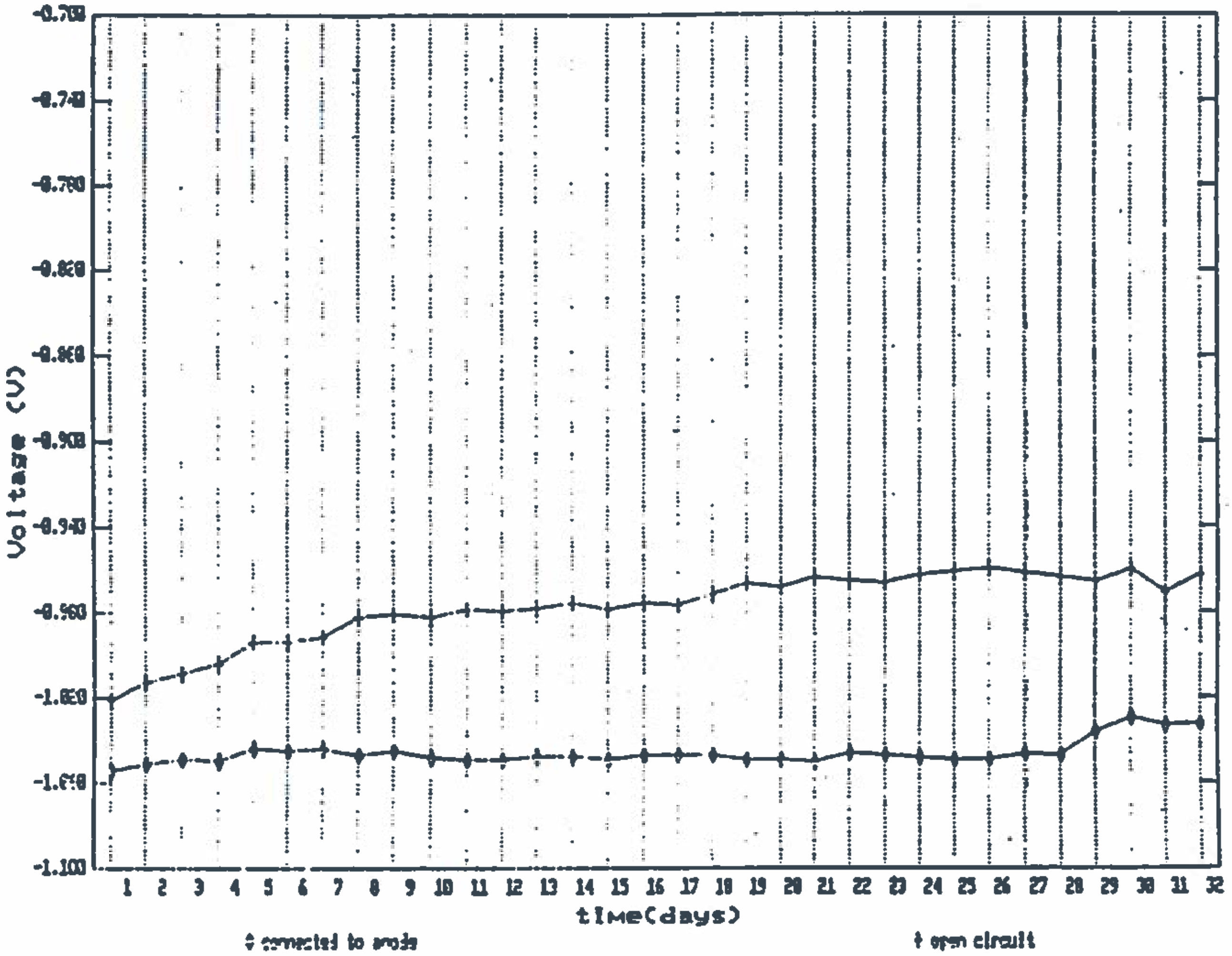

Figure E-4. Connected and open circuit potential of polymeric galvanized steel (Supplier 2) in the large water tank.

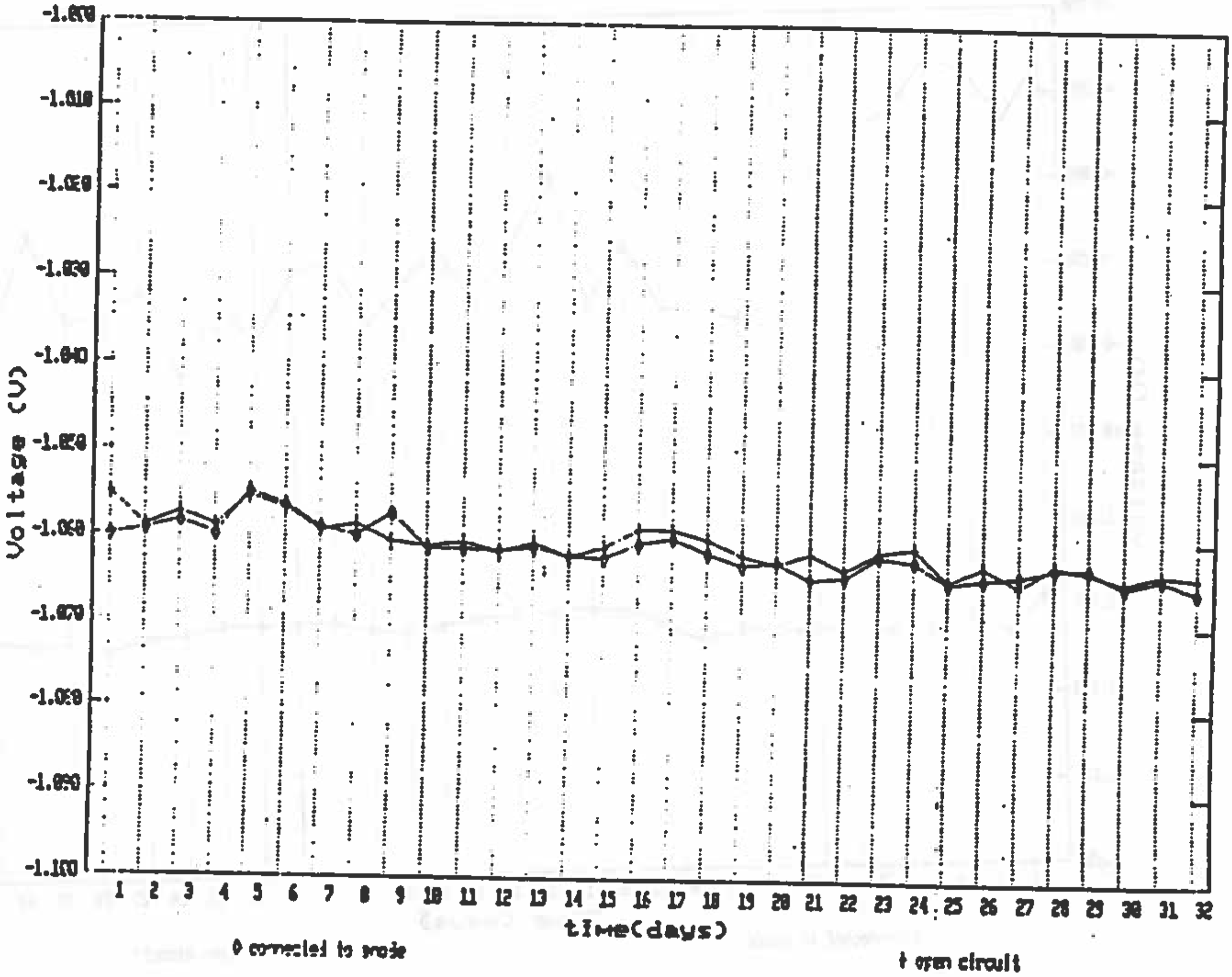

Figure E-5. Connected and open circuit potential of galvanized steel in the large water tank.

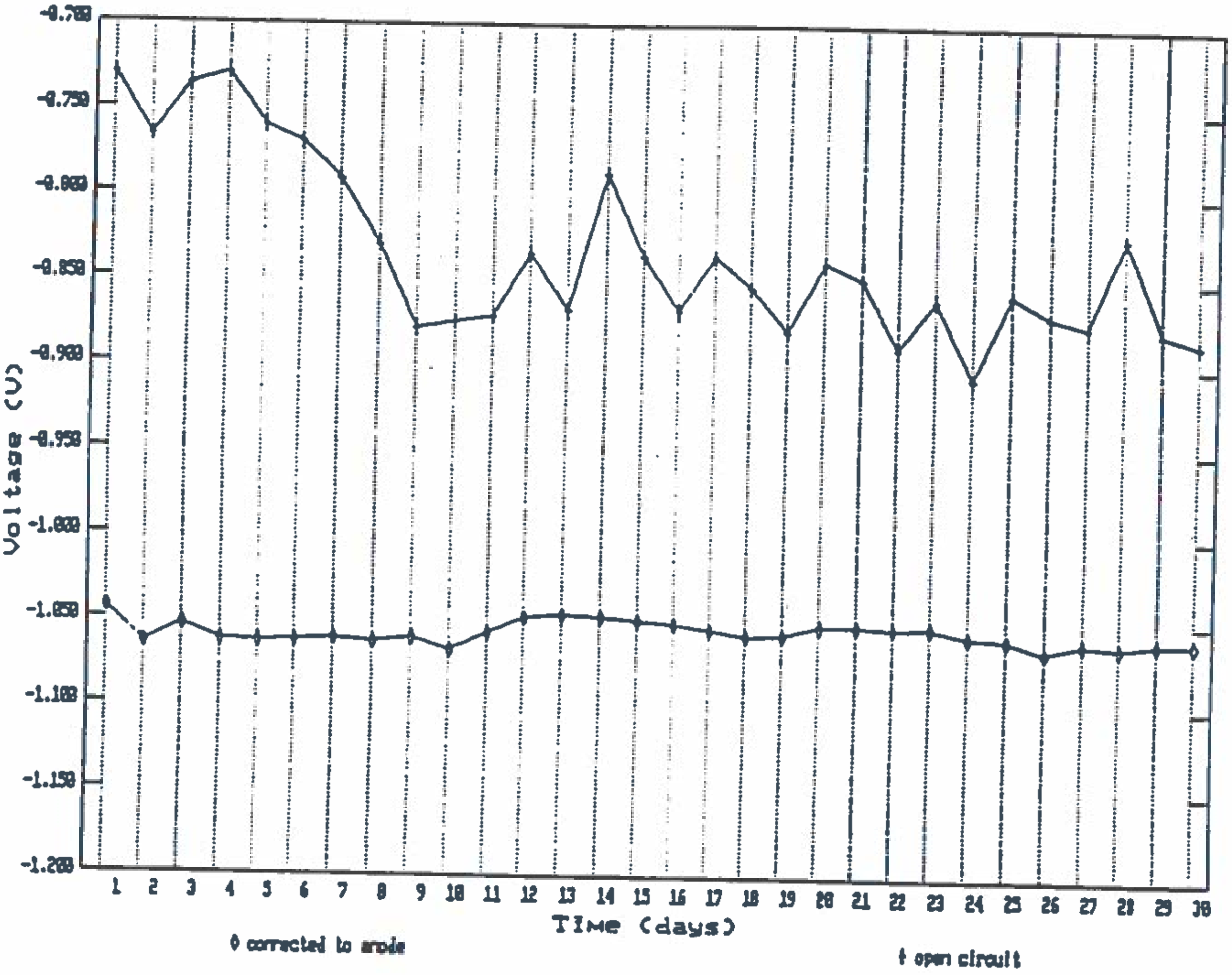

Figure E-6. Connected and open circuit potential of polymeric aluminized Type I in the large water tank.

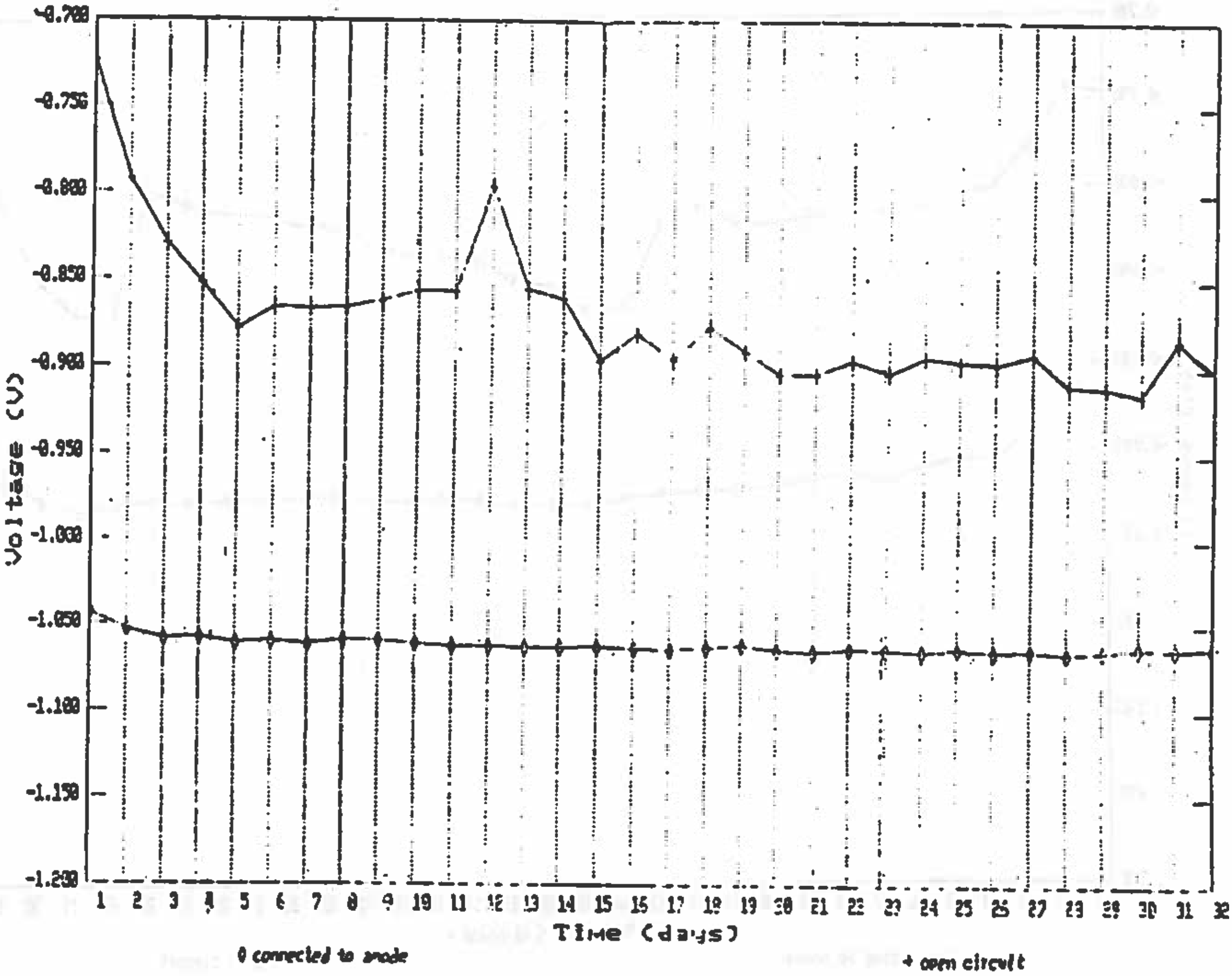

Figure E-7. Connected and open circuit potential of polymeric aluminized Type II in the large water tank.

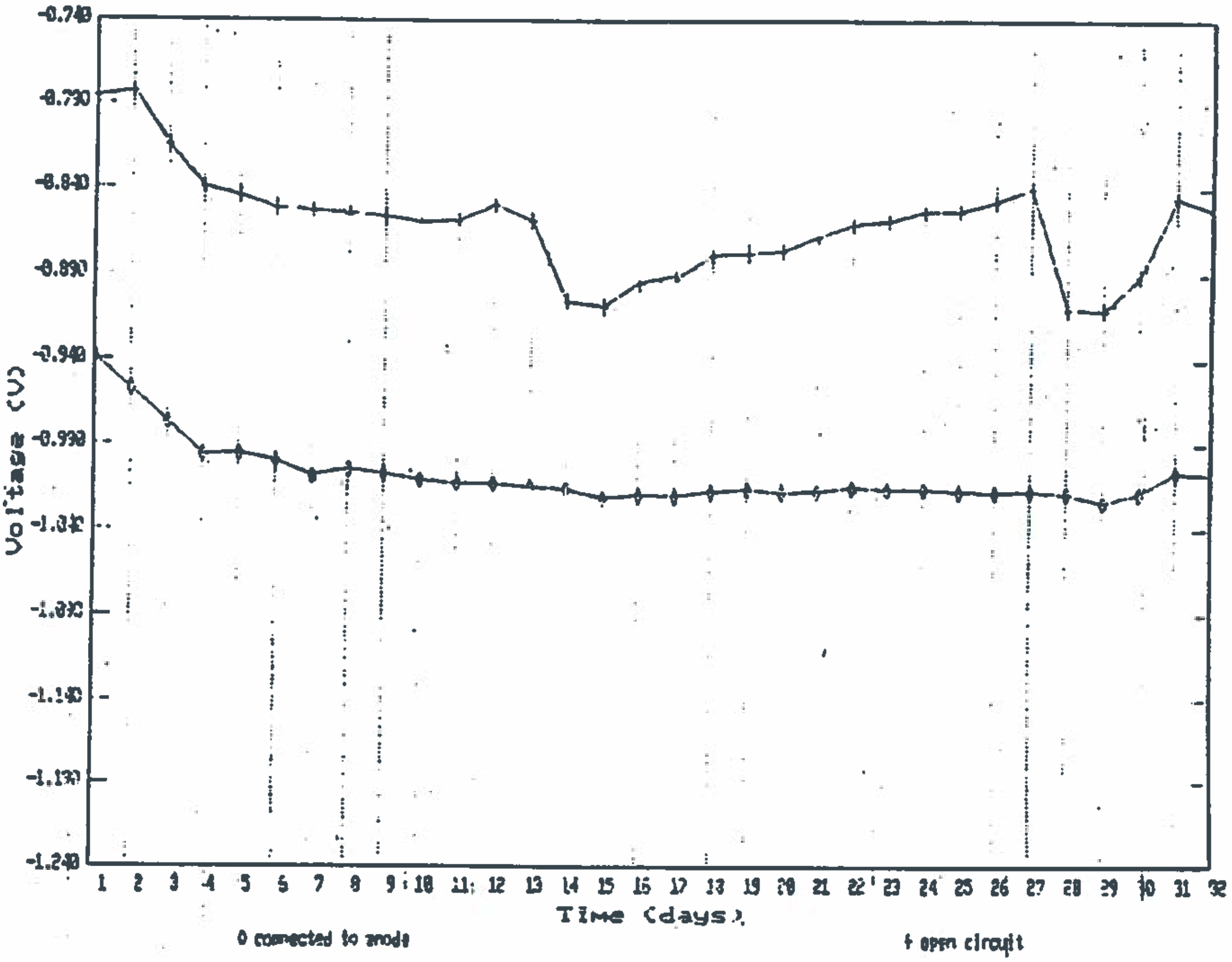

Figure E-8. Connected and open circuit potential of aluminized Type II in the large water tank.

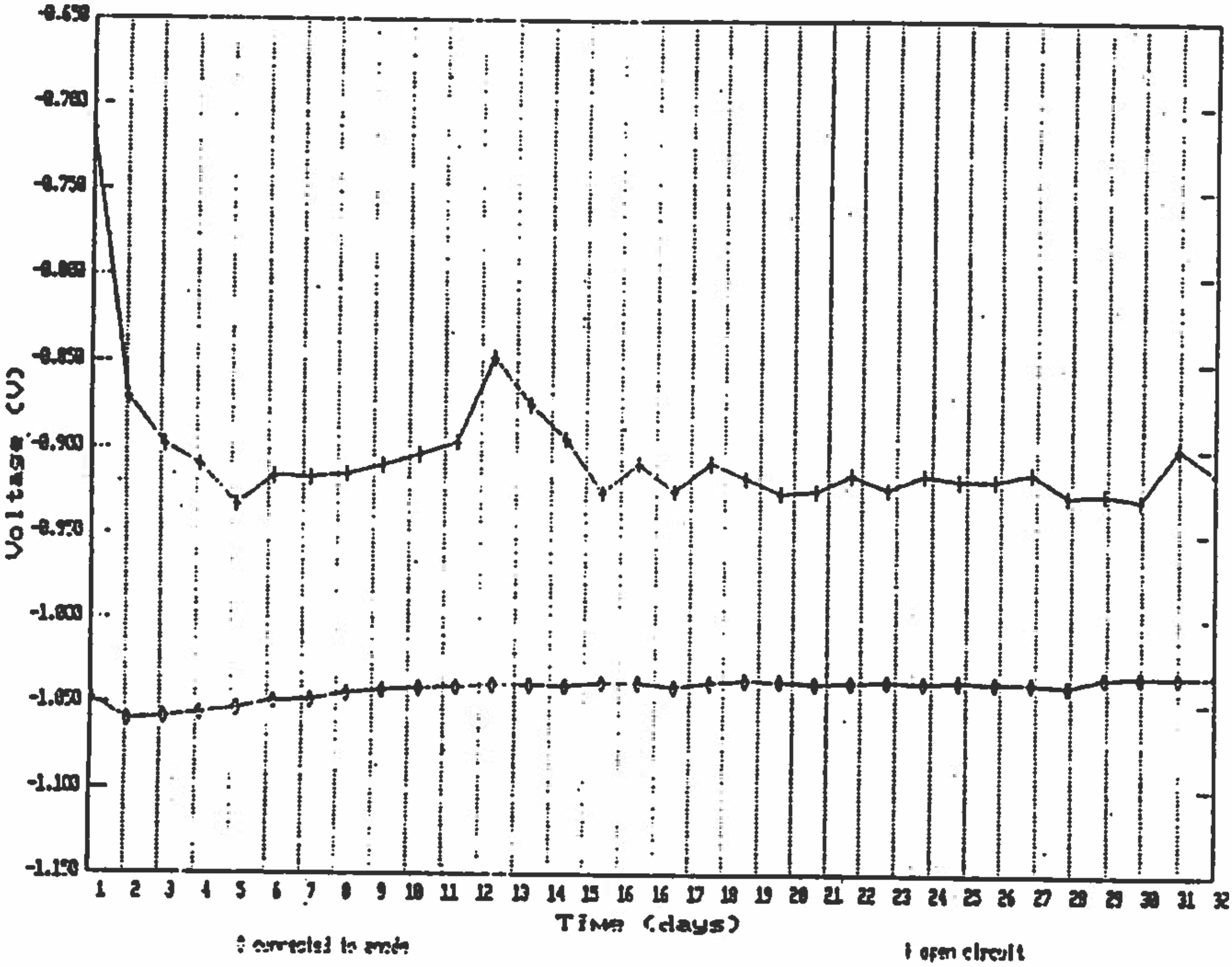

Figure E-9. Connected and open circuit potential of polymeric cold-rolled steel in the large water tank.

Appendix F

Large Water Tank Test
Current Versus Time

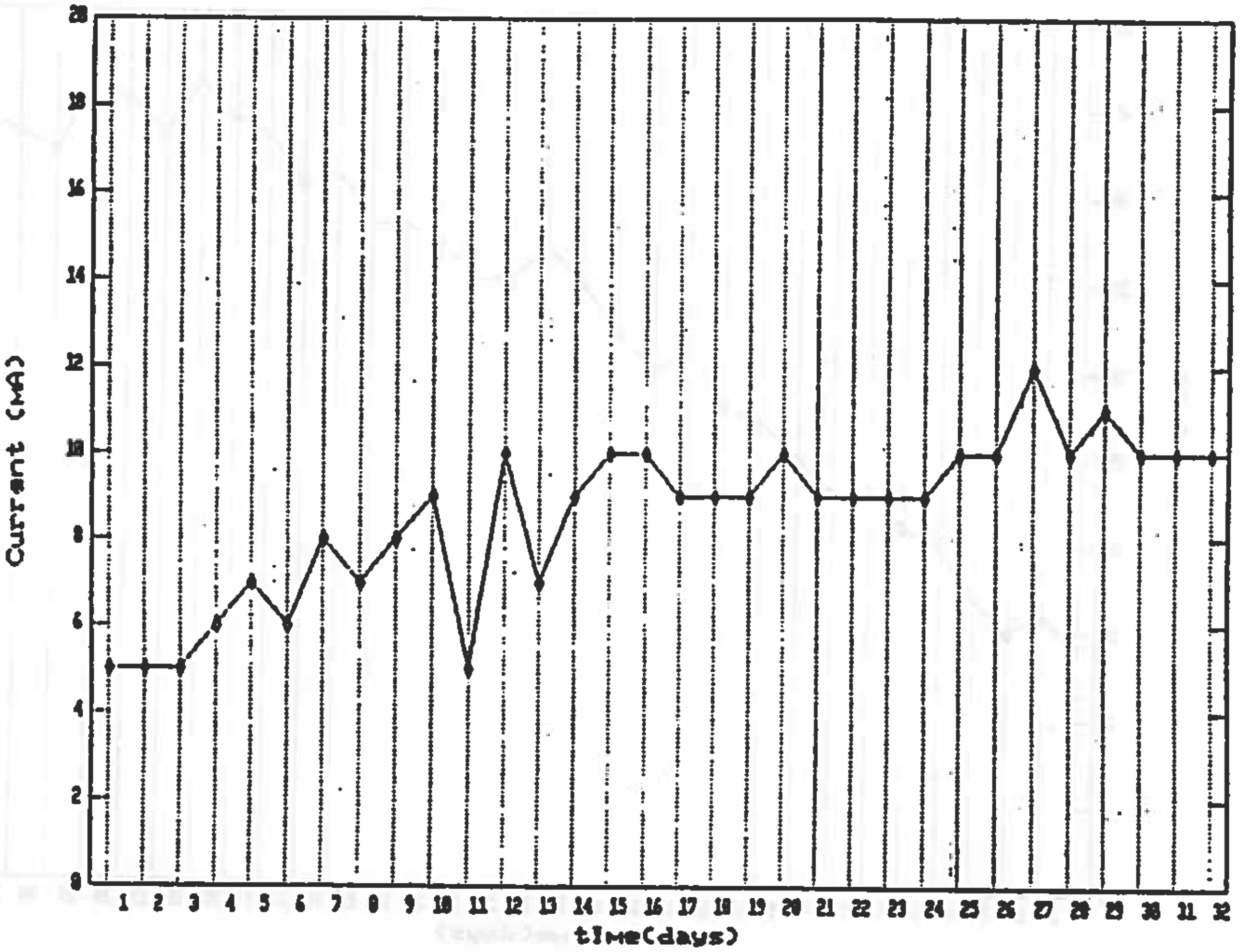

Figure F-1. Current required to shift the potential of the fiber-bonded bituminous galvanized culvert in the large water tank.

