FLORIDA DEPARTMENT OF TRANSPORTATION
CORROSION RESEACH LABORATORY
2006 North East Waldo Road, Gainesville, Florida 32609

Evaluation of Galvanic Battery
Power Supply for Cathodic Protection

Final Report

Prepared for
University of South Florida

March, 2001

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Agency No.	3. Recipient's Catalog No.
01-01A		

4. Title and Subtitle	5. Report Date
EVALUATION OF GALVANIC BATTERY POWER SUPPLY FOR CATHODIC PROTECTION	March 8, 2001
	6. Performing Org. Code
7. Author(s)	8. Performing Org. Report No.
R.G. Powers, I.R. Lasa, M.H. Duncan	01-03A
9. Performing Organization Name and Address	10. Work Unit No.
FLORIDA DEPARTMENT OF TRANSPORTATION STATE MATERIALS OFFICE 2006 North East Waldo Road Gainesville, Florida 32609	11. Contract or Grant No.
14. Sponsoring Organization Name and Address	12. Type of Report and Period Covered Final Report
UNIVERSITY OF SOUTH FLORIDA 4202 East Fowler Avenue Tampa, Florida 33620	13. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report discusses the performance of a galvanic battery power supply system specifically designed to provide DC electricity for cathodic protection of concrete structures. The batteries were tested under controlled laboratory conditions and at three cathodic protection actual field sites. All field sites were bridge structures owned and operated by the Florida Department of Transportation and were located in extremely aggressive corrosion environments.

Several arrangements of the batteries were evaluated including: stand alone service, and multiple batteries connected in parallel and/or in series. The evaluation also included providing cathodic protection to one or several bridge substructure components. Parameters observed included measurements to determine if adequate cathodic protection was provided and to determine the overall service life of the battery under different battery combination arrangements.

The general findings indicate that the batteries have the capability to provide adequate cathodic protection to concrete structure components and that the operational service life is concurrent with the manufacturer service rating. The study also concluded that for actual applications, the battery system should be carefully designed to attain the required service life. Such design should include an economic analysis of all the power supply alternatives.

17. Key Words	18. Distribution Statement
Anode, Battery, Bridge, Cathodic Protection, Concrete, Galvanic, Pile Jackets, Power Supply	