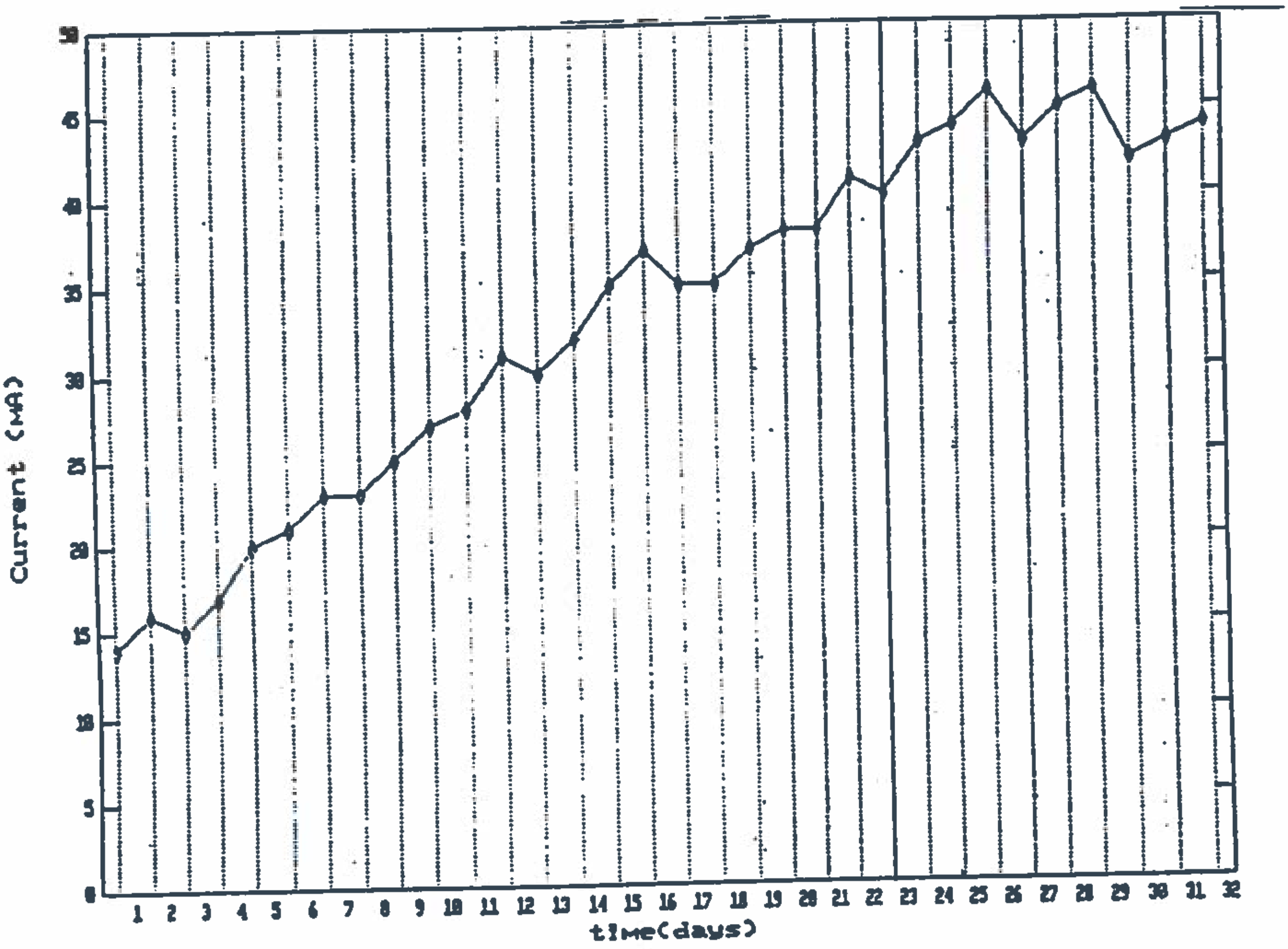

Figure F-2. Current required to shift the potential of the bituminous galvanized steel culvert in the large water tank.

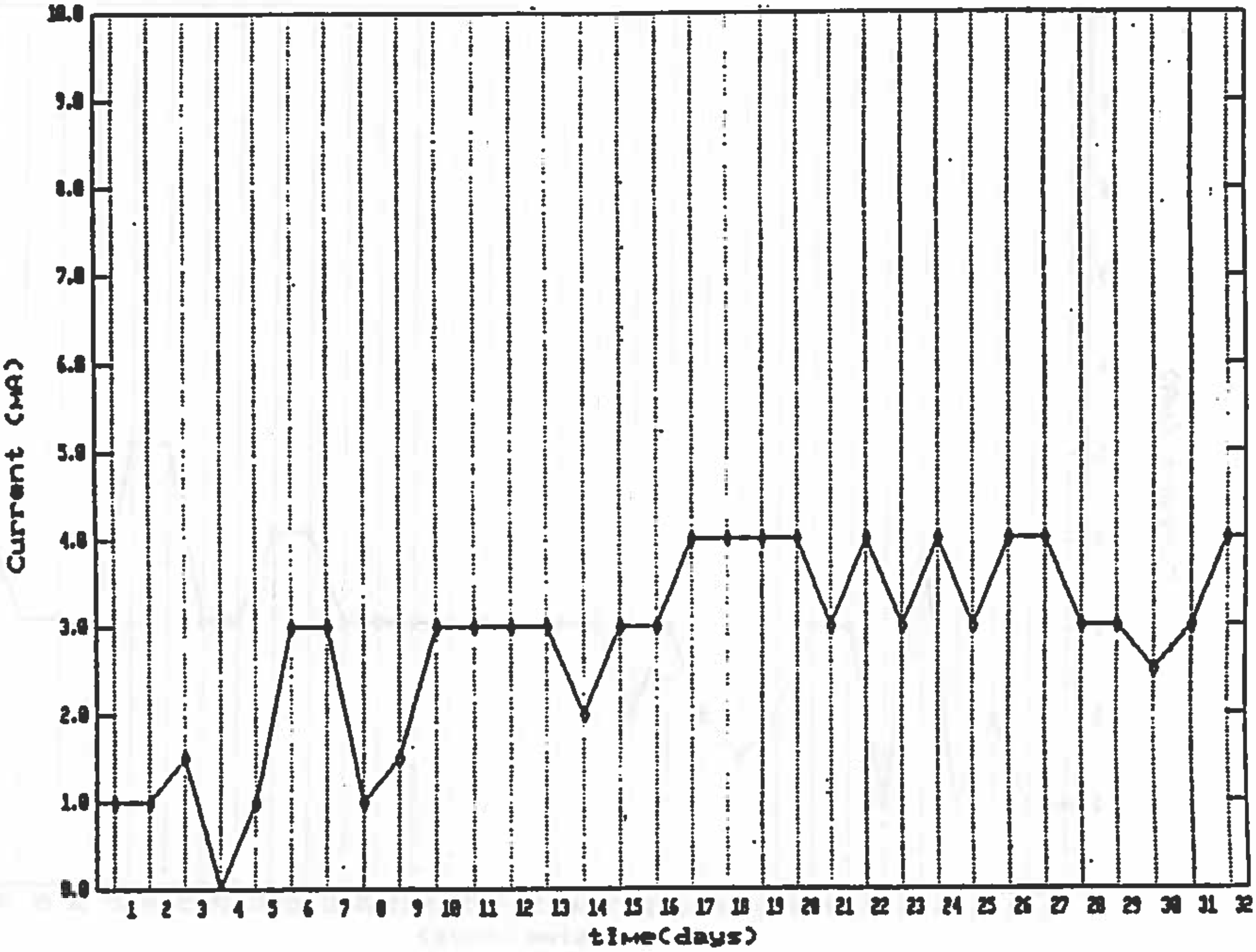

Figure F-3. Current required to shift the potential of the polymeric galvanized steel culvert (Supplier 1) in the large water tank.

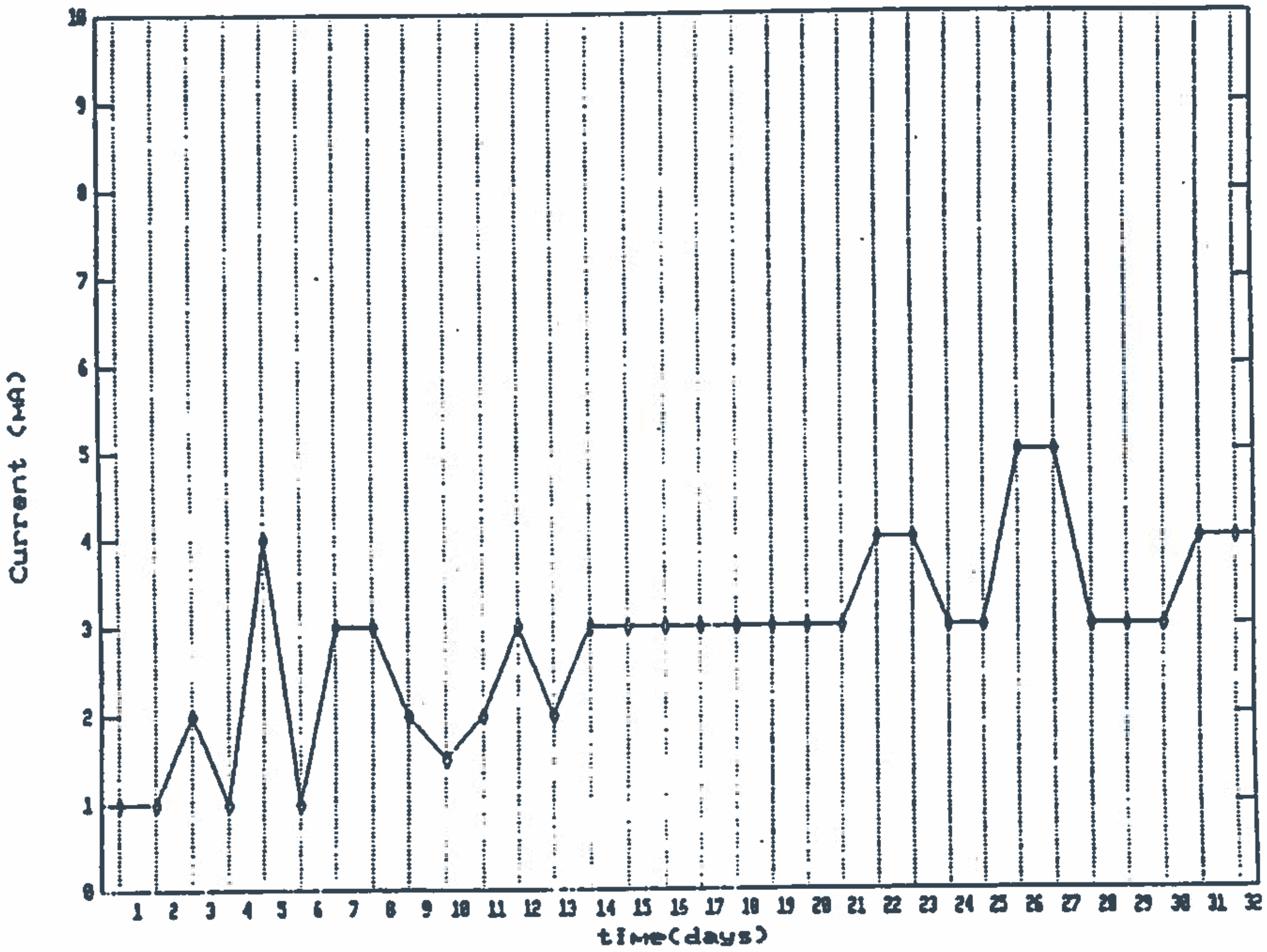

Figure F-4. Current required to shift the potential of the polymeric galvanized steel culvert (Supplier 2) in the large water tank.

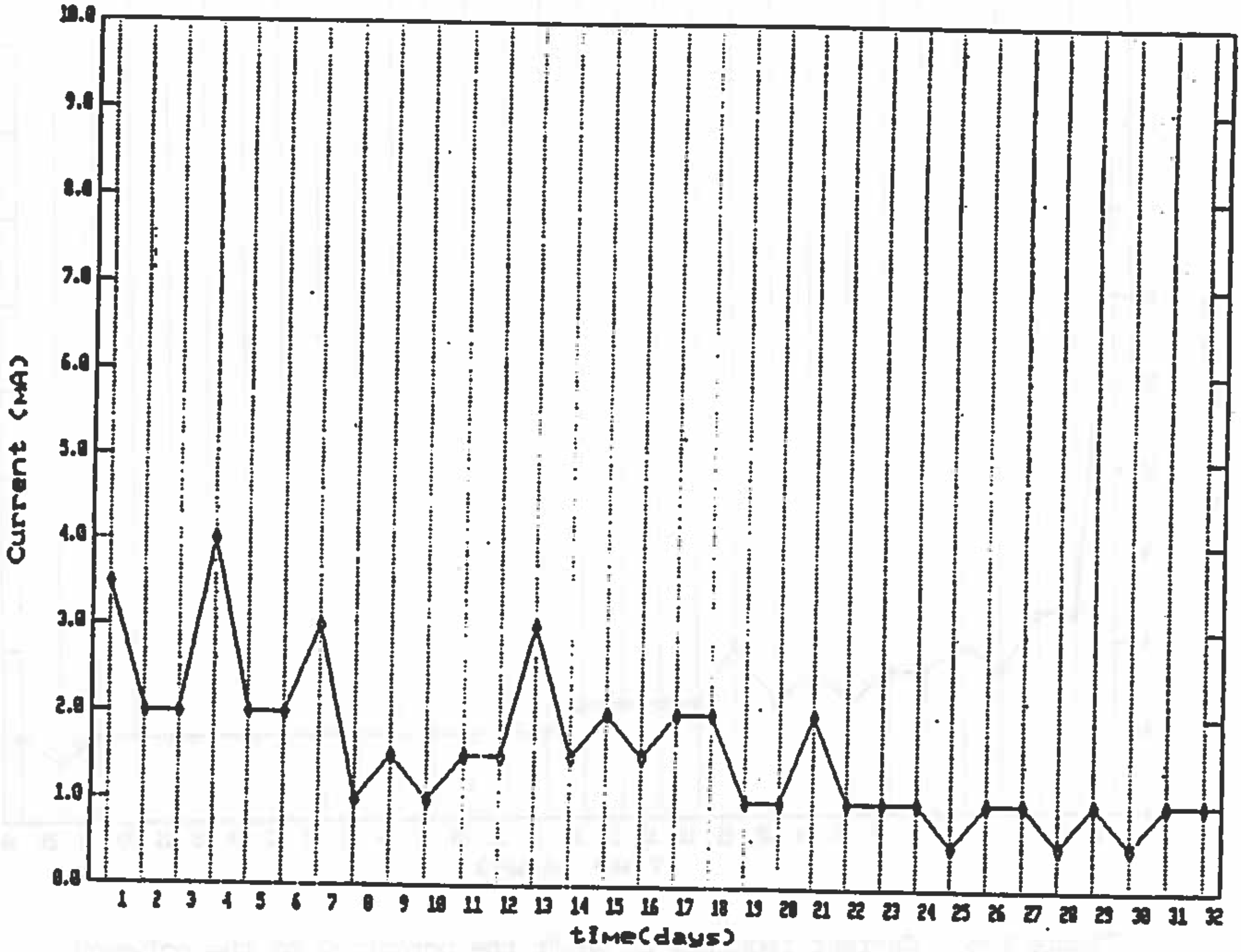

Figure F-5. Current required to shift the potential of the galvanized steel culvert in the large water tank.

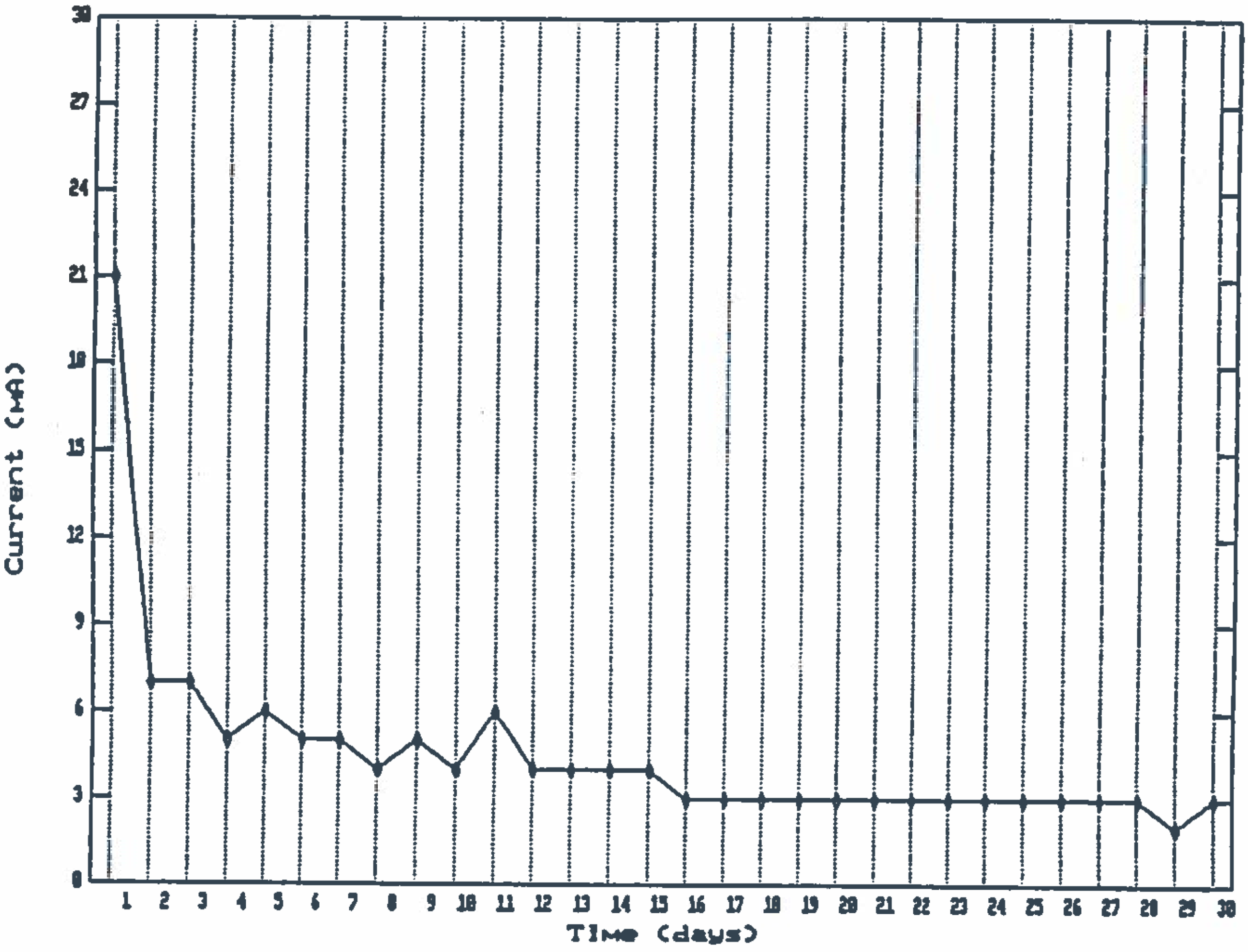

Figure F-6. Current required to shift the potential of the polymeric aluminized Type I culvert in the large water tank.

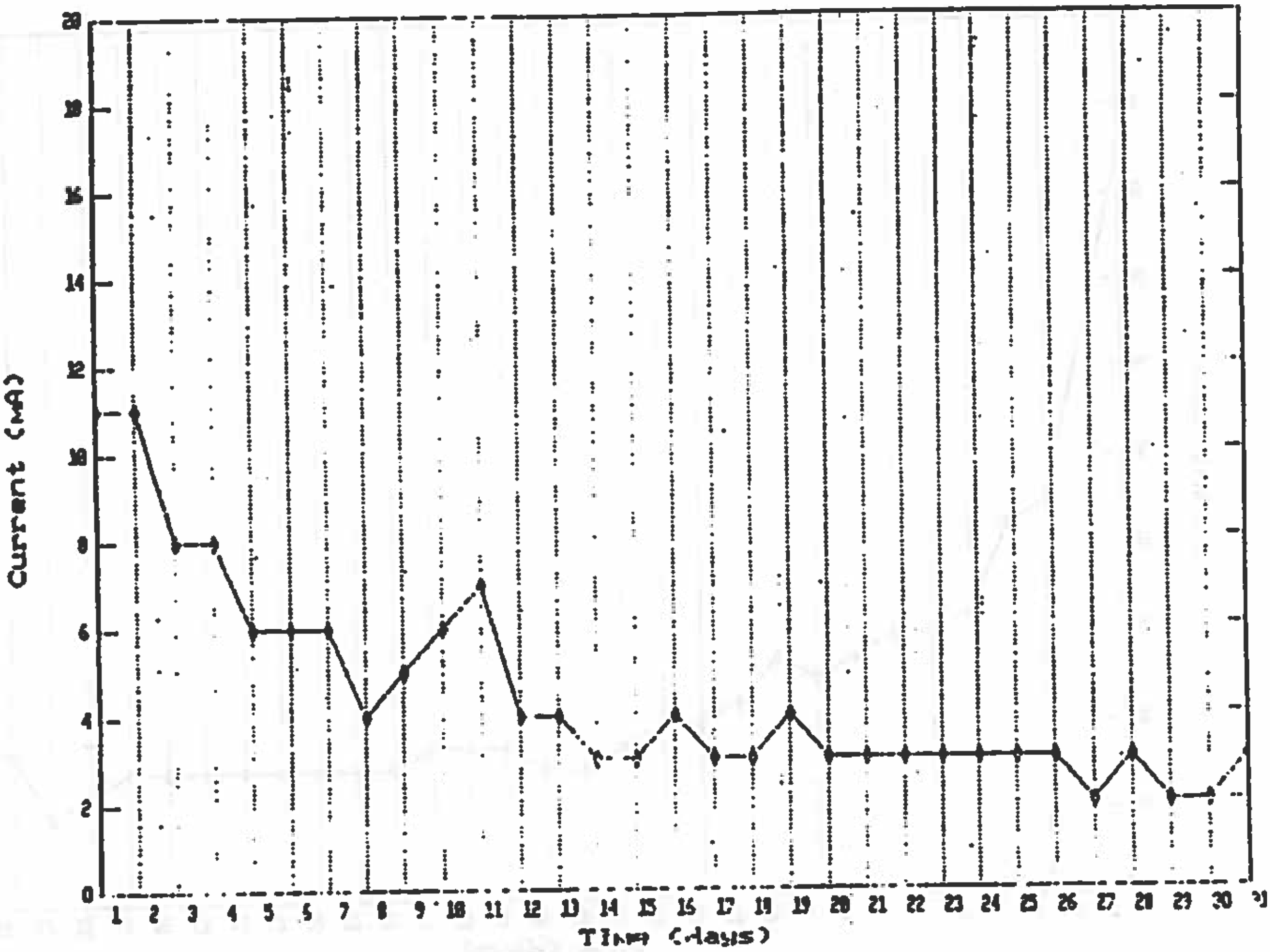

Figure F-7. Current required to shift the potential of the polymeric aluminized Type II culvert in the large water tank.

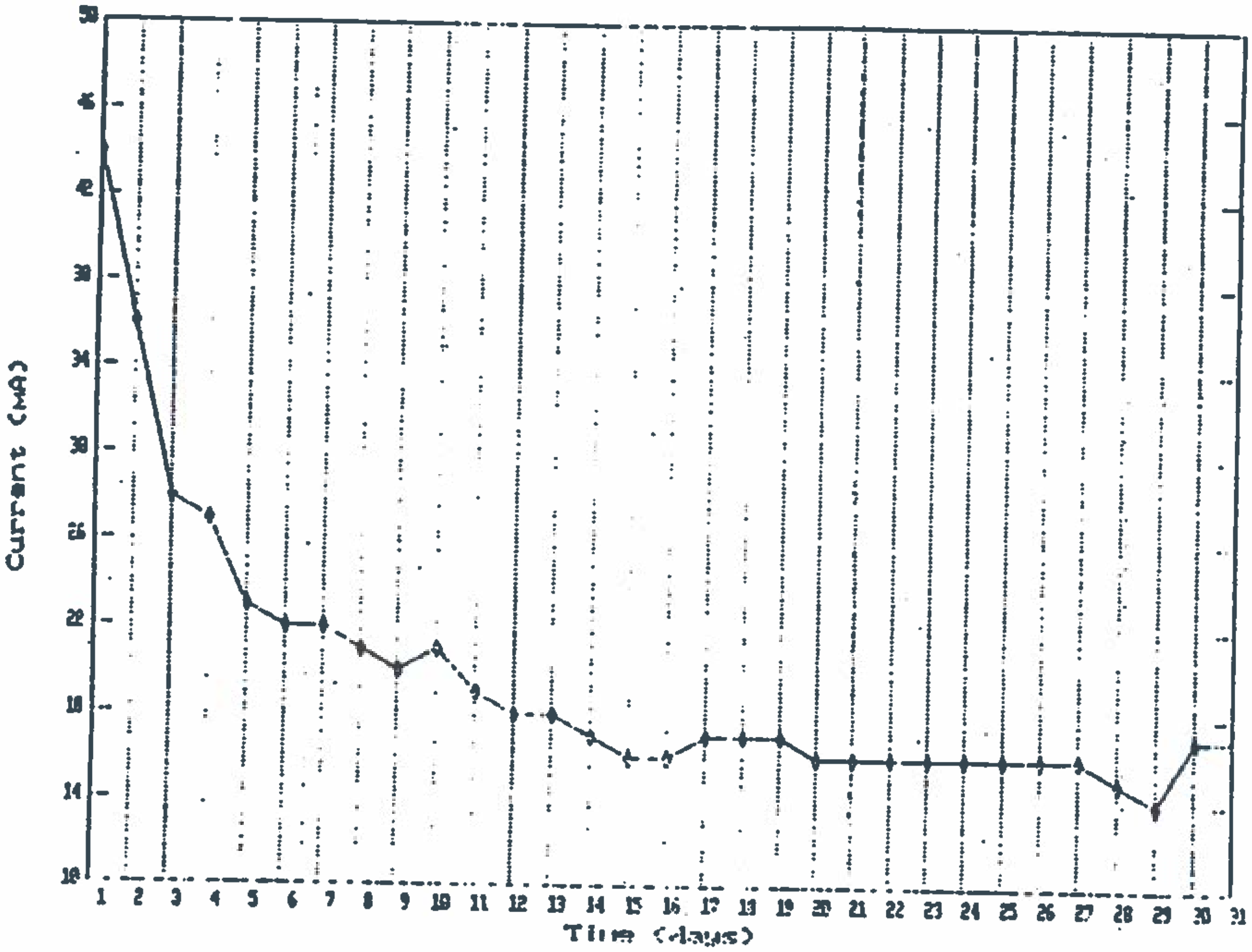

Figure F-8. Current required to shift the potential of the aluminized Type II culvert in the large water tank.

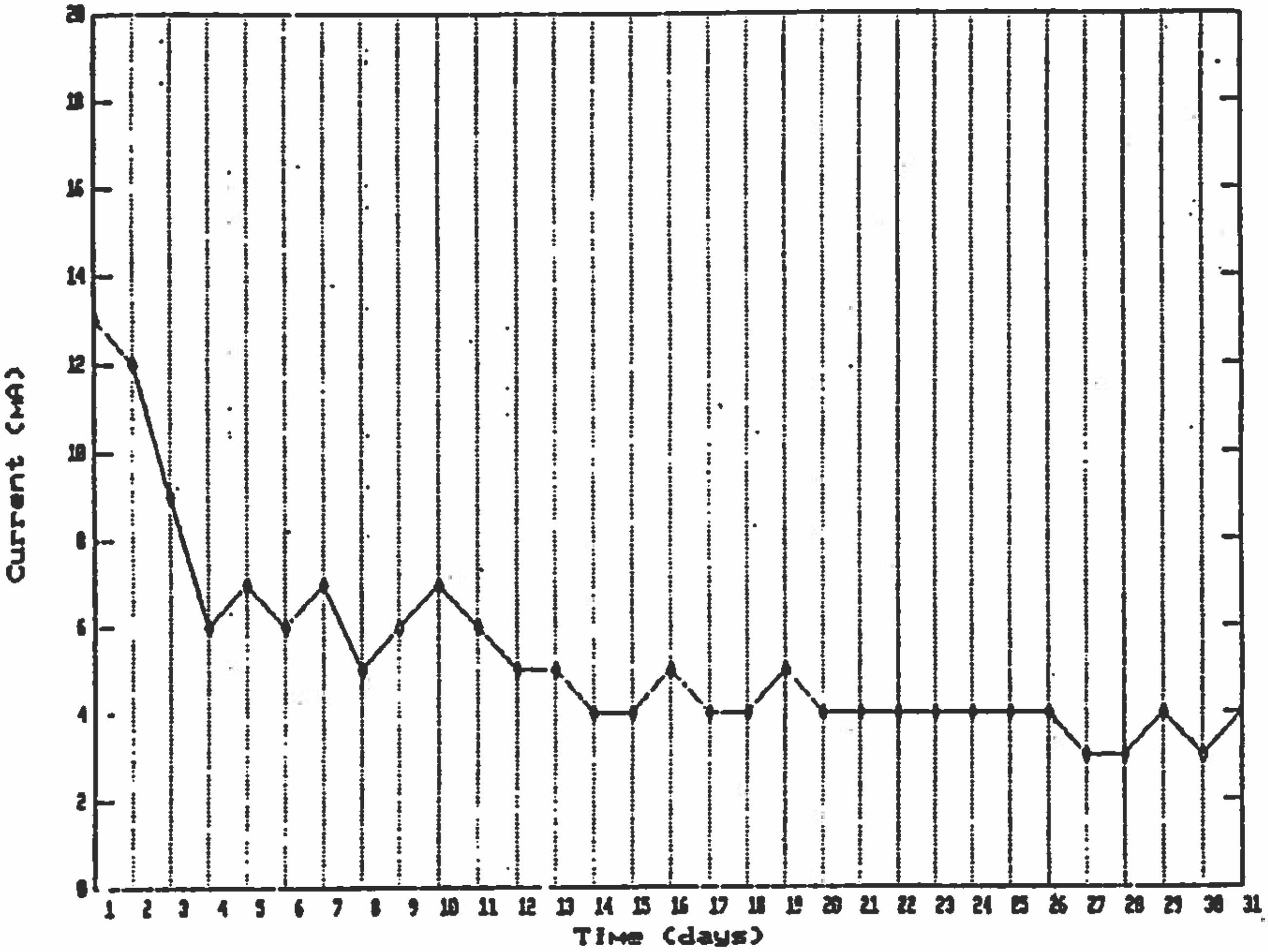

Figure F-9. Current required to shift the potential of the polymeric cold-rolled steel culvert in the large water tank.

Appendix G

Large Water Tank Test
Photographs of Exposed Culverts

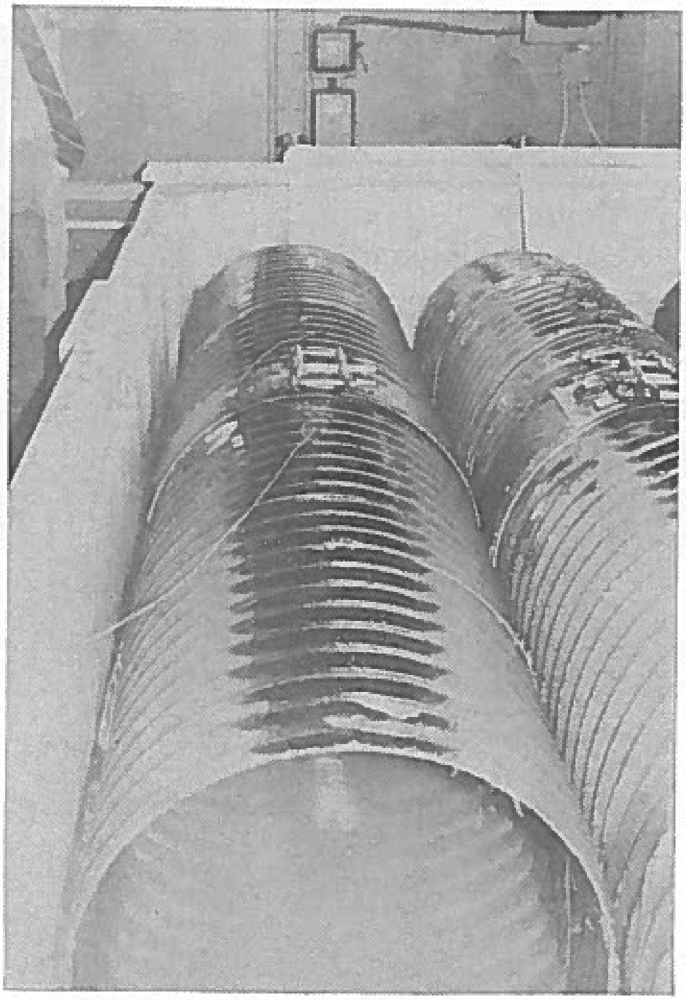

Figure G-1. This is the fiber-bonded bituminous galvanized culvert immediately after testing.

Figure G-2. The white deposits on exposed areas of the culvert can be seen.

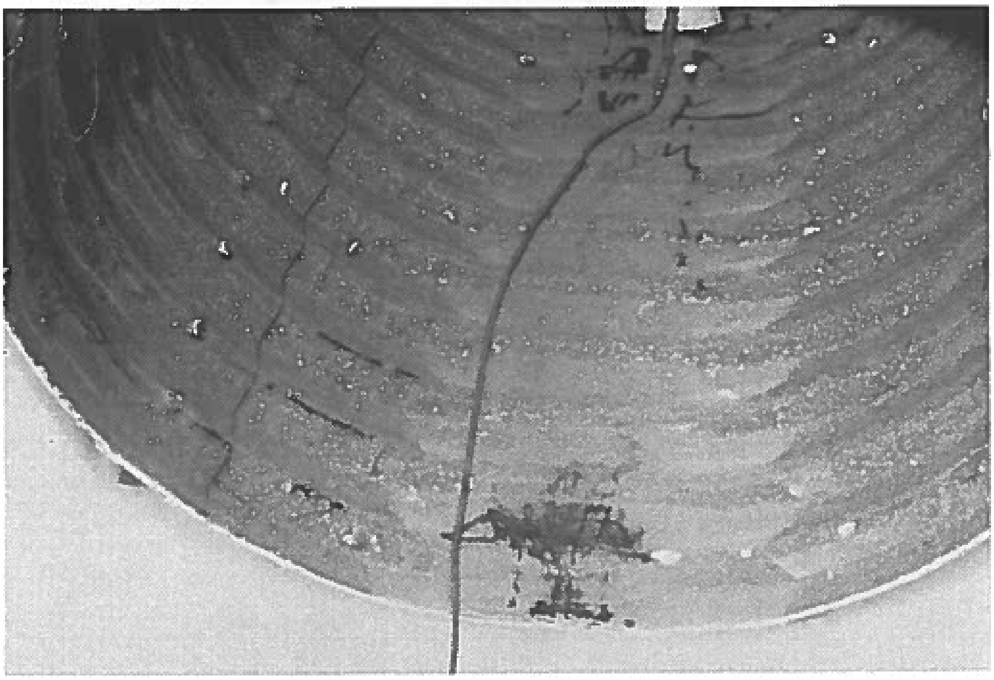

Figure G-3. A close-up view of the bottom of this culvert is shown.

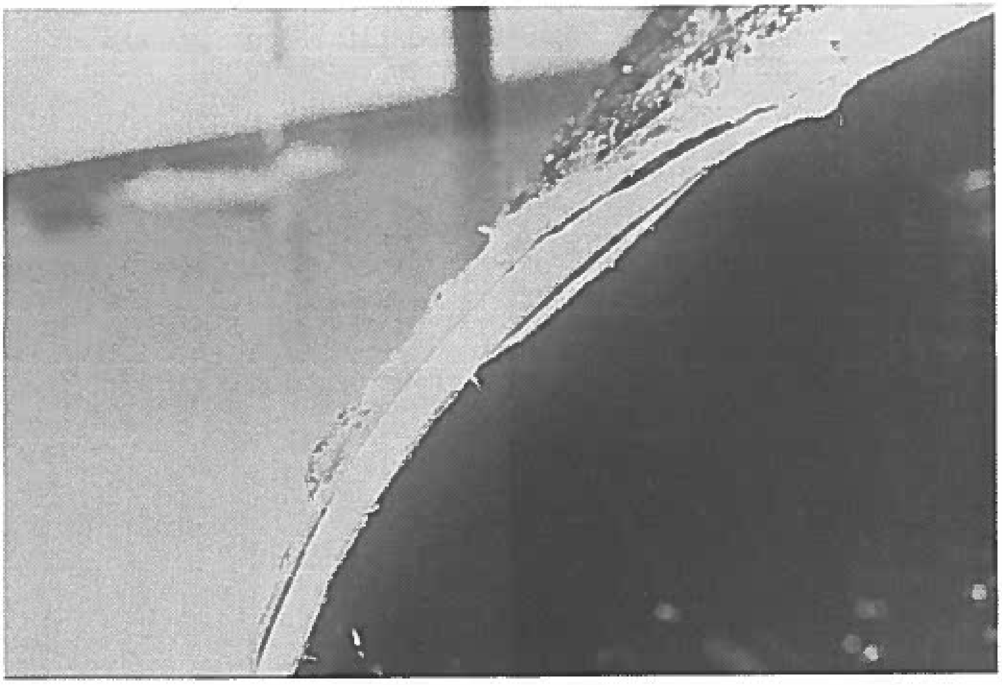

Figure G-4. This picture shows some disbondment occurring on the end of the culvert.

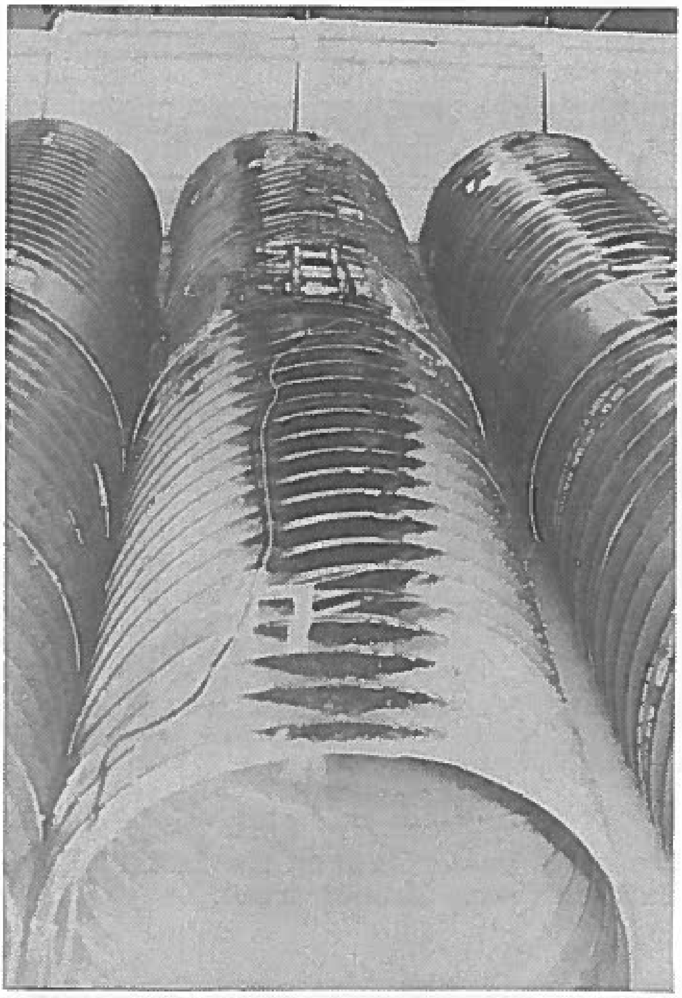

Figure G-5. This is the bituminous-coated galvanized culvert immediately after testing.

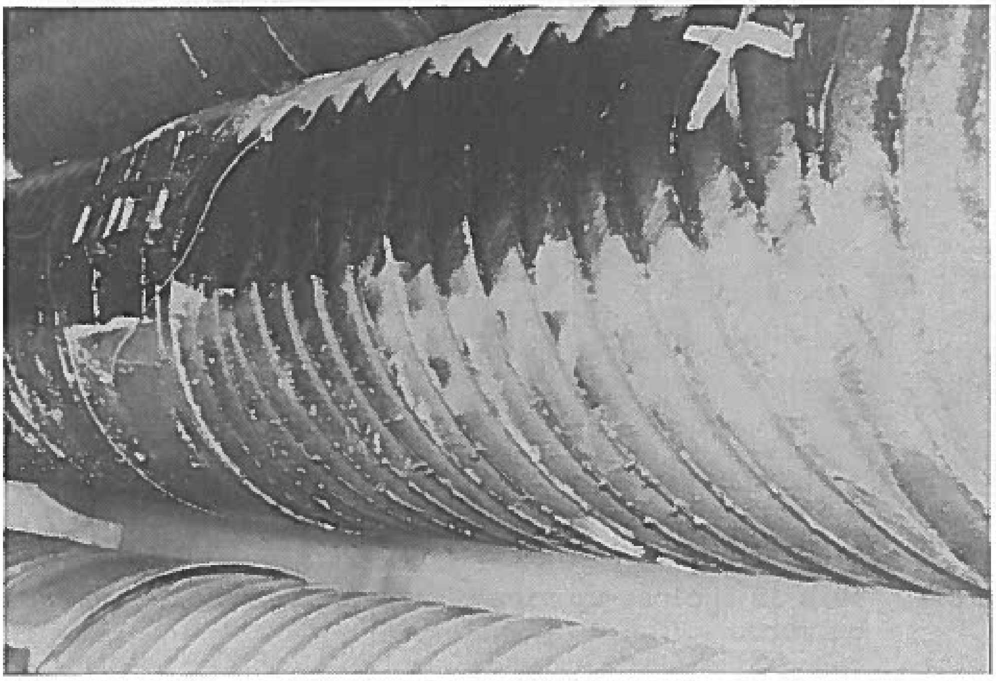

Figure G-6. A view of the outside of this culvert shows a substantial amount of deposited white powder.

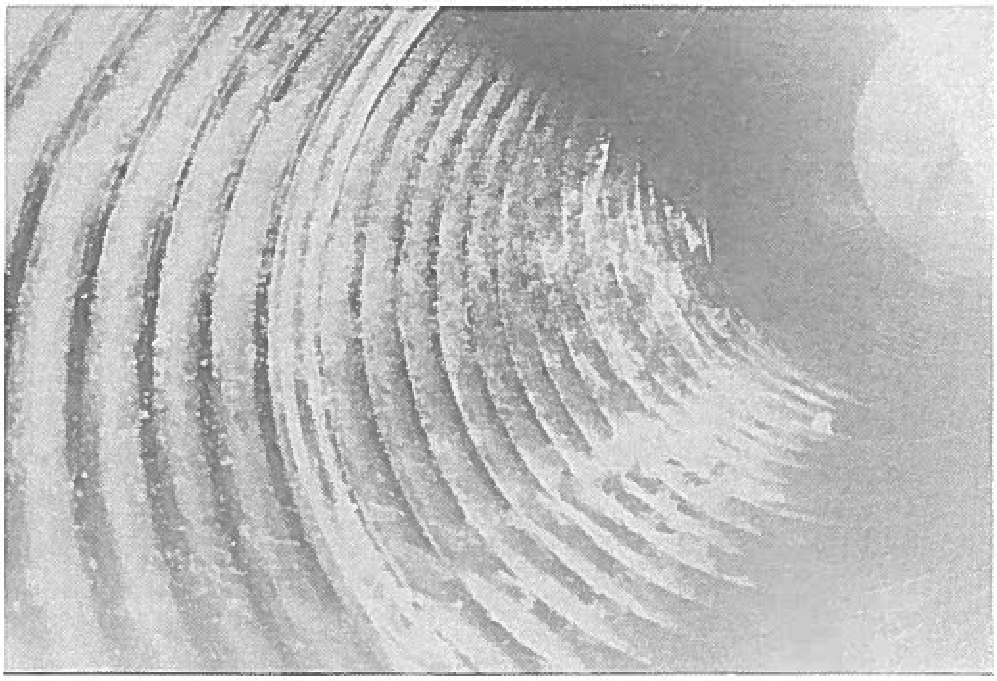

Figure G-7. The white powder seen on the inside of the culvert indicates some damaged areas.

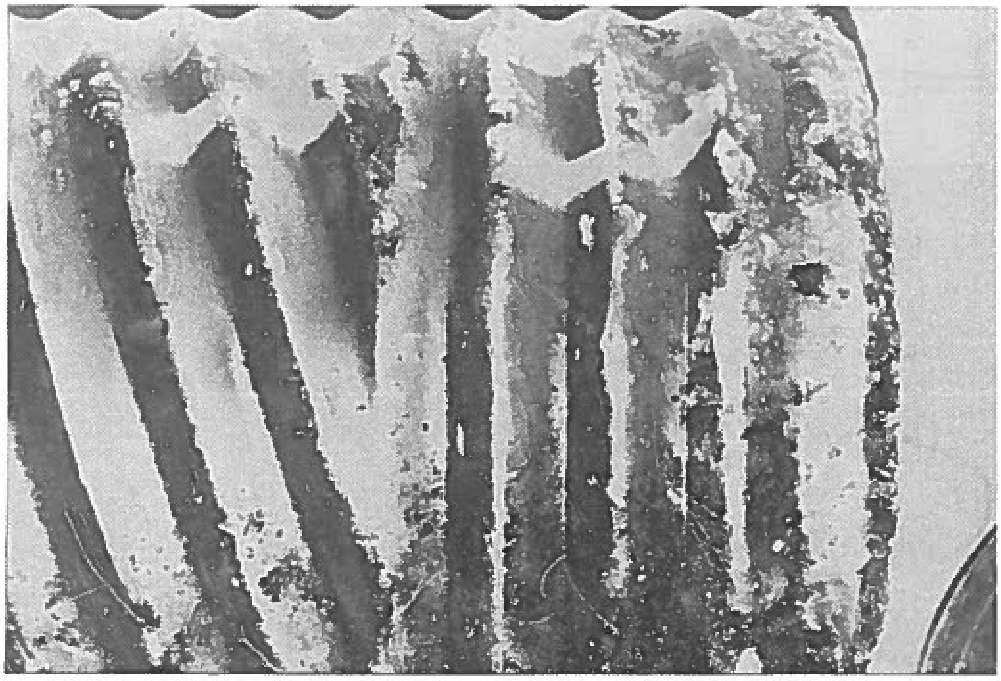

Figure G-8. This is a close-up view of the outside of the culvert.

Figure G-9. This is a close-up of the inside of the culvert.

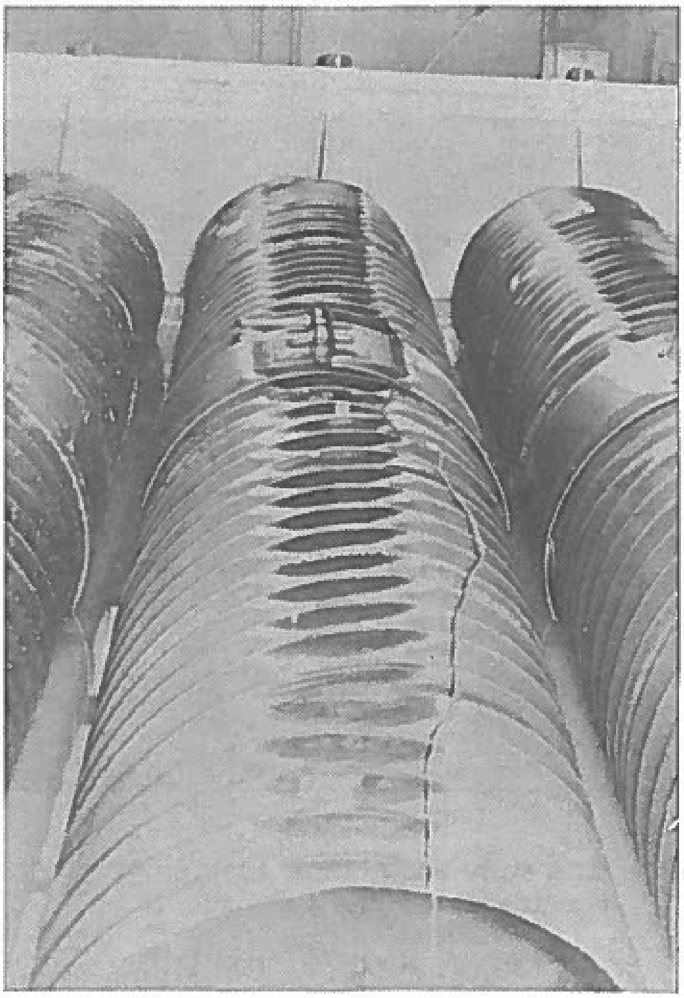

Figure G-10. This is the polymeric galvanized steel (Supplier 1) after one month of testing.