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

Form DOT F 1700.7

US Customary and SI Conversions for Typical Corrosion Units

1 A/ft^2	= 10.76 mA/m^2	1 in. water	= 248.8 Pa
1 Acre	= 4047 m^2 = 0.4047 ha	1 kg/mm^2	= 9.807 MPa
1 A/lb	= 20205 A-kg	1 kilocalorie	= 4.184 kJ
1 Angstrom	= 10^{-4} µm = 10^{-10} m	1 knot	= 0.515 m/s
1 atm	= 101.325 kPa	1 ksi	= 6.895 MPa
1 bar	= 100 kPa	1 lb	= 453.6 g = 0.4536 kg
1 bbl, oil (US)	= 159.0 L	1 lb/ft^2	= 47.88 Pa
1 BPD (oil)	= 159 L/d	1 lb/ft^3	= 0.01602 g/cm^3
1 BTU	= 1055 J	1 lb/100 U.S. gal	= 1.1981 g/L
1 BTU/ft^2	= 11,360 J/m^2	1 lb/1000 bbl	= 2.852 mg/L
1 BTU/ft^2/h	= 3.152 W.m^2 (K-factor)	1 mA/in^2	= 0.155 mA/cm^3
1 BTU/ft^2/h/F	= 5.674 W/m^2- k	1 mA/ft^2	= 10.76 mA/m^2
1BTU/ft^2/h/F/in.	= 0.144 W/m-k	1 MBPD (oil)	= 159 kL/d
1 cfm	= 28.3 L/min	1 mile	= 1.609 km
	= 0.0283 m^3/min	1 sq.mile	= 2.59 km^2
	= 40.75 m^3/d	1 mi. (naut.)	= 1.852 km
1 cup	= 236.6 mL	1 mil	= 0.0254 mm = 25.4 µm
1 cycle/s	= 1 Hz	1 MMCFD	= 2.28 x 10^4 m^3/d
1 ft	= 0.3048 m	1 mm mercury	= 0.1333 kPa
1 ft^2	= 0.0929 m^2 = 929 cm^2	1 mph	= 1.609 km/h
1 ft^3	= 0.02832 m^3 = 28.32 L	1 mpy	= 0.0254 mm/y = 25.4 µm/y
1 ft-lb (force)	= 1.356 J	1 oz	= 28.35 g
1 ft-lb (torque)	= 1.356 N-m	1 oz fluid (Imp.)	= 28.41 mL
1 ft/s	= 0.3048 m/s	1 oz fluid (U.S.)	= 29.57 mL
1 gal (lmp.)	= 4.546 L = 0.004546 m^3	1 oz/ft^2	= 2.992 Pa
1 gal (U.S.)	= 3.785 L = 0.003785 m^3	1 oz/U.S. gal	= 7.49 g/L
1 gal/bag (U.S.)	= 89 mL/kg (water/cement ratio)	1 part/1000 bbl	= 2.32 mg/L
		1 psi	= 0.006895 MPa = 6.895 kPa
1 grain	= 0.066480 g = 64.80 mg	1 qt (Imp.)	= 1.1365 L
1 grain/ft^3	= 2.212 g/m^3	1 qt (U.S.)	= 0.9464 L
1 grain/100 ft^3	= 22.12 mg/m^3	1 teaspoon (tsp)	= 4.929 mL
1 hp	= 0.7457 kW	1 ton	= 907.2 kg = 0.9072 ton metric
1 microinch	= 0.0254 µm = 25.4 nm	1 torr	= 133.2 Pa
1 in	= 2.54 cm = 25.4 mm	1 U.S. bag cement	= 42.63 kg (94 lb)
1 in^2	= 6.452 cm^2	1 yd	= 0.9144 m
1 in^3	= 16.387 cm^3 = 0.01639 L	1 yd^2	= 0.8361 m^2
1 in-lb (torque)	= 0.113 N-m	1 yd^3	= 0.7646 m^3
1 in.mercury	= 3.387 kPa		

Units for Corrosion Measurement

corrosion rate	µm/y or mm/y	anode output	A/y/kg
anode current density	mA/m^2 or A/m^2	coating thickness	mils or µm
		coating coverage	ft^2/gal or m^2.L
anode consumption	kg/A/y	coating resistance	ohms-ft^2 or ohms-m^2
potential	v	current	Amps or mAmp

Acknowledgements

The authors would like to take this opportunity to express their gratitude to the following persons who generously assisted us during various phases of the project.

Testing, Monitoring, and Construction Quality Assurance

R. M. Langley; FDOT Corrosion Research Laboratory

Remote Monitoring and Data Collection

Bradley P. Choi; FDOT Corrosion Research Laboratory
R. M. Langley; FDOT Corrosion Research Laboratory

Technical Assistance

Nick Shuster; Enser Corporation
Greg J. Gabert; Enser Corporation

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INTRODUCTION

Corrosion of reinforcing steel in concrete bridge elements has been determined to be the principal inducing factor of deterioration of bridge substructures in marine environment.

Corrosion is a natural process which under the proper conditions may affect all metals. Under favorable conditions however, steel in concrete will be protected from corrosion and retain its strength for many years. Reinforced concrete is probably the most widely used construction material in the United States. Normally in reinforced structures, the reinforcing rebars are protected from corrosion by the alkaline properties of the concrete. A protective oxide film forms on the surface of the steel at the prevailing pH values of around 12 to 13 due to the high alkalinity of the cement paste[1]. This protective film is sometimes disturbed by carbonation of the concrete or by the intrusion of chloride ions to the concrete surrounding the rebar[2]. The chloride contamination occurs due to the diffusion of chloride ions through the concrete or by direct ingression via cracks present in the concrete. This change typically produces a concentration cell on the concrete and corrosion is initiated (Figure 1).