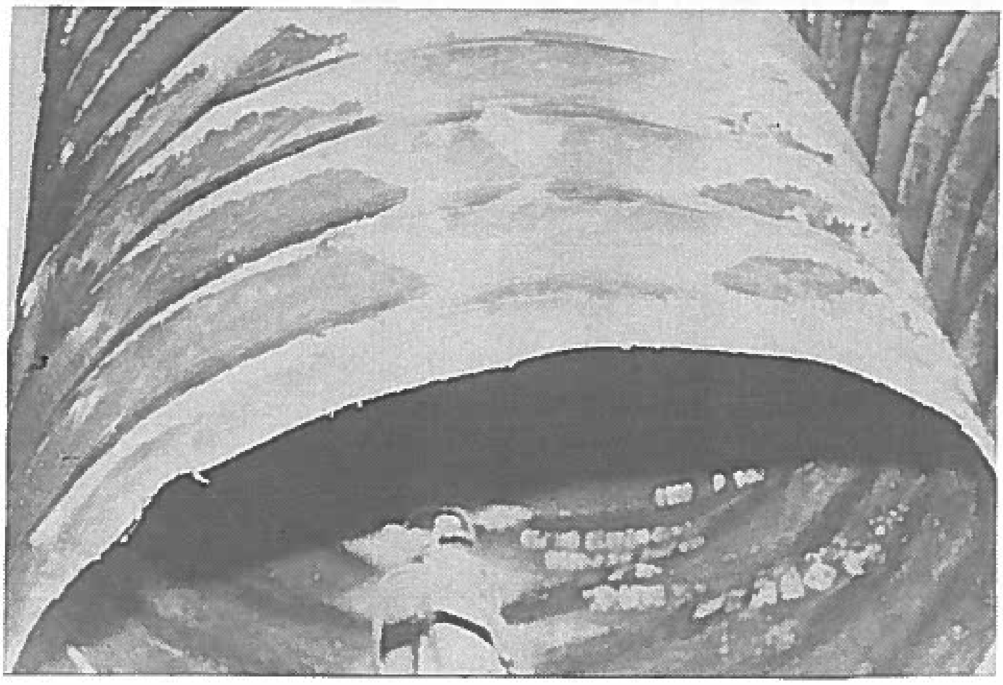

Figure G-11. A close-up of the outside of this culvert suggests a small amount of damage to the coating.

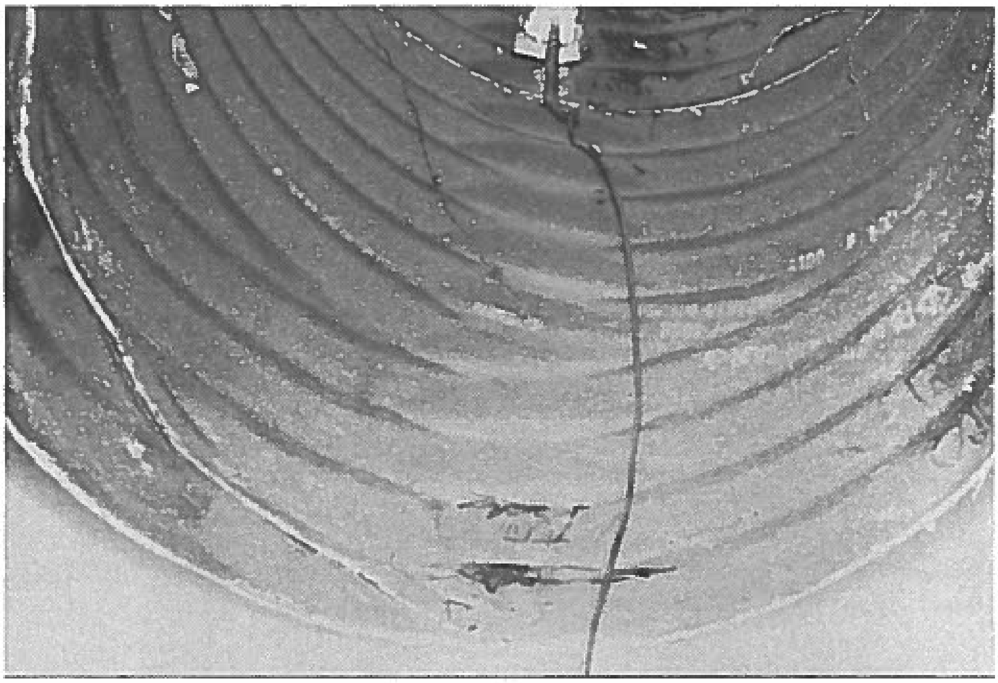

Figure G-12. This view shows some rust spots that formed on the inside of the culvert.

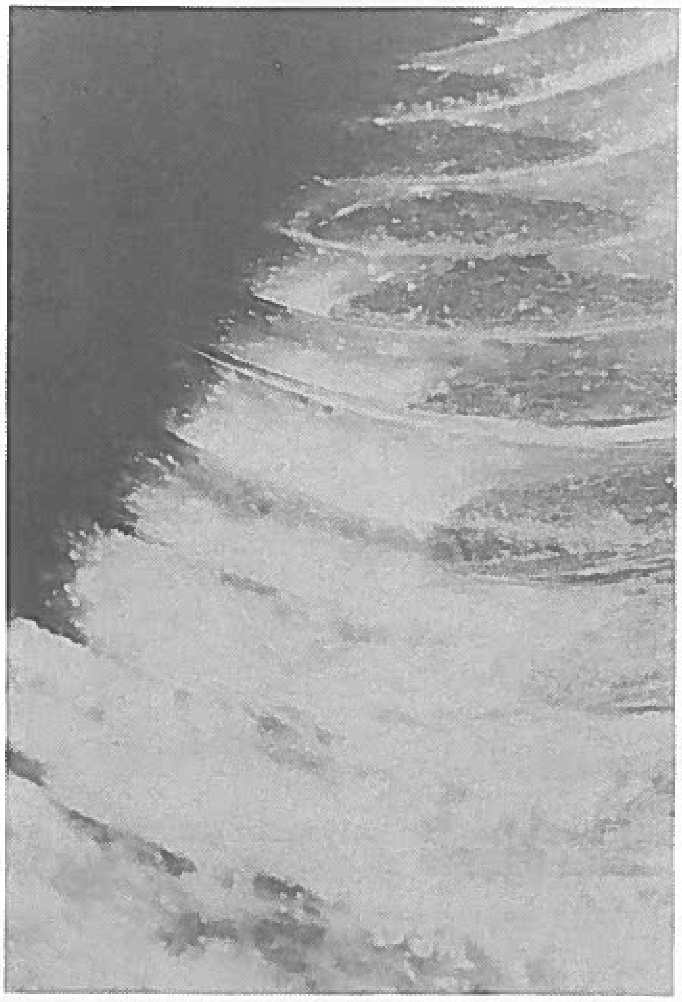

Figure G-13. This view shows a close-up of the deposits on the inside of the culvert.

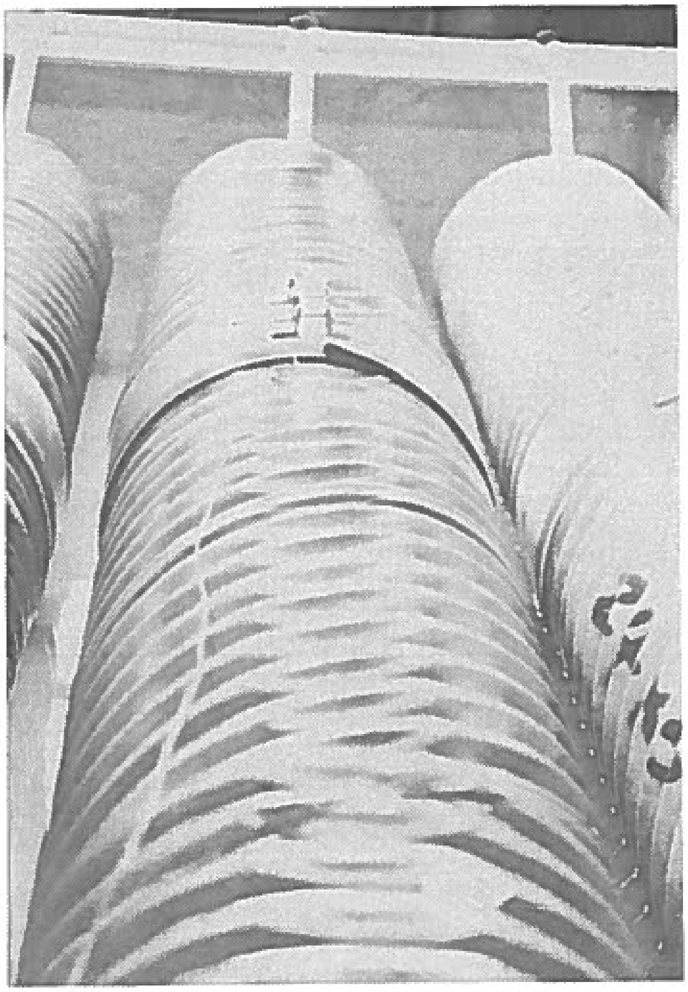

Figure G-14. This is how the polymeric galvanized steel culvert (from Supplier 2) appeared after the one-month test.

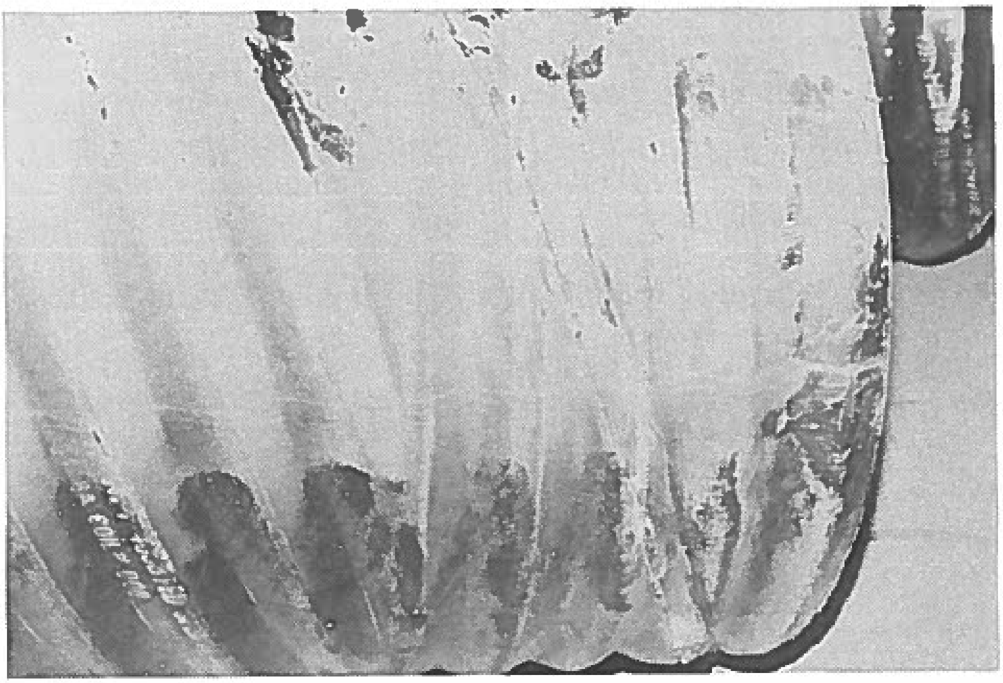

Figure G-15. This view shows very little white powder on the outside of the culvert.

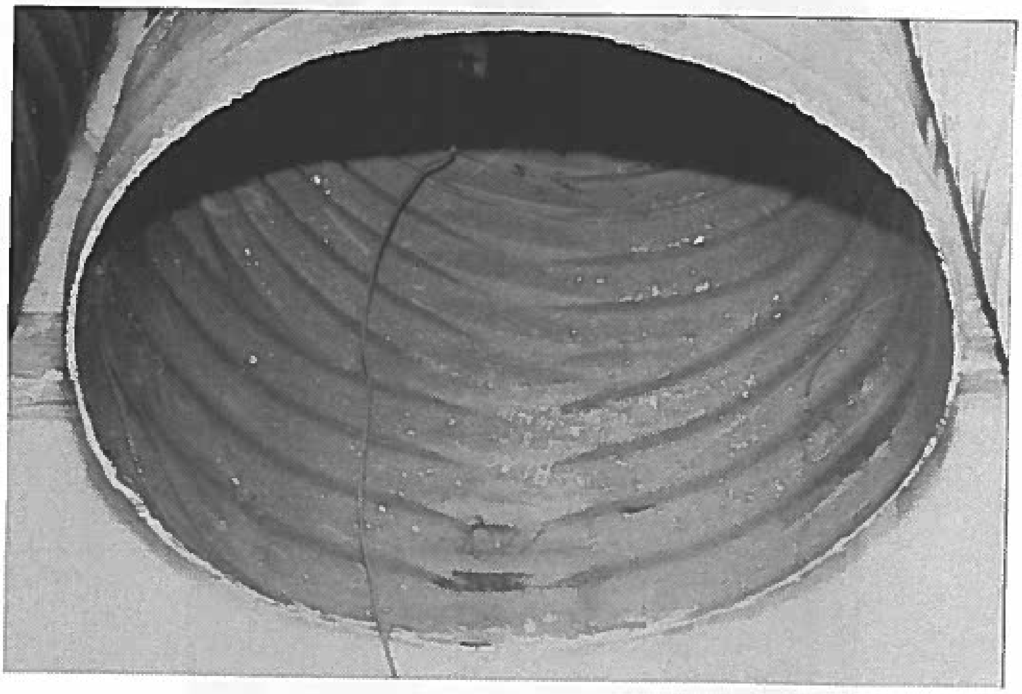

Figure G-16. This view of the inside of the culvert shows very little rust deposited in this area.

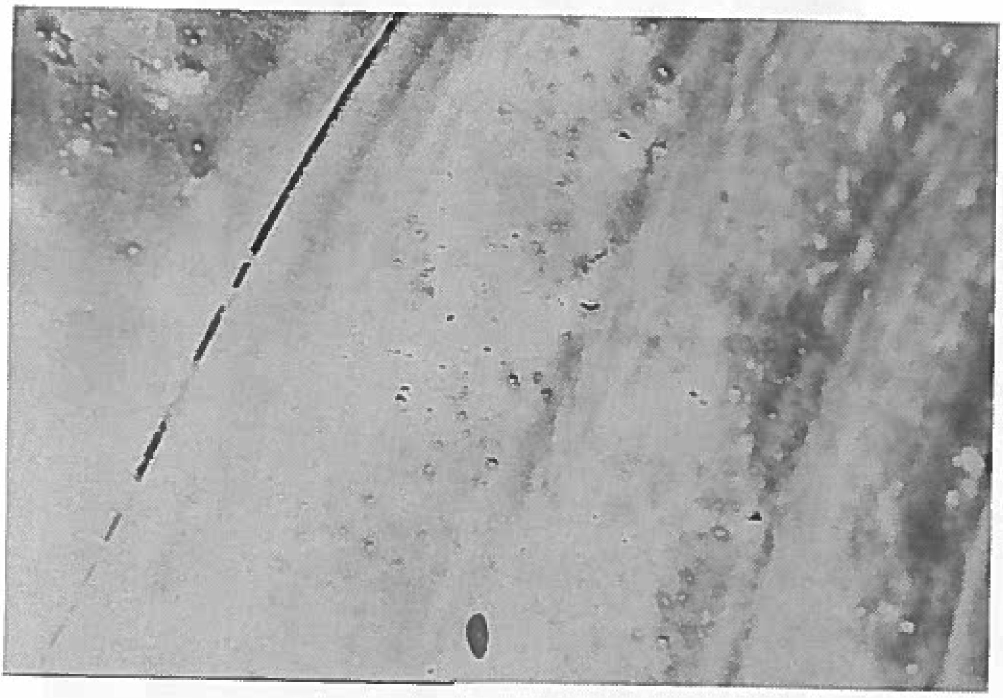

Figure G-17. This is a close-up view of the inside of the culvert showing that the deposits appear to be sediment.

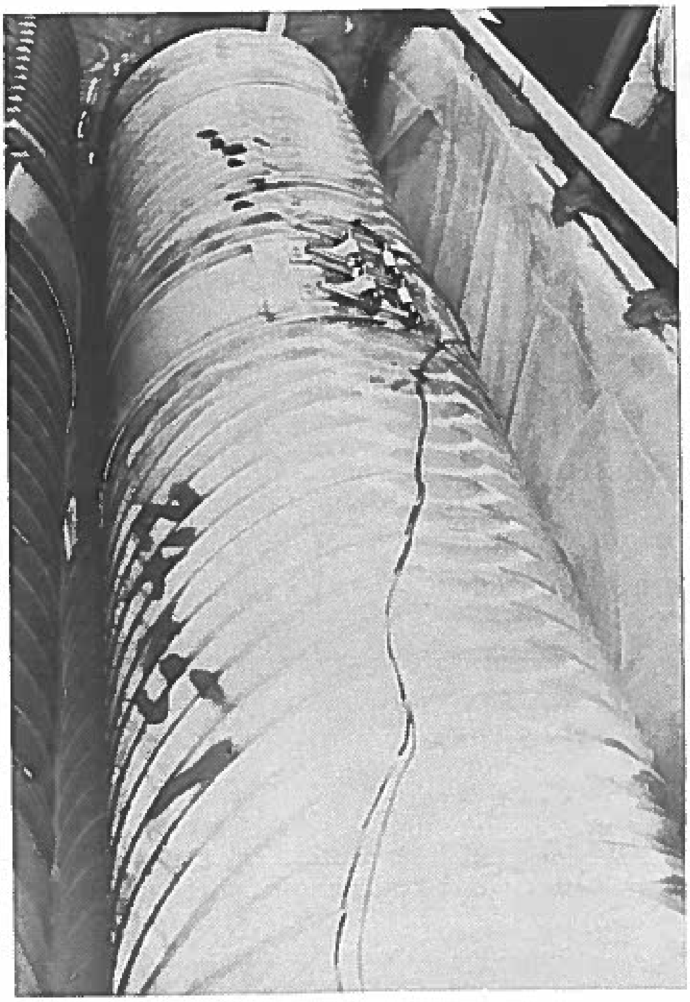

Figure G-18. This is the galvanized culvert after one month of testing.

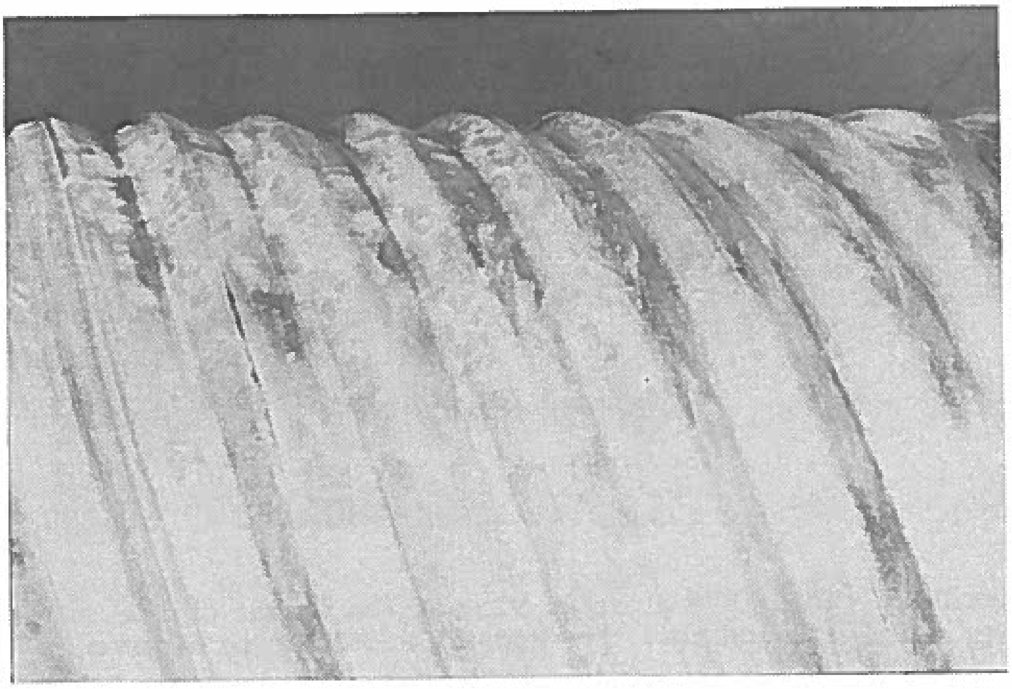

Figure G-19. This external view of the culvert shows some attack has occurred on the galvanizing.

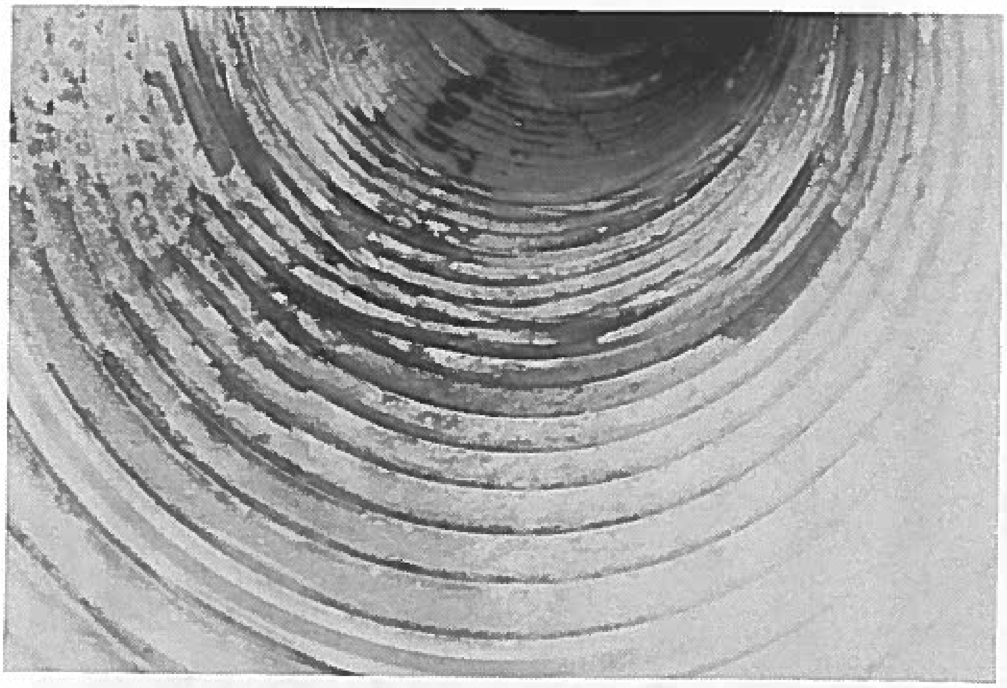

Figure G-20. An internal view of this culvert is shown in this photograph.

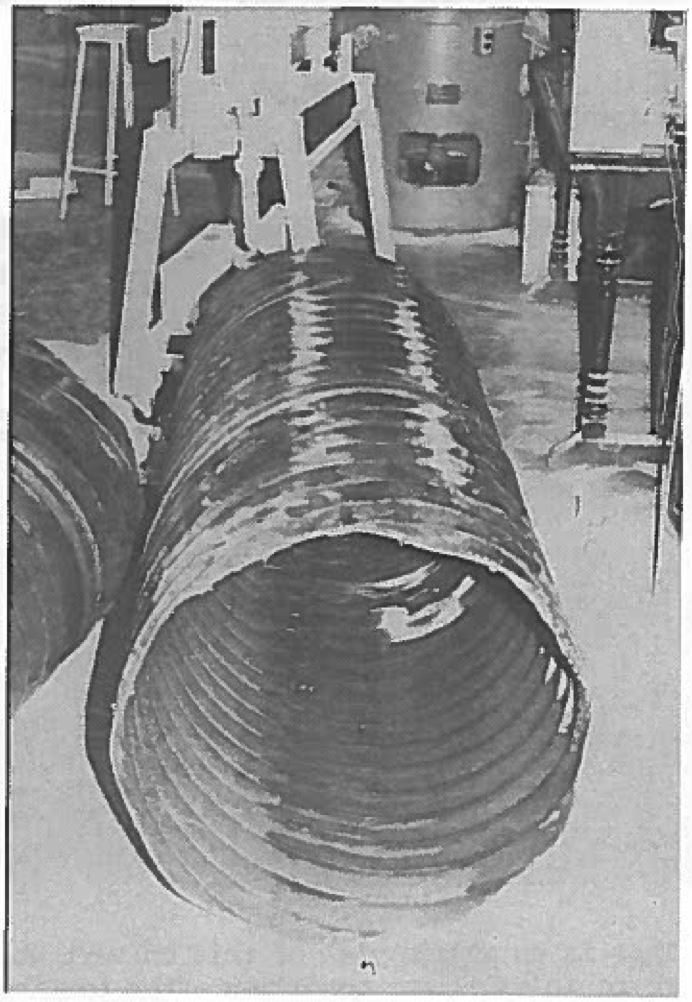

Figure G-21. This is a view of the polymeric aluminized Type I culvert after one month of testing.

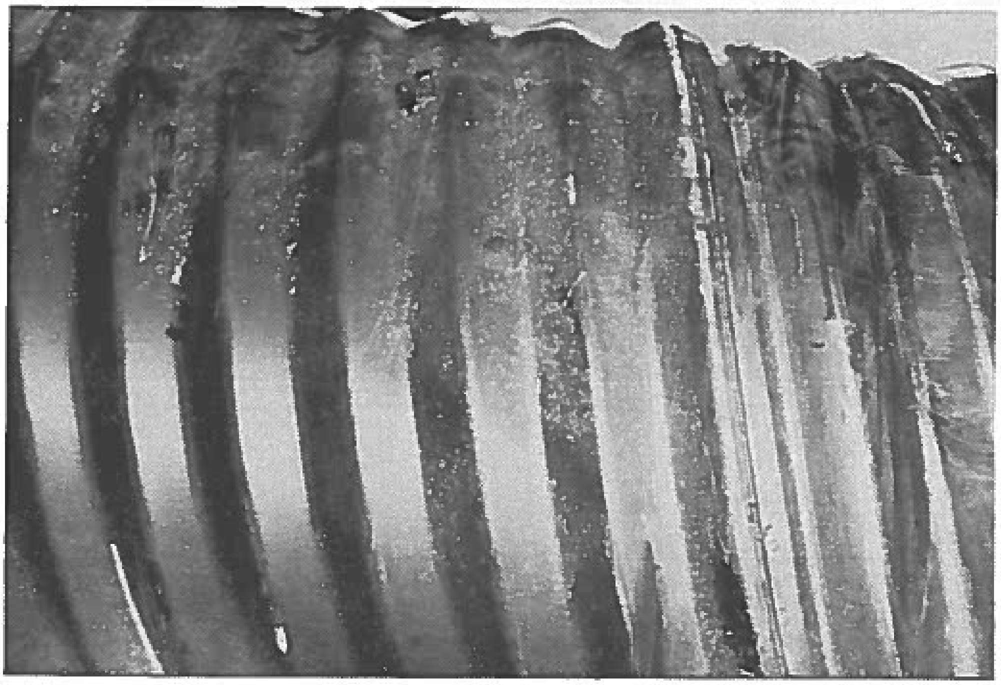

Figure G-22. This is a close-up view of the outside of this culvert showing its very good condition.

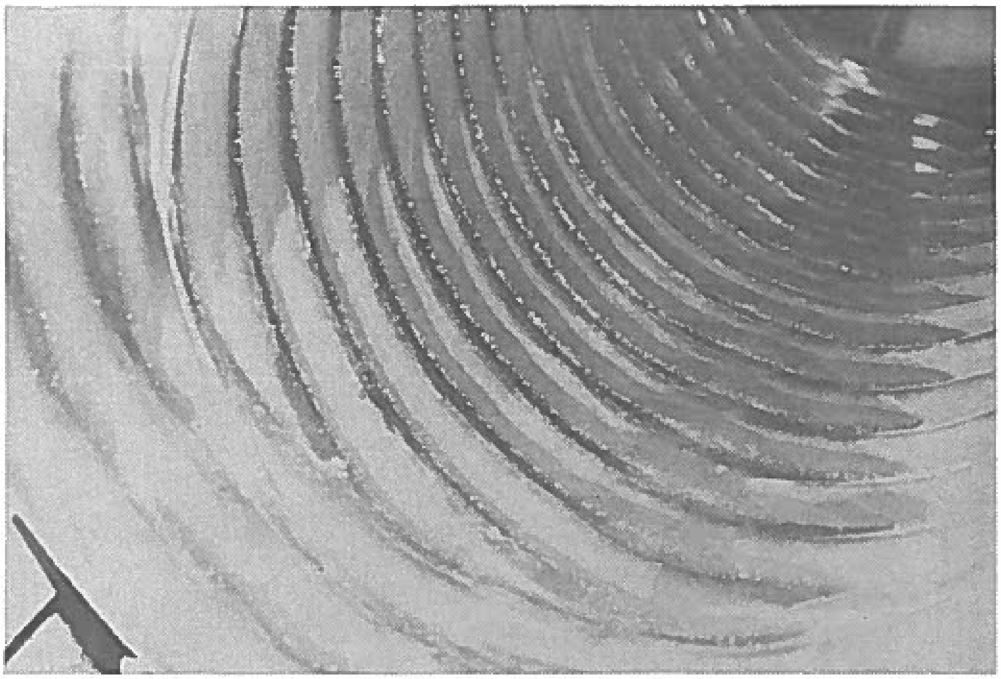

Figure G-23. This is an inside view of this culvert which appears to be in excellent condition after testing.

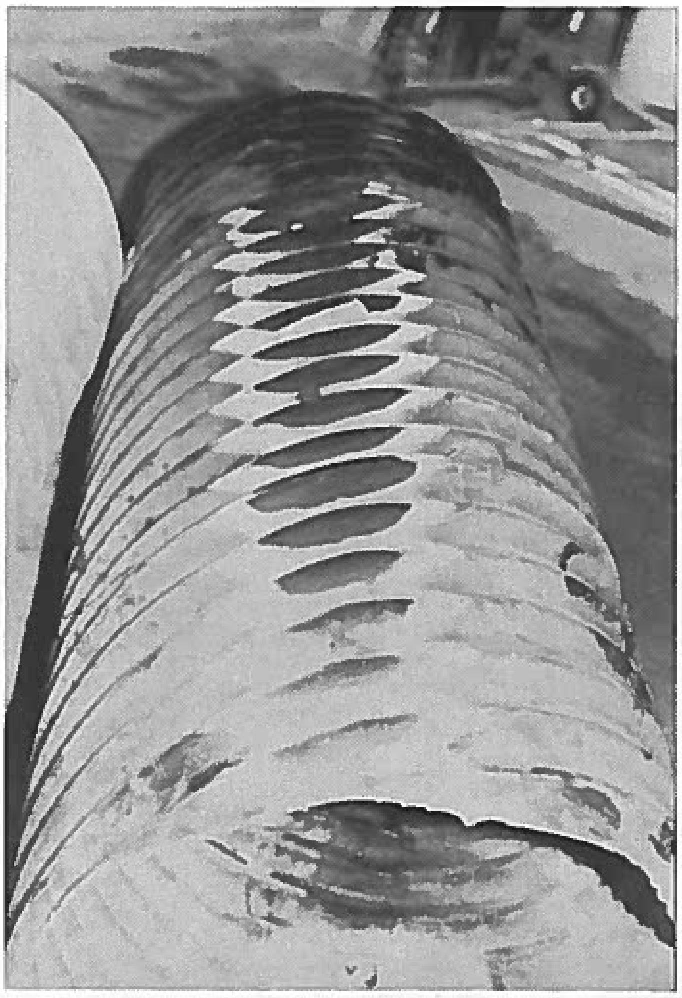

Figure G-24. This is the polymeric aluminized Type II culvert after one month of testing.

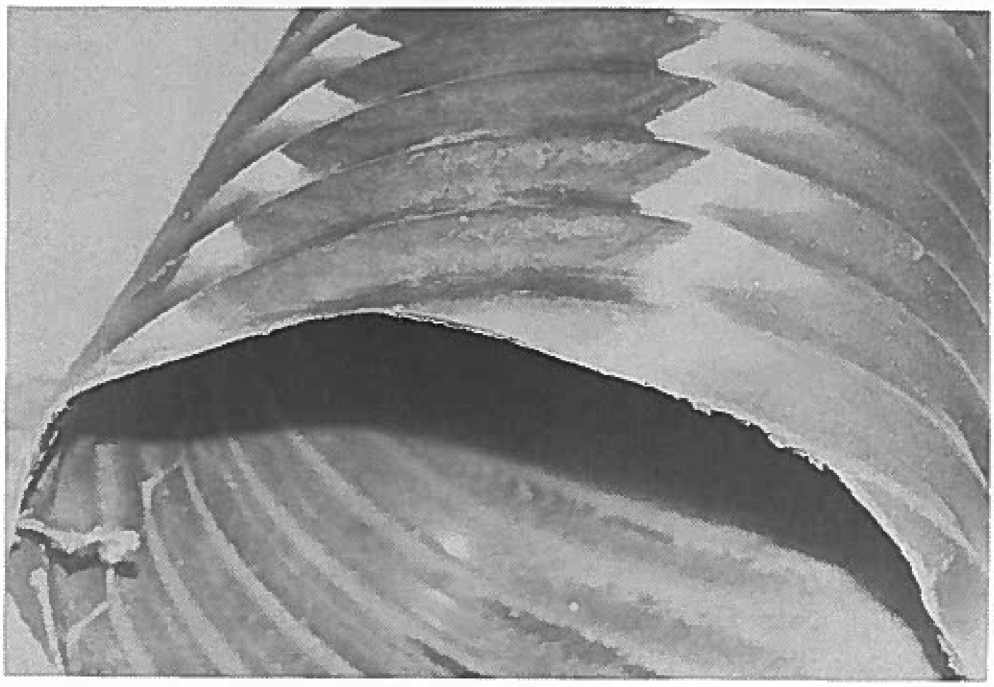

Figure G-25. This outside view of the culvert shows it to be in good condition.

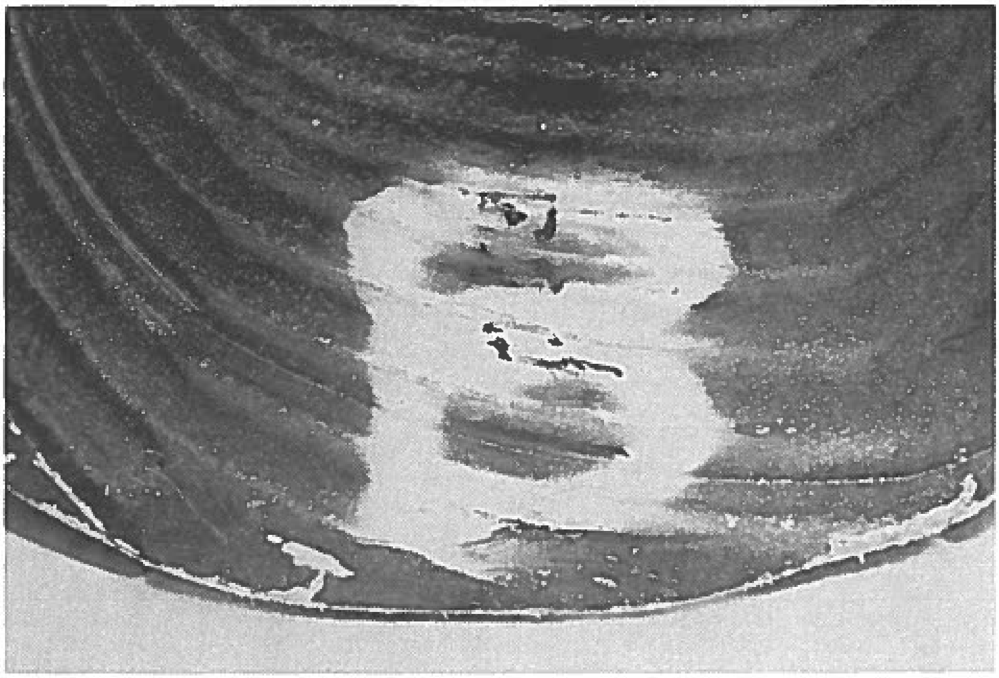

Figure G-26. The inside of this culvert shows a large number of rust spots.

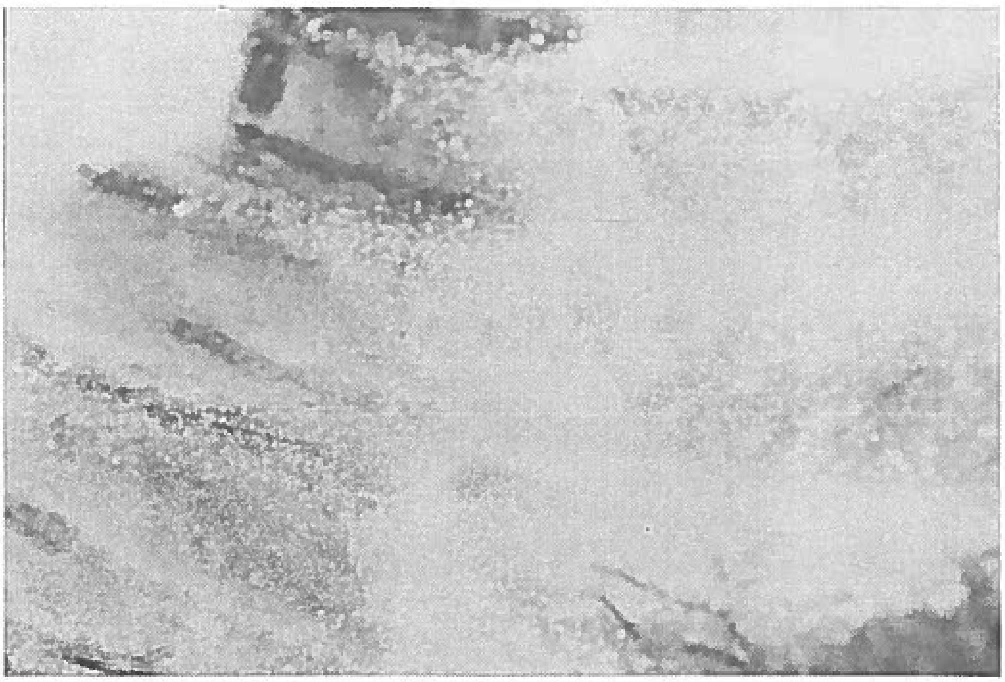

Figure G-27. This is a close-up view of the inside of this culvert which shows corrosion attack.

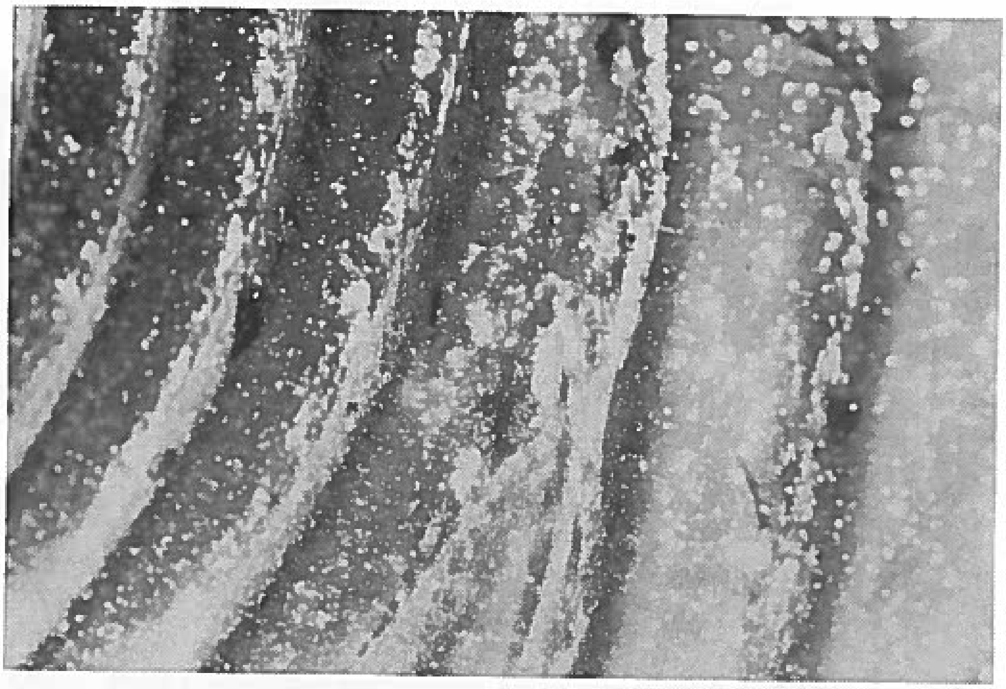

Figure G-28. Another view of the inside of this culvert shows rust as well as white powder being deposited.

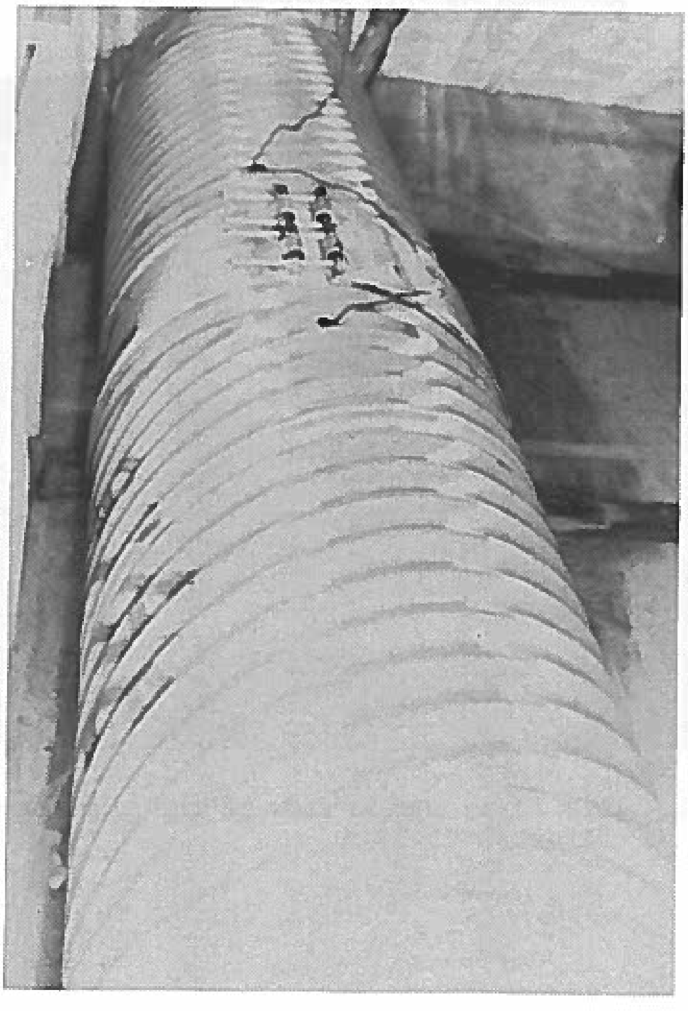

Figure G-29. This is the aluminized Type II culvert after one month of testing.

Figure G-30. This photograph shows that external attack has occurred on this culvert.

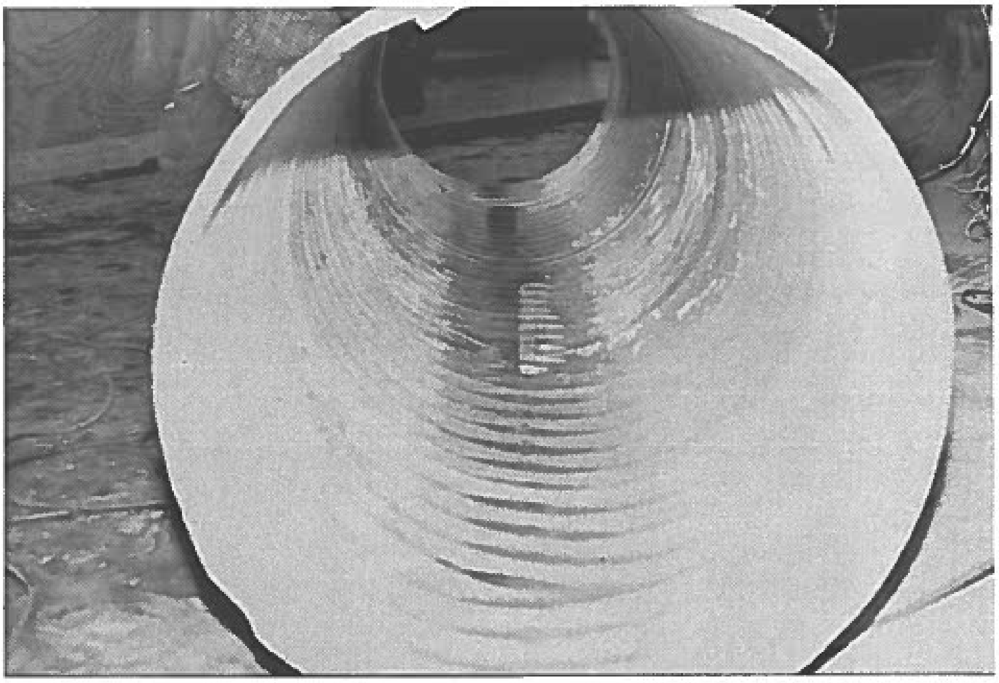

Figure G-31. This is an inside view of the aluminized Type II culvert.

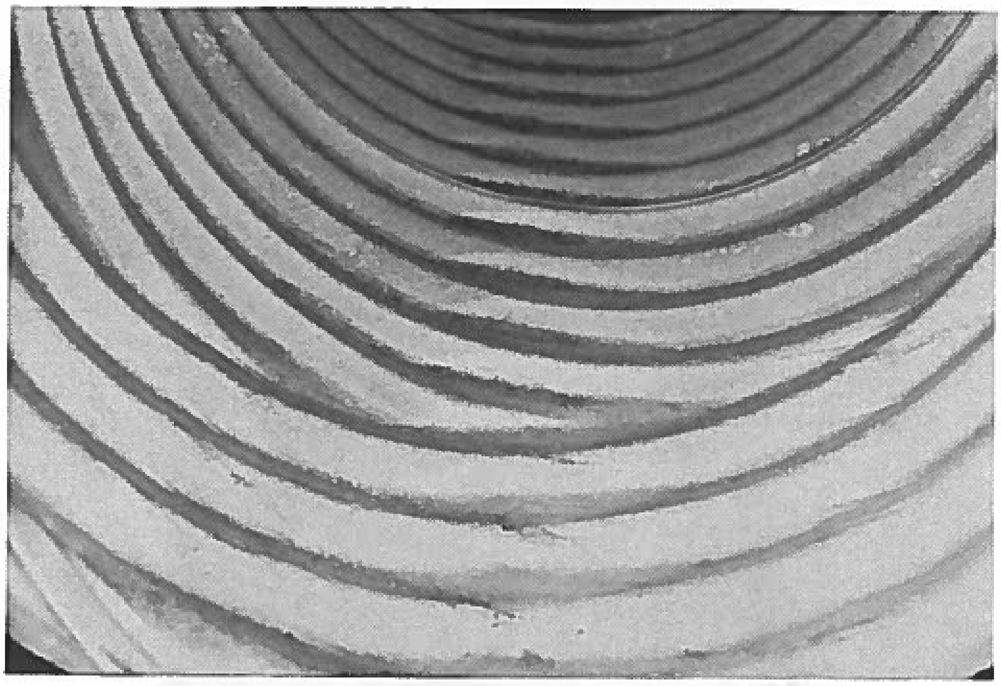

Figure G-32. A close-up view of the inside of the culvert shows that some attack has occurred.

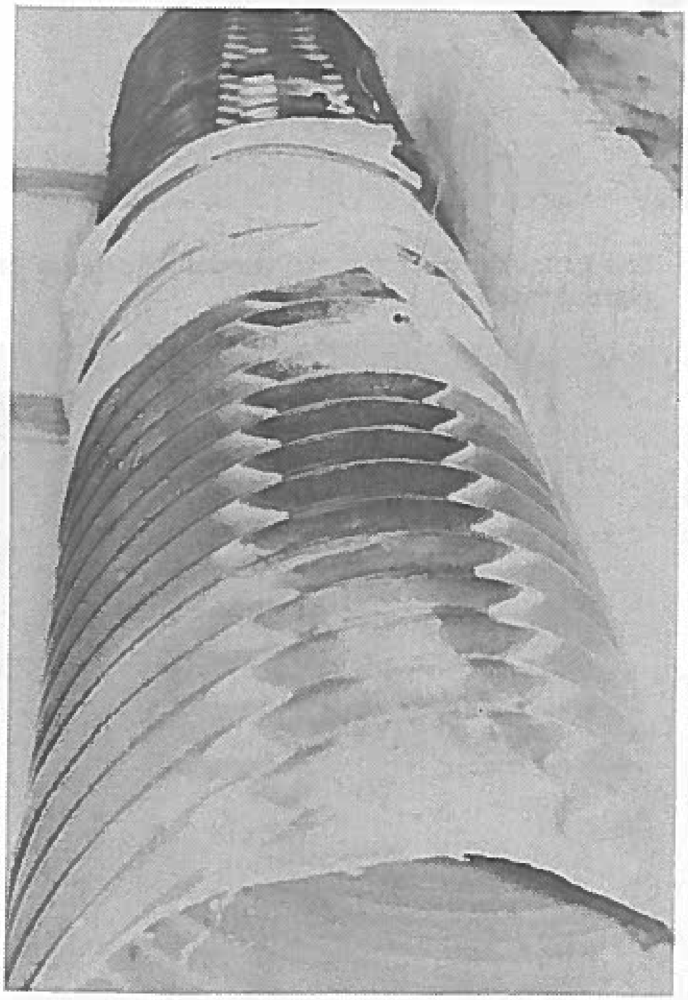

Figure G-33. This is the polymeric cold-rolled steel after one month of testing.

Figure G-34. The outside of this culvert looks good in this photograph.

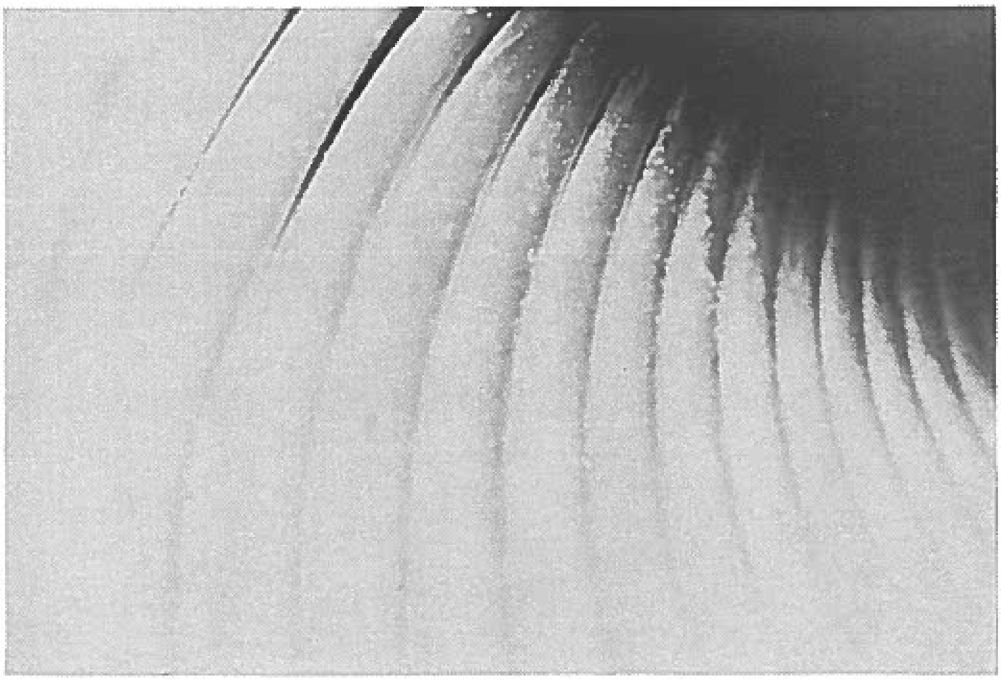

Figure G-35. This shows that the inside of the culvert was in relatively good condition.

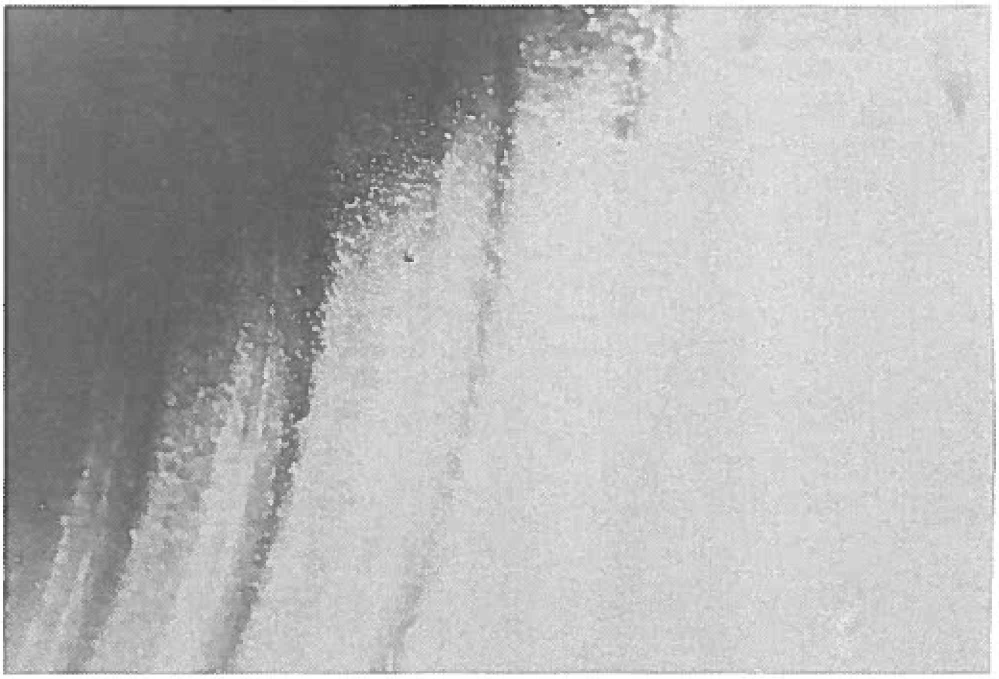

Figure G-36. This shows the white scale on the inside of the culvert.

Appendix H

Field Test Results

Internal and External Potential of the Protected and Unprotected Culverts Versus Time

Table H-1

Internal Potential Readings of the Protected Culverts

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type 2	3 Polymeric Aluminized Type 1	4 Polymeric Galvanized Steel Supplier 2	No. of Days
6/13/89	-1.122	-1.137	-1.130	-1.158	0
6/20/89	-1.087	-1.098	-1.098	-1.142	7
6/30/89	-1.052	-1.070	-1.078	-1.112	17
7/30/89	-1.020	-1.040	-1.070	-1.125	47
8/31/89	-0.990	-1.033	-1.073	-1.120	79
9/30/89	-1.018	-1.043	-1.070	-1.120	109
10/31/89	-1.010	-1.035	-1.073	-1.125	140
11/30/89	-1.010	-1.023	-1.055	-1.112	170
1/30/90	-1.010	-1.031	-1.062	-1.073	321
3/30/90	-1.031	-1.042	-1.073	-1.079	290
5/30/90	-1.038	-1.050	-1.074	-1.084	351
8/31/90	-1.052	-1.063	-1.071	-1.088	444
11/30/90	-1.032	-1.052	-1.060	-1.072	535
2/28/91	-1.039	-1.058	-----*	-1.070	625
6/13/91	-1.052	-1.057	-1.067	-1.077	730

*Measurements indicated that the culvert was disconnected from the anode. Repair was performed before the next readings were made.

TABLE H-1 (Continued)

INTERNAL POTENTIAL READINGS OF THE PROTECTED CULVERTS

Date	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized Steel	No. of Days
6/13/89	-1.140	-1.150	-1.144	-1.152	0
6/20/89	-1.117	-1.103	-1.120	-1.102	7
6/30/89	-1.094	-1.082	-1.118	-1.050	17
7/30/89	-1.060	-1.050	-1.112	-1.012	47
8/31/89	-1.050	-1.060	-1.090	-1.047	79
9/30/89	-1.060	-1.055	-1.090	-1.050	109
10/31/89	-1.050	-1.068	-1.092	-1.052	140
11/30/89	-1.036	-1.043	-1.058	-1.030	170
1/30/90	-1.050	-1.070	-1.057	-1.021	231
3/30/90	-1.065	-1.081	-1.055	-1.026	290
5/30/90	-1.075	-1.090	-1.064	-1.043	351
8/31/90	-1.075	-1.092	-1.061	-1.049	444
11/30/90	-1.059	-1.057	-1.018	-1.052	535
2/28/91	-1.061	-1.061	-1.030	-1.031	625
6/13/91	-1.069	-1.063	-1.027	-1.051	730

TABLE H-2

INTERNAL POTENTIAL READINGS OF THE UNPROTECTED CULVERTS

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type 2	3 Polymeric Aluminized Type 1	4 Polymeric Galvanized Steel Supplier 2	No. of Days
6/13/89	-1.080	-0.755	-0.743	-1.107	0
6/20/89	-1.050	-0.797	-0.785	-1.037	7
6/30/89	-0.972	-0.764	-0.785	-0.990	17
7/30/89	-0.822	-0.730	-0.758	-0.884	47
8/31/89	-0.735	-0.718	-0.723	-0.784	79
9/30/89	-0.705	-0.718	-0.721	-0.780	109
10/31/89	-0.682	-0.705	-0.712	-0.740	140
11/30/89	-0.667	-0.687	-0.690	-0.718	170
1/30/90	-0.678	-0.703	-0.705	-0.706	231
3/30/90	-0.674	-0.709	-0.706	-0.707	290
5/30/90	-0.677	-0.709	-0.714	-0.706	351
8/31/90	-0.687	-0.709	-0.717	-0.676	444
11/30/90	-0.663	-0.676	-0.702	-0.658	535
2/28/91	-0.623	-0.660	-0.682	-0.640	625
6/13/91	-0.651	-0.662	-0.690	-0.661	730

TABLE H-2 (Continued)

INTERNAL POTENTIAL READINGS OF THE UNPROTECTED CULVERTS

	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized	No. of Days
6/13/89	-1.119	-1.138	-1.160	-1.136	0
6/20/89	-1.108	-1.085	-1.118	-1.061	7
6/30/89	-1.090	-1.024	-1.133	-0.984	17
7/30/89	-0.936	-0.948	-1.095	-0.900	47
8/31/89	-0.856	-0.934	-1.088	-0.840	79
9/30/89	-0.790	-0.940	-1.090	-0.840	109
10/31/89	-0.775	-0.956	-1.080	-0.892	140
11/30/89	-0.757	-0.940	-1.070	-0.878	170
1/30/90	-0.741	-0.949	-1.075	-0.806	231
3/30/90	-0.774	-1.007	-1.034	-0.783	290
5/30/90	-0.764	-1.008	-1.022	-0.779	351
8/31/90	-0.767	-0.981	-0.997	-0.756	444
11/30/90	-0.729	-1.023	-0.996	-0.882	535
2/28/91	-0.724	-0.978	-0.956	-0.828	625
6/13/91	-0.731	-0.965	-0.931	-0.775	730

TABLE H-3

EXTERNAL POTENTIAL READINGS OF THE PROTECTED CULVERTS

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type II	3 Polymeric Aluminized Type I	4 Polymeric Galvanized Steel Supplier 2	Nos. of Days
7/30/89	-1.003	-1.040	-1.064	-1.067	47
8/31/89	-0.988	-1.016	-1.054	-1.054	79
9/30/89	-1.003	-1.027	-1.054	-1.060	109
10/31/89	-1.010	-1.027	-1.063	-1.064	140
11/30/89	-1.004	-1.030	-1.050	-1.055	170
1/30/90	-1.006	-1.028	-1.054	-1.070	231
3/30/90	-1.024	-1.029	-1.065	-1.075	290
5/30/90	-1.034	-1.048	-1.073	-1.082	351
8/31/90	-1.045	-1.054	-1.068	-1.082	444
11/30/90	-1.028	-1.048	-1.059	-1.067	535
2/28/91	-1.035	-1.064	---*	-1.068	625
6/13/91	-1.055	-1.066	-1.075	-1.076	730

*Measurements indicated that the culvert was disconnected from the anode. Repair was performed before the next readings were made.

TABLE H-3 (Continued)

EXTERNAL POTENTIAL READINGS OF THE PROTECTED CULVERTS

Date	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized	No. of Days
7/30/89	-1.056	-1.044	-1.117	-1.007	47
8/31/89	-1.040	-1.033	-1.046	-1.011	79
9/30/89	-1.048	-1.035	-1.043	-1.006	109
10/31/89	-1.053	-1.046	-1.035	-1.018	140
11/30/89	-1.038	-1.028	-1.018	-0.998	170
1/30/90	-1.046	-1.053	-1.015	-1.006	231
3/30/90	-1.065	-1.060	-1.012	-1.000	290
5/30/90	-1.068	-1.061	-1.007	-0.999	351
8/31/90	-1.073	-1.060	-1.009	-1.027	444
11/30/90	-1.056	-1.042	-0.996	-1.015	535
2/28/91	-1.066	-1.045	-1.003	-1.022	625
6/13/91	-1.076	-1.059	-1.001	-1.045	730

TABLE H-4

EXTERNAL POTENTIAL READINGS OF THE UNPROTECTED CULVERTS

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type II	3 Polymeric Aluminized Type I	4 Polymeric Galvanized Steel Supplier 2	No. of Days
7/30/89	-0.831	-0.735	-0.753	-0.883	47
8/31/89	-0.730	-0.712	-0.725	-0.780	79
9/30/89	-0.703	-0.710	-0.720	-0.774	109
10/31/89	-0.684	-0.708	-0.712	-0.740	140
11/30/89	-0.670	-0.688	-0.698	-0.720	170
1/30/90	-0.679	-0.693	-0.707	-0.707	231
3/30/90	-0.682	-0.701	-0.708	-0.706	290
5/30/90	-0.678	-0.697	-0.713	-0.700	351
8/31/90	-0.683	-0.704	-0.713	-0.656	444
11/30/90	-0.662	-0.674	-0.700	-0.657	535
2/28/91	-0.631	-0.659	-0.638	-0.644	625
6/13/91	-0.662	-0.662	-0.689	-0.666	730

TABLE H-4 (Continued)

EXTERNAL POTENTIAL READINGS OF THE UNPROTECTED CULVERTS

Date	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized	No. of Days
7/30/89	-0.934	-0.940	-1.093	-0.892	47
8/31/89	-0.853	-0.928	-1.047	-0.836	79
9/30/89	-0.788	-0.936	-1.034	-0.840	109
10/31/89	-0.775	-0.958	-1.034	-0.900	140
11/30/89	-0.755	-0.940	-1.018	-0.880	170
1/30/90	-0.736	-0.922	-0.999	-0.805	231
3/30/90	-0.767	-0.945	-0.991	-0.778	290
5/30/90	-0.755	-0.953	-0.982	-0.761	351
8/31/90	-0.740	-0.967	-0.927	-0.741	444
11/30/90	-0.729	-1.027	-0.967	-0.884	535
2/28/91	-0.722	-0.952	-0.933	-0.812	625
6/13/91	-0.734	-0.945	-0.909	-0.766	730

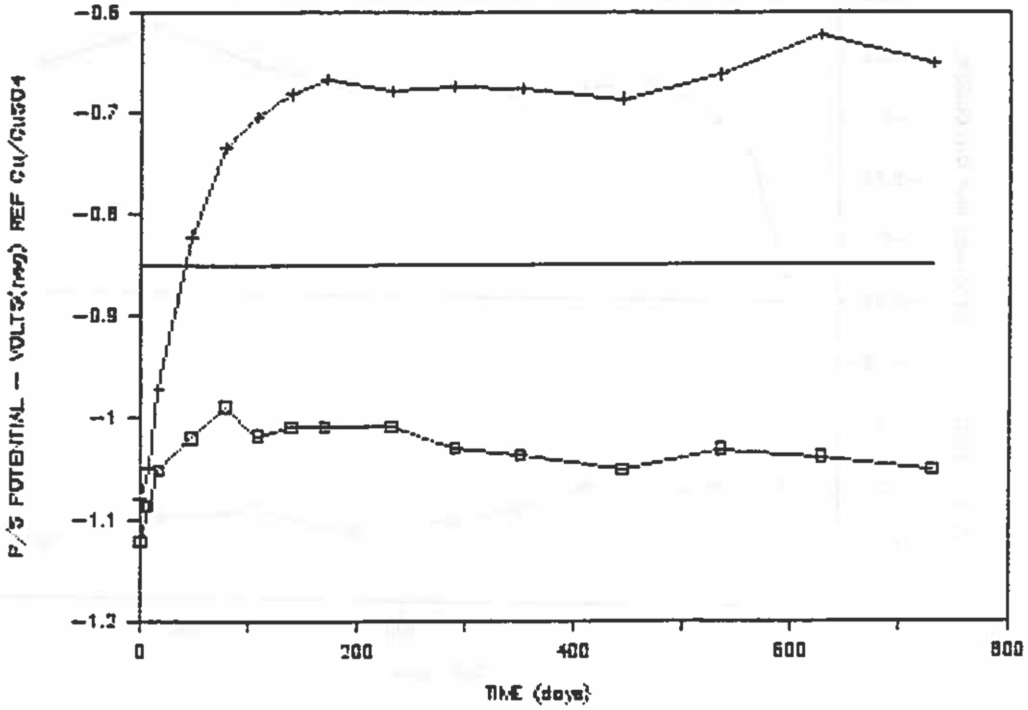

Figure H-1. Internal potential readings of the protected (□) and unprotected (+) polymeric cold-rolled steel culvert.

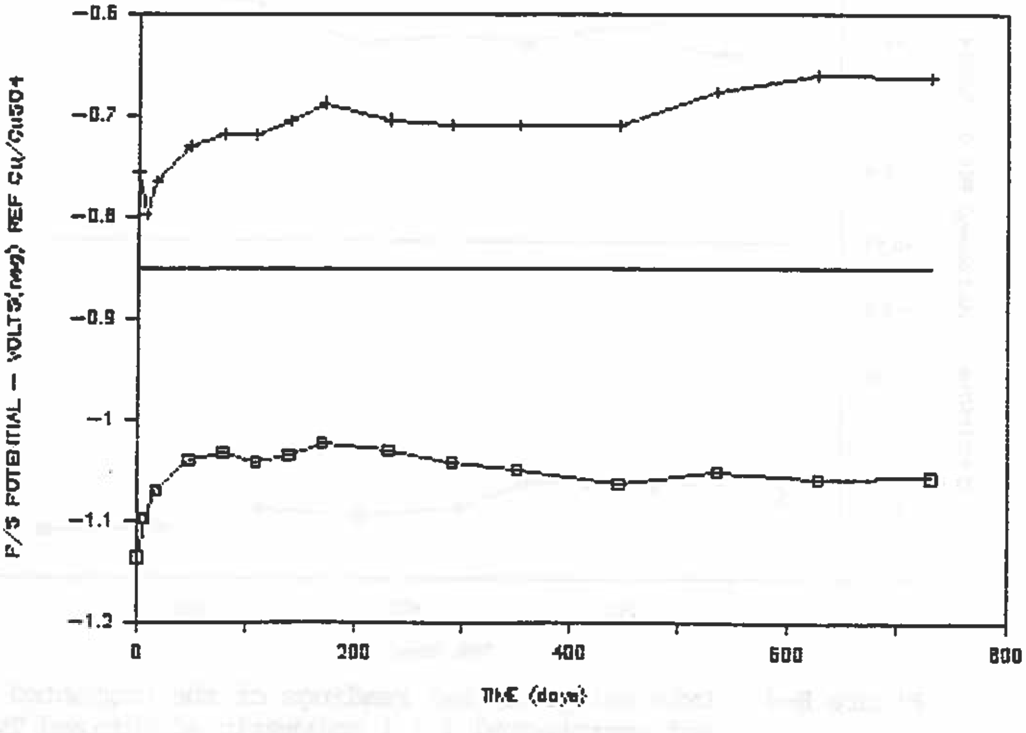

Figure H-2. Internal potential readings of the protected (□) and unprotected (+) polymeric aluminized Type II culvert.

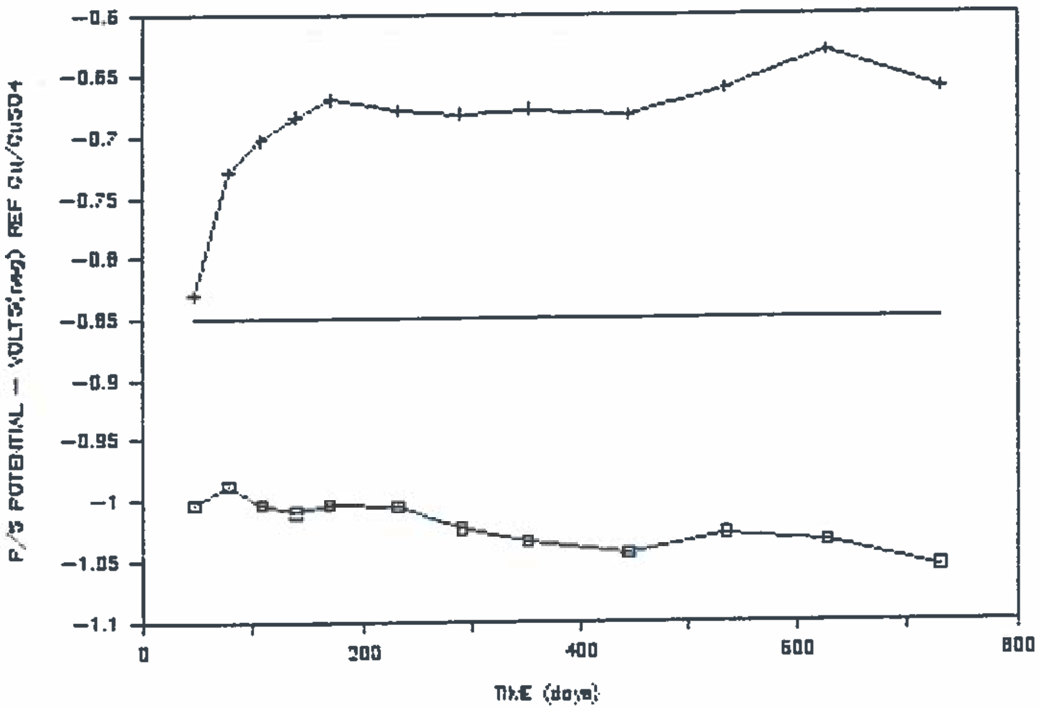

Figure H-3. External potential readings of the protected (□) and unprotected (+) polumeric cold-rolled steel culvert.

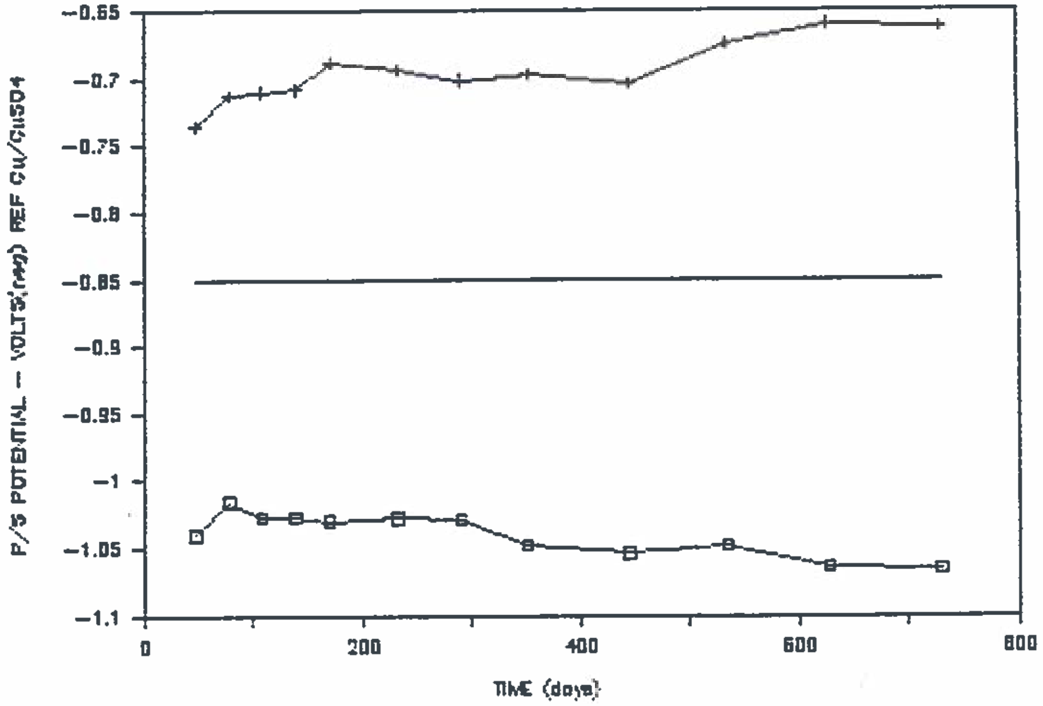

Figure H-4. External potential readings of the protected (□) and unprotected (+) polymeric aluminized Type II culvert.

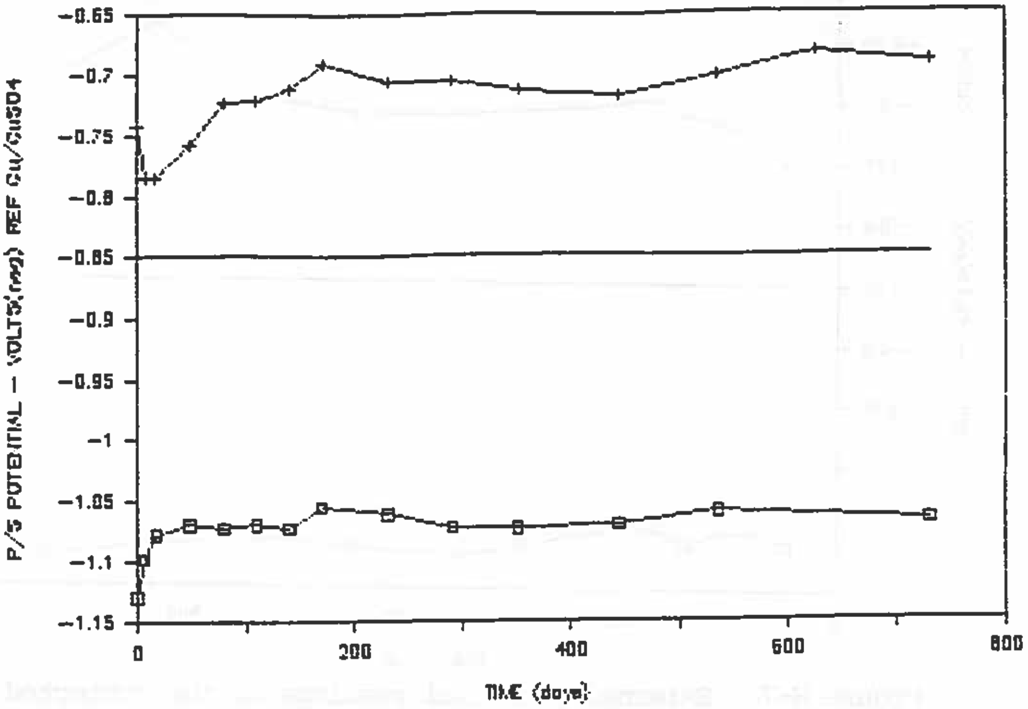

Figure H-5. Internal potential readings of the protected (□) and unprotected (+) polymeric aluminized Type I culvert.

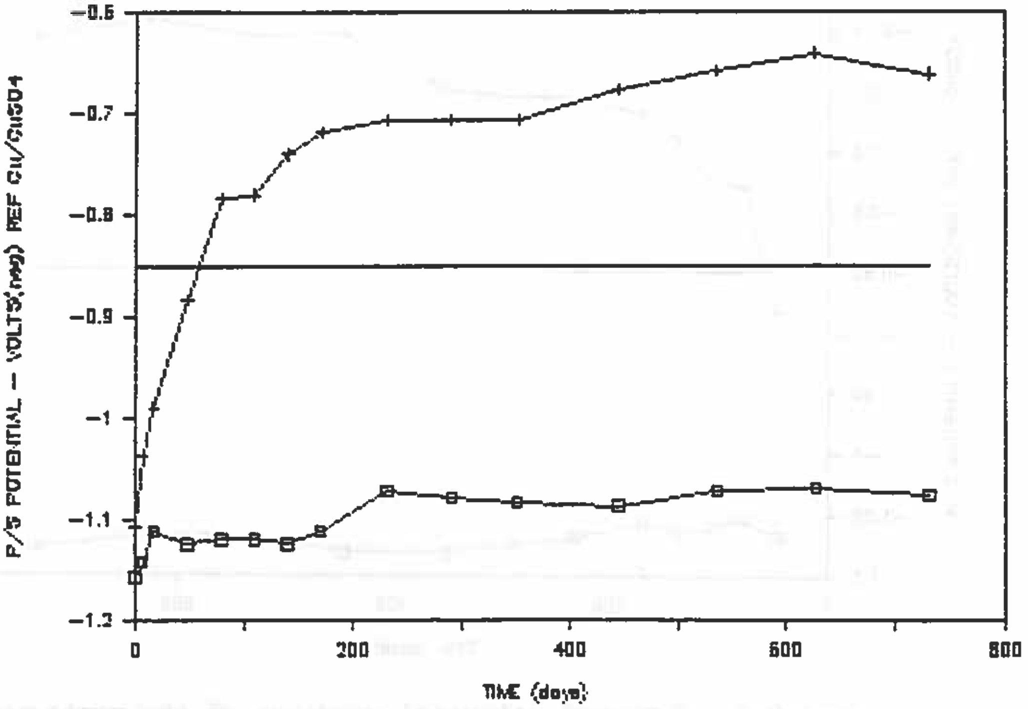

Figure H-6. Internal potential readings of the protected (□) and unprotected (+) polymeric galvanized (Supplier 2) culvert.

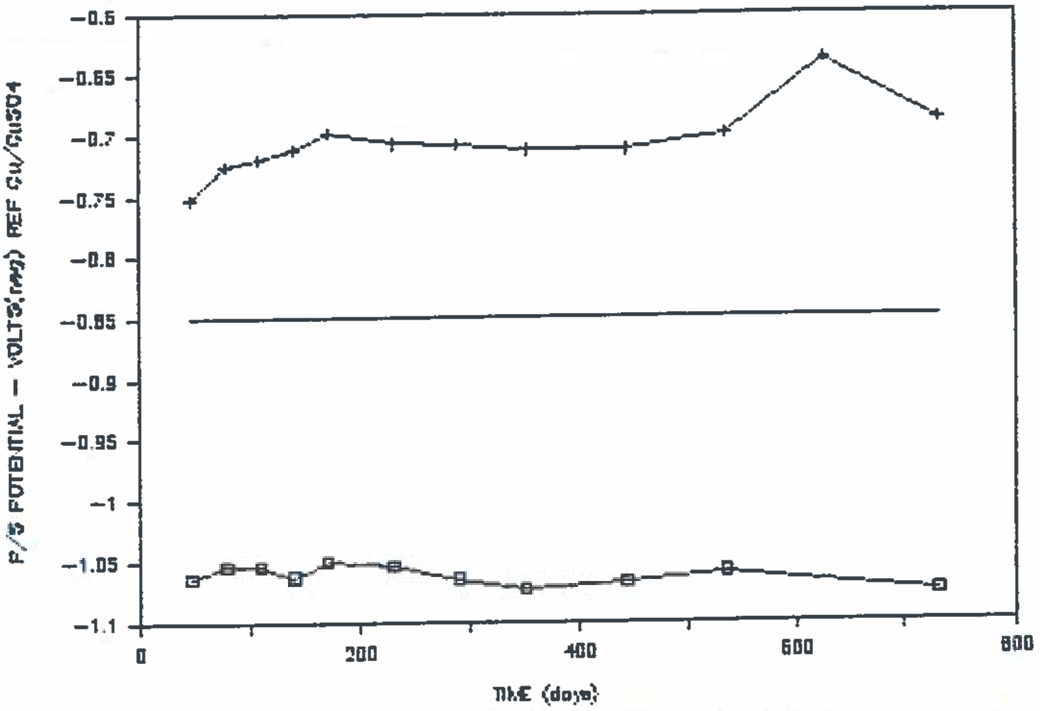

Figure H-7. External potential readings of the protected (□) and unprotected (+) polymeric aluminized Type I culvert.

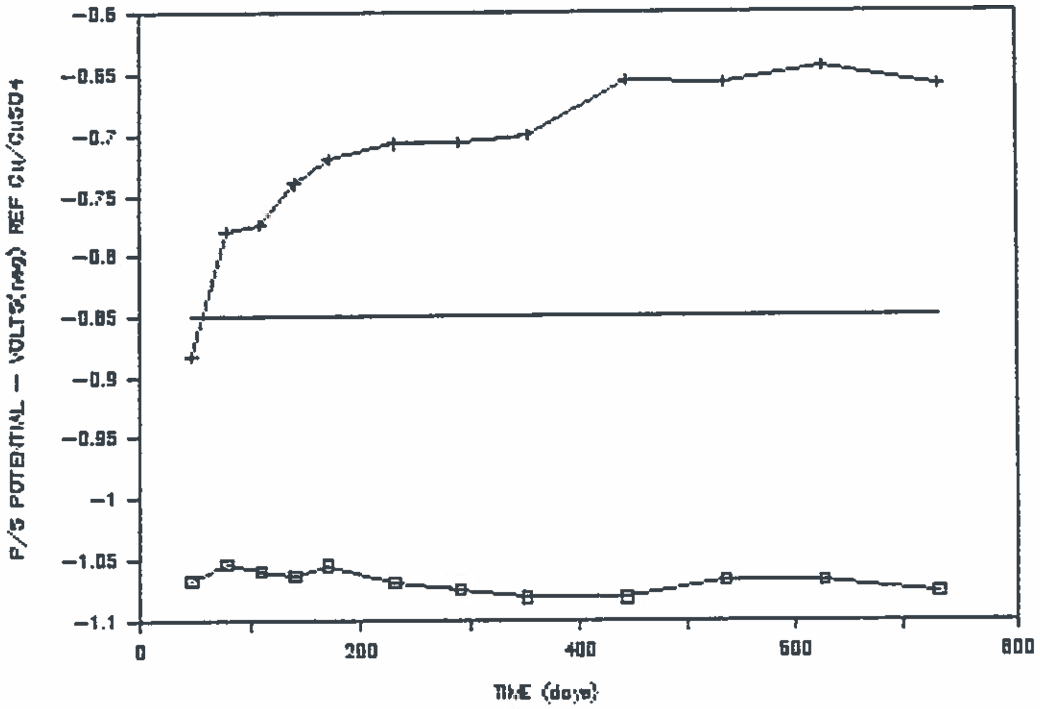

Figure H-8. External potential readings of the protected (□) and unprotected (+) polymeric galvanized (Supplier 2) culvert.

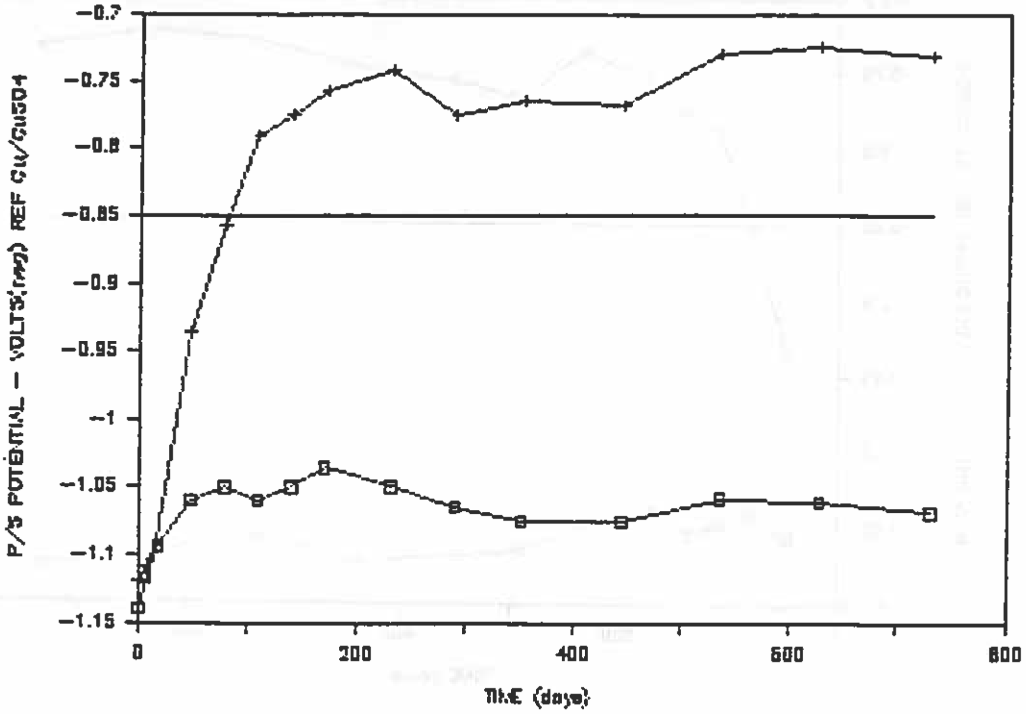

Figure H-9. Internal potential readings of the protected (□) and unprotected (+) polymeric galvanized (Supplier 1) culvert.

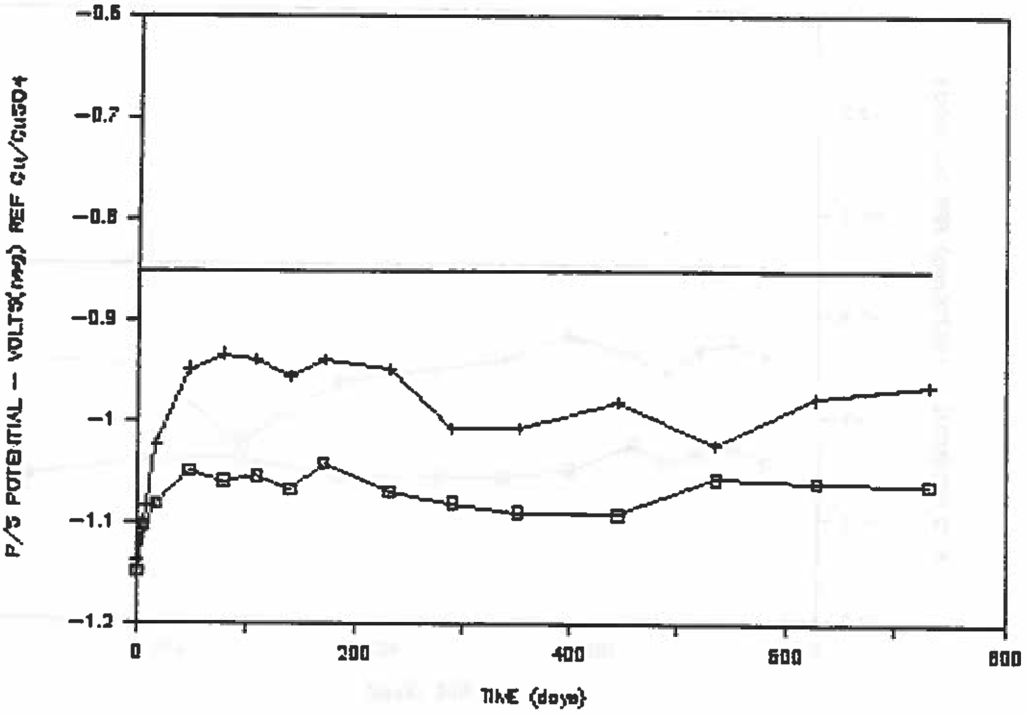

Figure H-10. Internal potential readings of the protected (□) and unprotected (+) bituminous galvanized culvert.

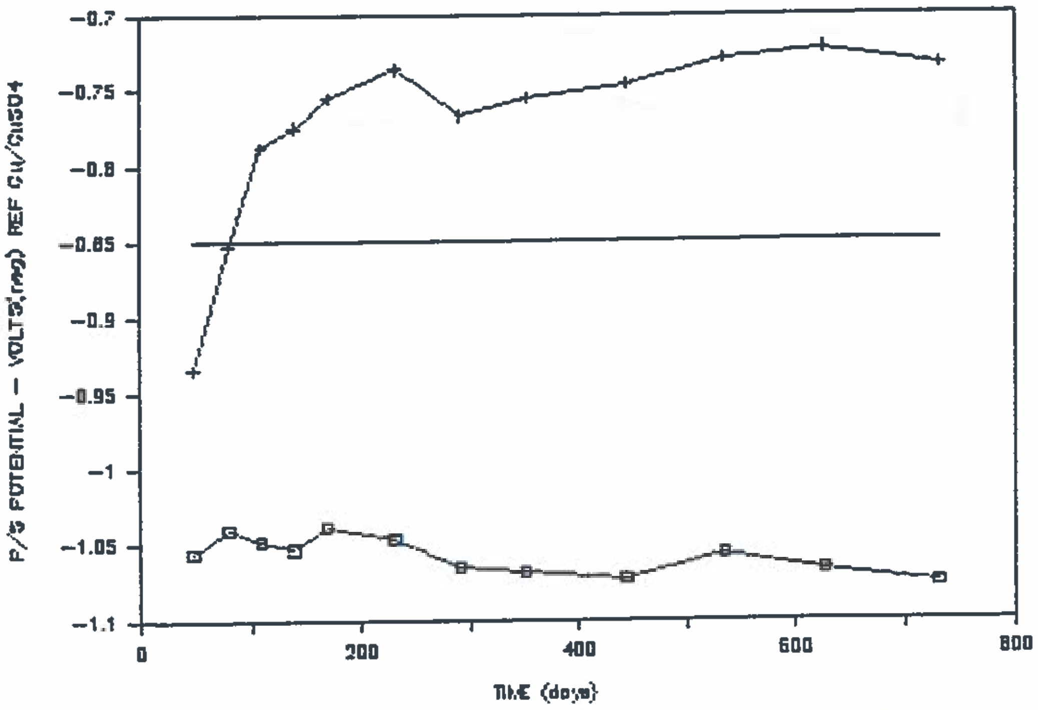

Figure H-11. External potential readings of the protected (□) and unprotected (+) polymeric galvanized (Supplier 1) culvert.

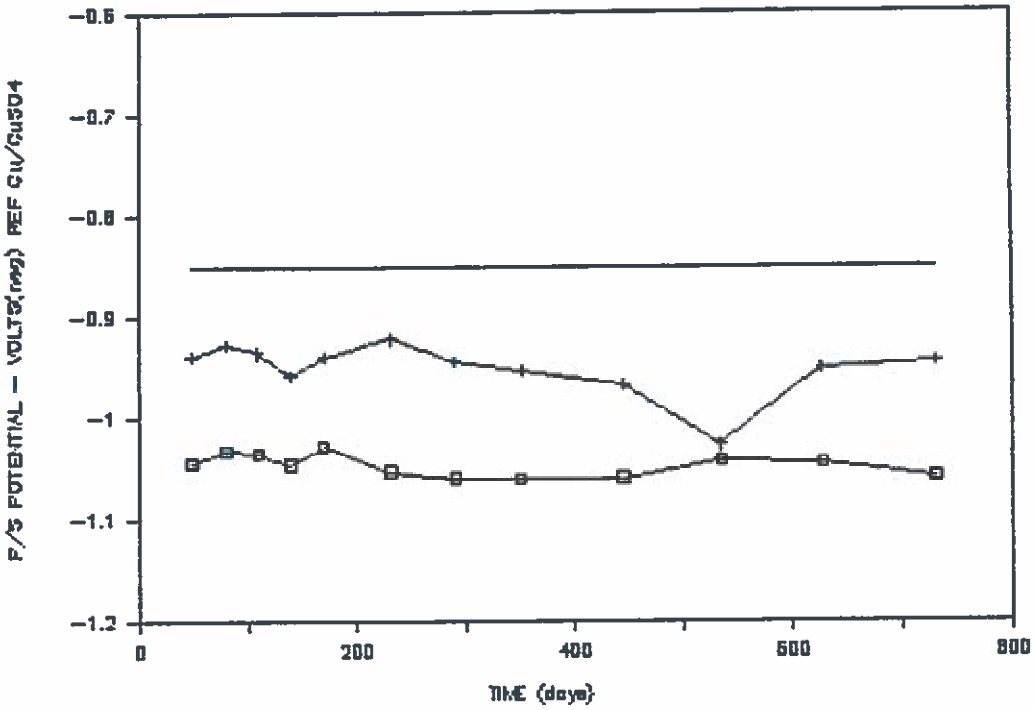

Figure H-12. External potential readings of the protected (□) and unprotected (+) bituminous galvanized culvert.

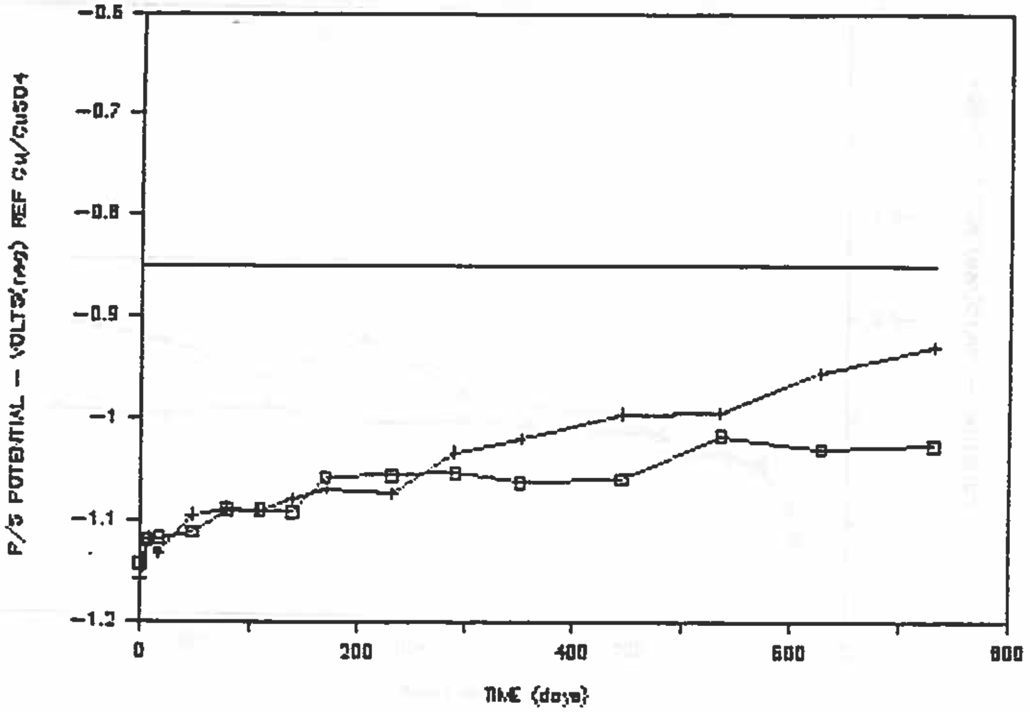

Figure H-13. Internal potential readings of the protected (□) and unprotected (+) galvanized culvert.

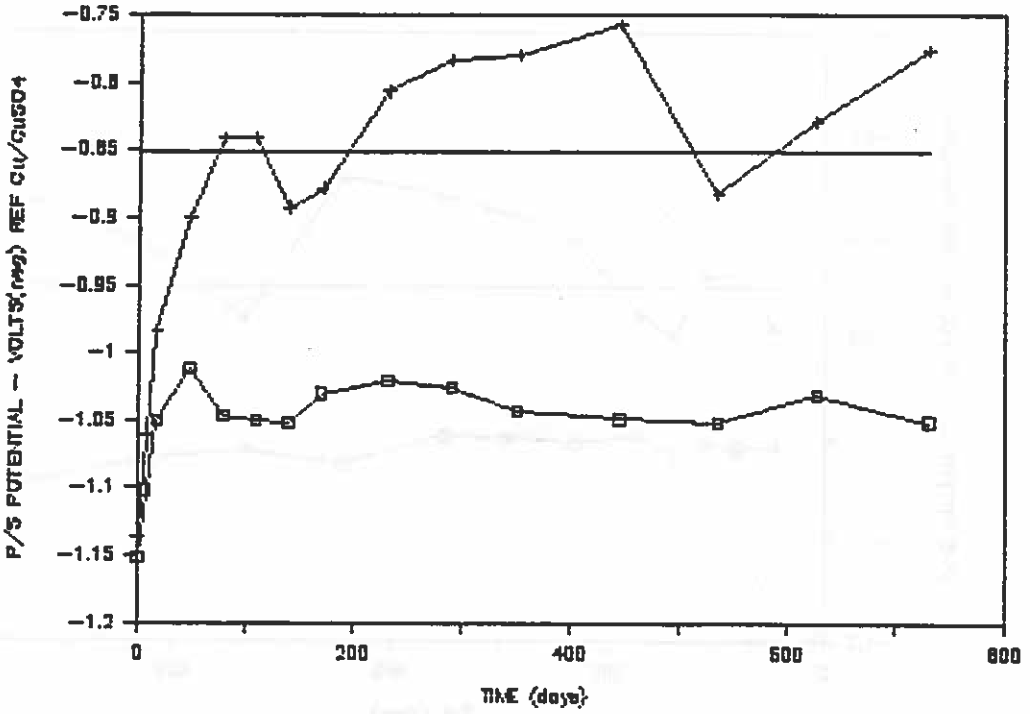

Figure H-14. Internal potential readings of the protected (□) and unprotected (+) fiber-bonded bituminous galvanized culvert.

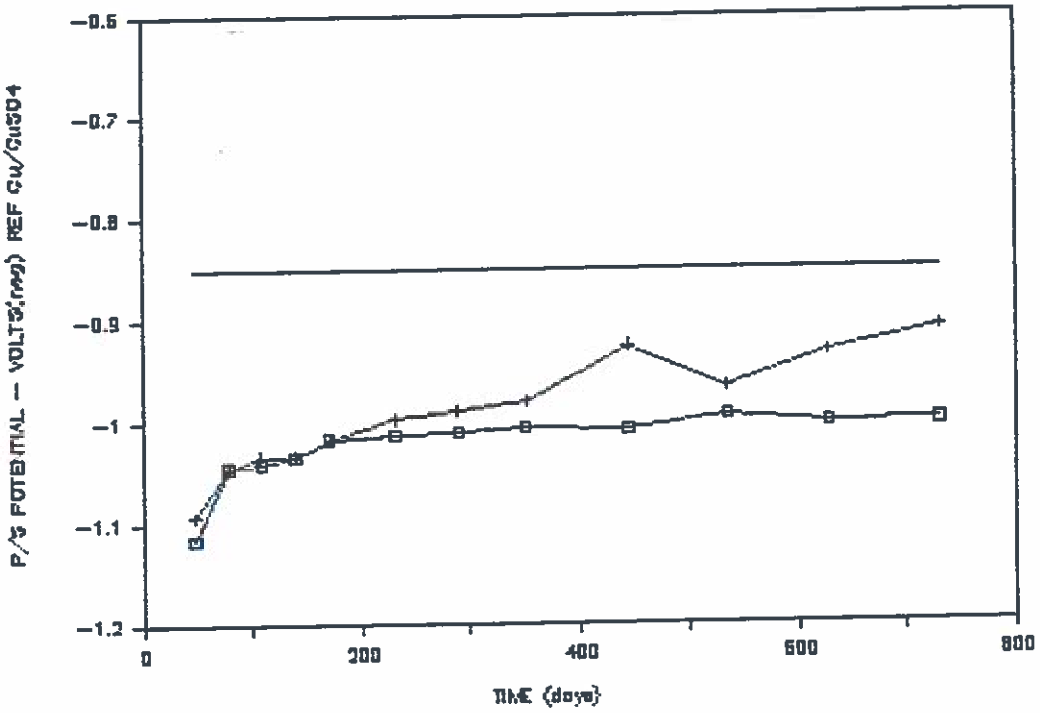

Figure H-15. External potential readings of the protected (□) and unprotected (+) galvanized culvert.

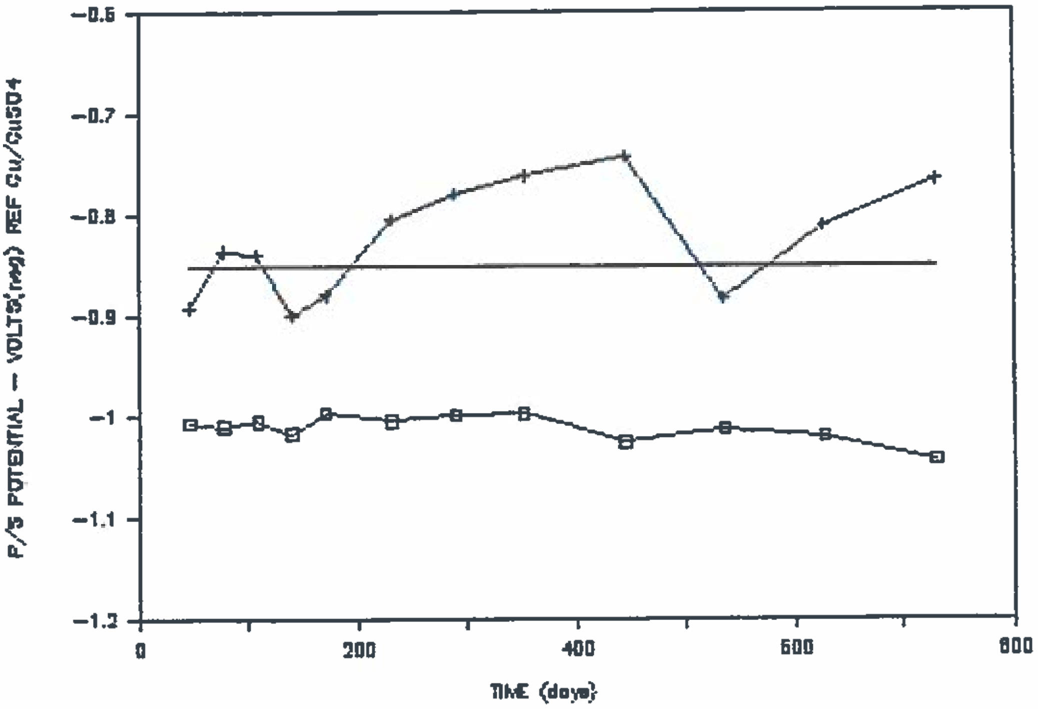

Figure H-16. External potential readings of the protected (□) and unprotected (+) fiber-bonded bituminous galvanized culvert.

Appendix I

Field Test Results

Internal and External Current Measurements on the Protected Culverts Versus Time

TABLE I-1

CURRENT OUTPUT - MILLIAMPS (MA) INTERNAL ANODES

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type II	3 Polymeric Aluminized Type I	4 Polymeric Galvanized Steel Supplier 2	No. of Days
6/13/89	34	16	24	3	0
6/20/89	27	18	19	5	7
6/30/89	25	21	12	4	17
7/30/89	30	20	20	20	47
8/31/89	30	23	15	16	79
9/30/89	23	15	10	10	109
10/31/89	13	10	11	11	140
11/30/89	27	20	15	14	170
1/30/90	13	12	12	8	231
3/30/90	10	10	8	5	290
5/30/90	16	14	8	7	351
8/31/90	17	19	19	10	444
11/30/90	18	16	13	10	535
2/28/91	20	18	---*	15	625
6/13/91	11	15	12	8.5	730
Avg. values	21	17	14	10	

*Measurements indicated that the culvert was disconnected from the anode. Repair was performed before the next readings were made.

TABLE I-1 (Continued)

CURRENT OUTPUT - MILLIAMPS (MA)
INTERNAL ANODES

Date	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized Steel	No. of Days
6/13/89	8	6	9	7	0
6/20/89	7	10	7	11	7
6/30/89	9	15	9	22	17
7/30/89	20	20	10	21	47
8/31/89	23	20	11	22	79
9/30/89	16	10	9	16	109
10/31/89	26	12	12	17	140
11/30/89	23	15	15	15	170
1/30/90	15	8	9	11	231
3/30/90	9	2	5	11	290
5/30/90	10	2	5	15	351
9/31/90	19	10	20	21	444
11/30/90	18	14	30	20	535
2/28/91	21	17	15	16	625
6/13/91	16	17	28	10	730
Avg. values	16	17	13	16	

TABLE I-2

CURRENT OUTPUT - MILLIAMPS (MA)
EXTERNAL ANODES

Date	1 Polymeric Cold-Rolled Steel	2 Polymeric Aluminized Type II	3 Polymeric Aluminized Type I	4 Polymeric Galvanized Steel Supplier 2	No. of Days
6/13/89	15	12	4	1	0
6/20/89	52	38	20	10	7
6/30/89	85	72	24	9	17
7/30/89	130	90	50	40	47
8/31/89	150	112	55	33	79
9/30/89	120	90	50	28	109
10/31/89	116	80	35	28	140
11/30/89	95	78	48	32	170
1/30/90	89	77	50	22	231
3/30/90	76	70	39	20	290
5/30/90	78	72	41	22	351
8/31/90	70	63	45	21	444
11/30/90	64	44	34	17	535
2/28/91	64	44	--*	25	625
6/13/91	60	48	38	20	730
Avg. values	84	66	38	22	

*Measurements indicated that the culvert was disconnected from the anode. Repair was performed before the next readings were made.

TABLE I-2 (Continued)

CURRENT OUTPUT - MILLIAMPS (MA)
EXTERNAL ANODES

Date	5 Polymeric Galvanized Steel Supplier 1	6 Bituminous Galvanized Steel	7 Galvanized Steel	8 Fiber-Bonded Bituminous Galvanized	No. of Days
6/13/89	0	1	0	3	0
6/20/89	4	8	0	19	7
6/30/89	9	11	3	52	17
7/30/89	30	40	6	60	47
8/31/89	48	64	10	110	79
9/30/89	40	60	14	89	109
10/31/89	52	55	30	87	140
11/30/89	48	54	30	80	170
1/30/90	43	44	44	85	231
3/30/90	31	34	60	85	290
5/30/90	30	32	81	82	351
8/31/90	33	39	92	75	444
11/30/90	32	43	87	57	535
2/28/91	38	47	80	52	625
6/13/91	30	41	100	49	730
Avg. values	31	38	42	66	

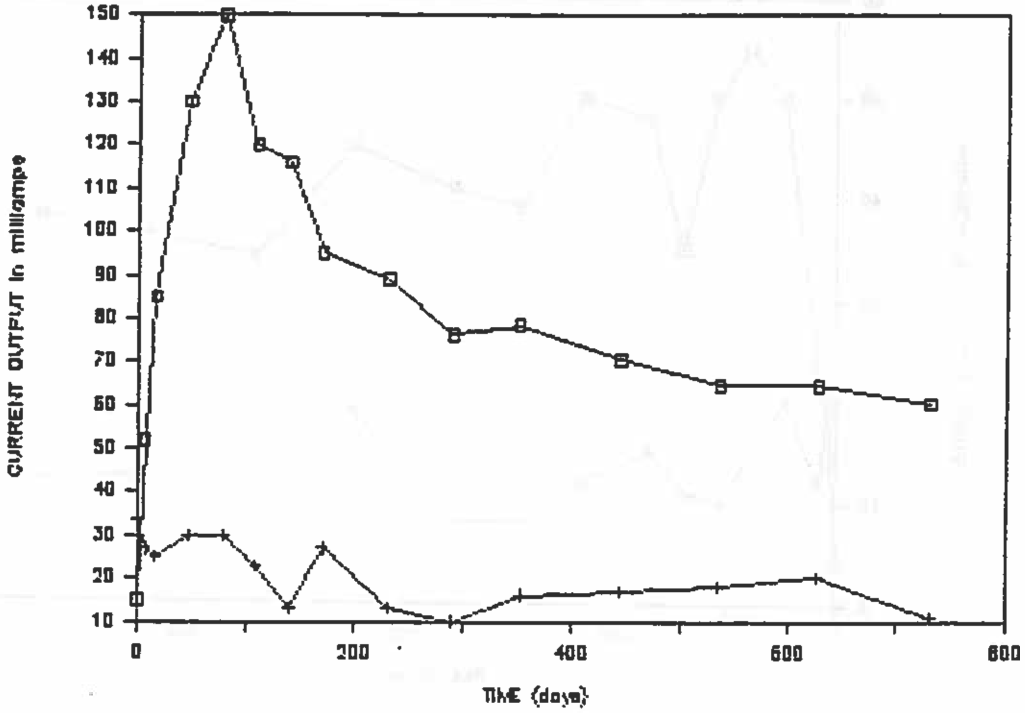

Figure I-1. Internal (+) and external (□) current readings for the polymeric cold-rolled steel culvert.

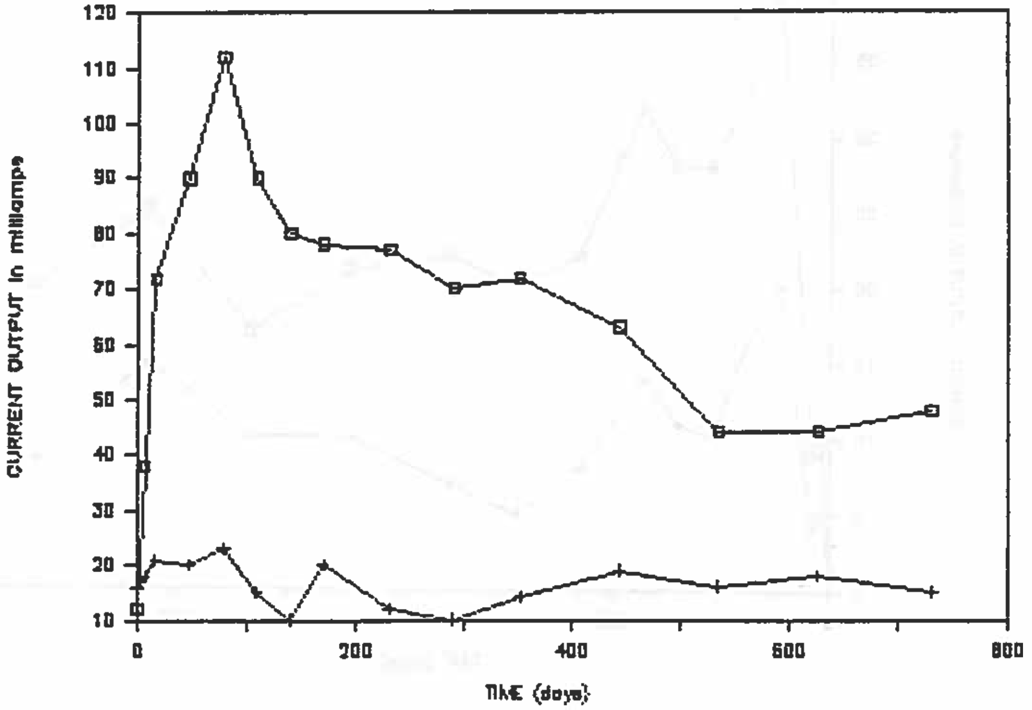

Figure I-2. Internal (+) and external (□) current readings for the aluminized Type II culvert.

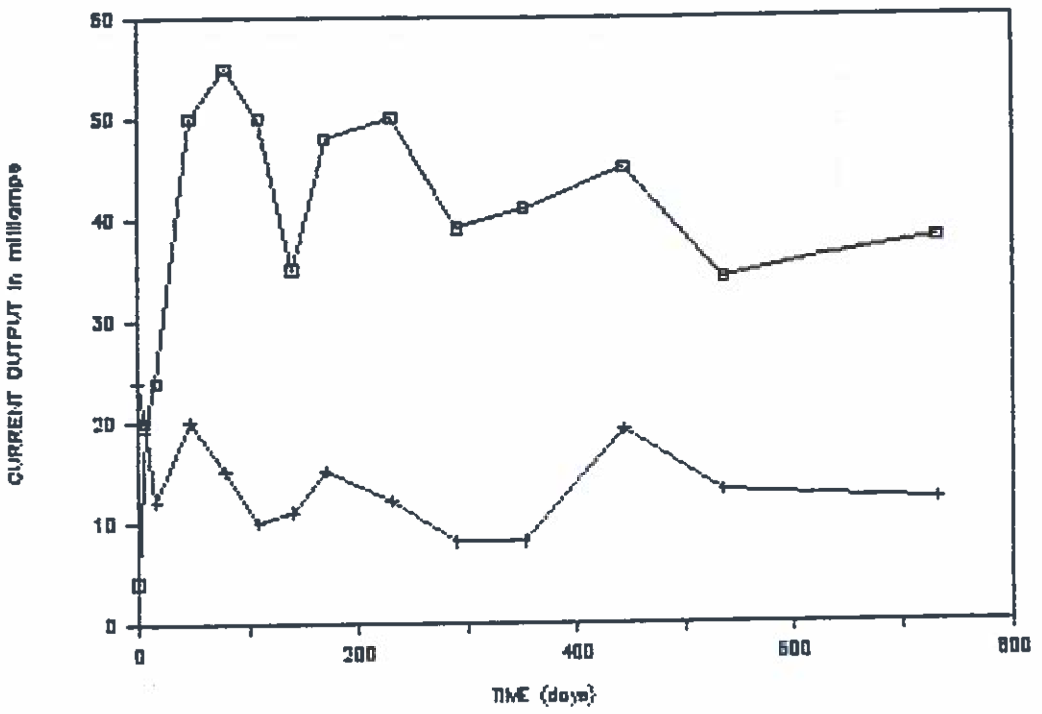

Figure I-3. Internal (+) and external (□) current readings for the aluminized Type I culvert.

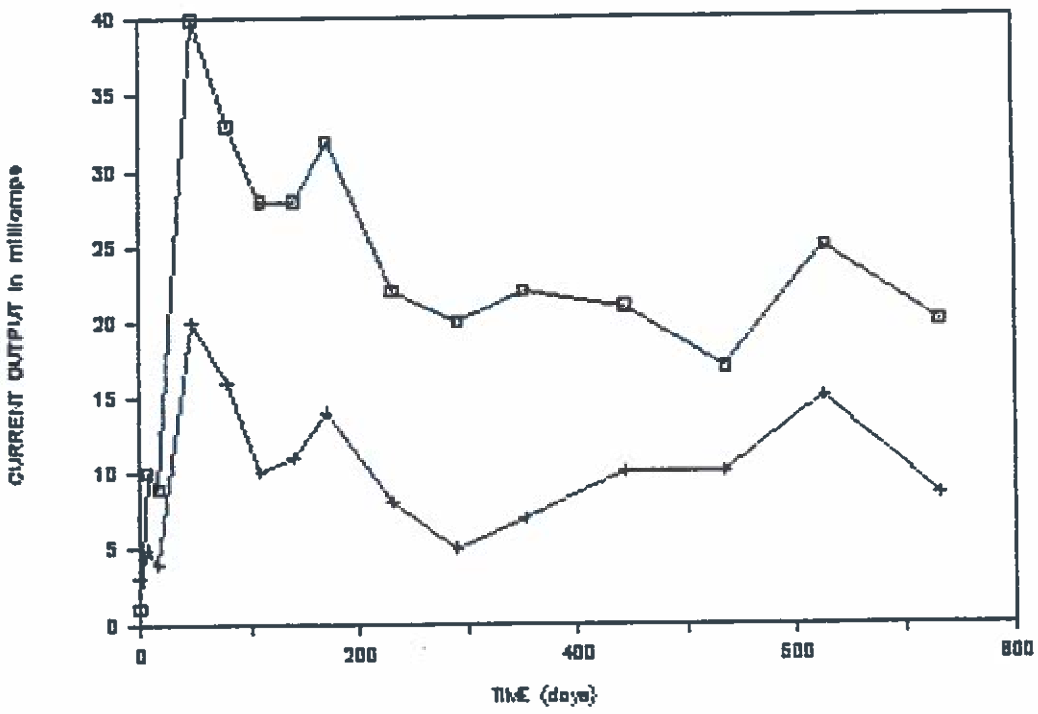

Figure I-4. Internal (+) and external (□) current readings for the polymeric galvanized (Supplier 2) culvert.

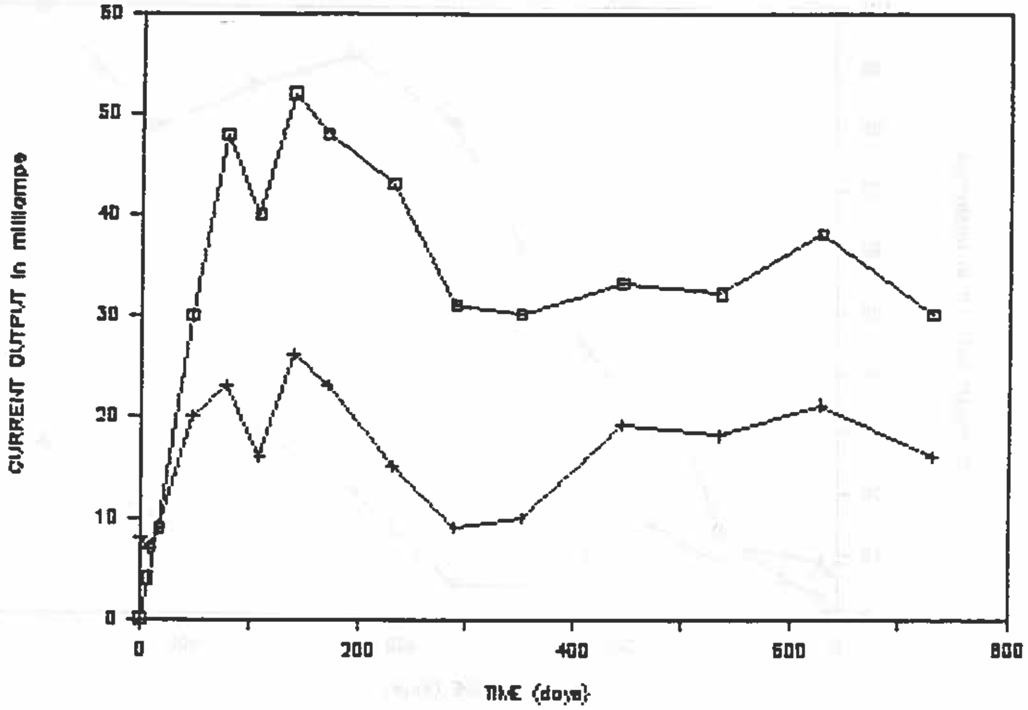

Figure I-5. Internal (+) and external (□) current readings for the polymeric galvanized (Supplier 1) culvert.

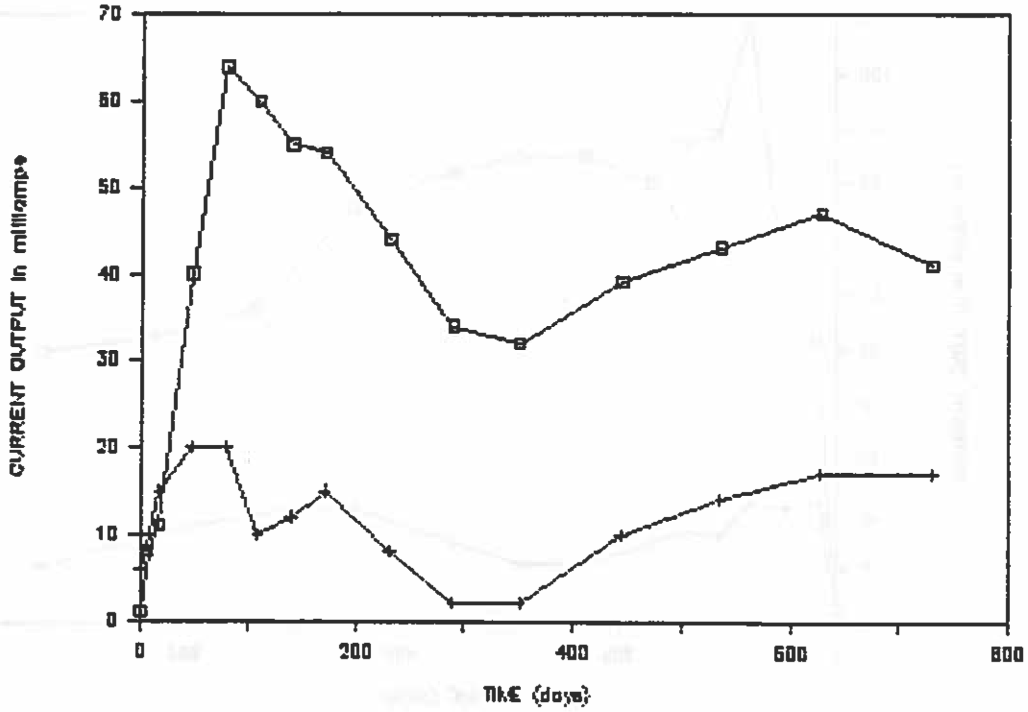

Figure I-6. Internal (+) and external (□) current readings for the bituminous galvanized steel.

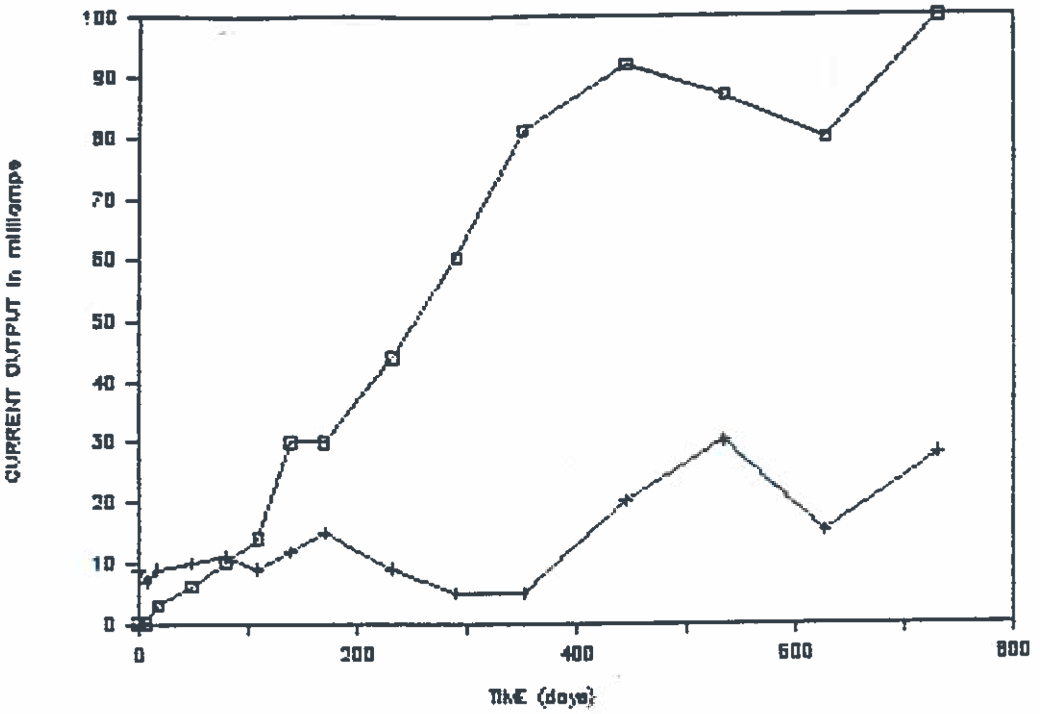

Figure I-7. Internal (+) and external (□) current readings for the galvanized culvert.

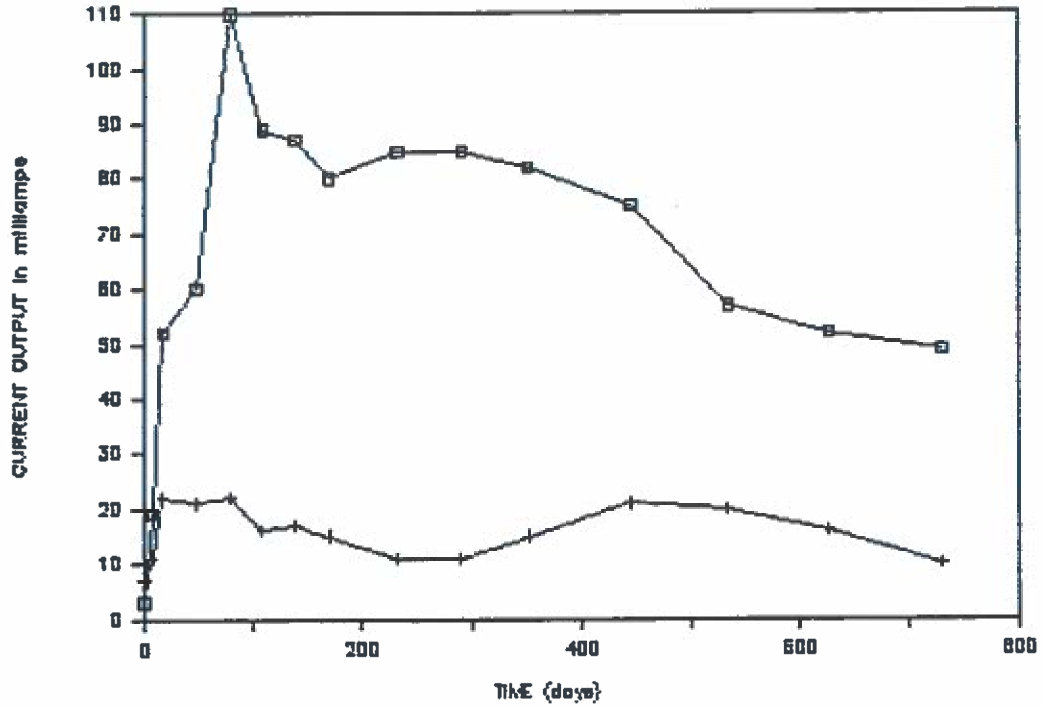

Figure I-8. Internal (+) and external (□) current readings for the fiber-bonded bituminous galvanized culvert.