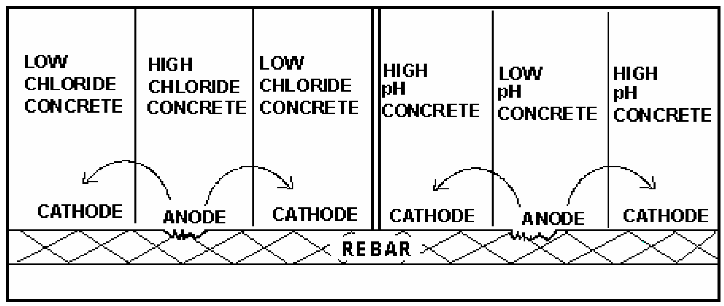

Figure 1: Typical Corrosion Cell. Ionic current discharges from the anodic areas where corrosion occurs.

Although today structures are designed with an expected minimum service life of seventy-five years, older structures in marine environments typically exhibit corrosion deterioration between fifteen and twenty years after construction. Due to the large amount of structures reaching an average age of twenty or more years over the last two decades, and with constant or periodic exposure to carbonation or chlorides, a concerning amount of corrosion deterioration on our structures now exists. It is estimated that approximately 30 percent of the Nation's 589,355 bridges are in deficient substandard conditions[3]. Most of these deficiencies are produced by corrosion of the reinforcement steel. Corrosion induced deficiencies are more noticeable on bridges which are located by or near marine environments and on bridges where de-icing salts are periodically used.

In the state of Florida where no de-icing salts are used on the roadways but with over 1250 miles of coastline, approximately 3000 bridges are located in corrosion aggressive marine environments[4]. Chloride intrusion to the substructure concrete elements on these bridges generates severe corrosion problems. This compels the State to support an aggressive bridge maintenance program. It is estimated that the annual rehabilitation cost of corrosion induced deterioration on these bridges reaches between 30 and 50 million dollars. Because of this, the Florida Department of Transportation is constantly involved in laboratory and field experimentation directed toward the development of new materials and techniques for corrosion control.

One of these techniques is cathodic protection. Since corrosion is an electrochemical reaction by nature, it is obvious that by controlling the electron flow of the process, the reaction itself may then be controlled. Cathodic protection does this.

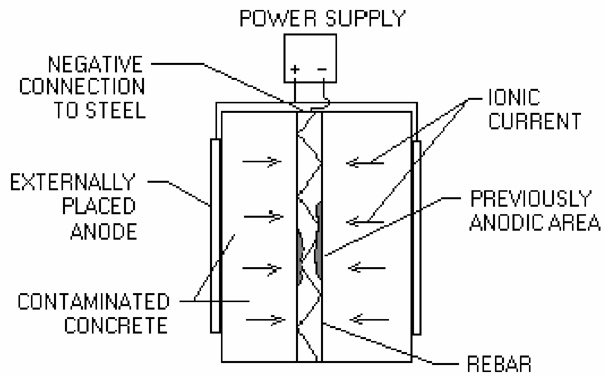

Figure 2: Typical mechanism of an impressed current cathodic protection system. On a galvanic system, the anode is directly connected to the steel.

Corrosion of reinforcing steel in concrete occurs at the areas where the current discharges from onto the electrolyte (concrete). These are the anodic areas of the rebar. Where the current flows onto the rebars (cathodic areas), there is no corrosion. Once corrosion develops, conventional repairs provide only a temporary remedy since corrosion continues to damage the concrete.

The cathodic protection concept is based on the capability of a current to polarize the protected metal. When using cathodic protection, the objective is to force the entire surface of the bars in contact with the concrete to accept the polarization current (Figure 2). Cathodic protection forces a direct current flow to move from an external source (anode) onto all the surfaces of the steel thereby overpowering the natural corrosion currents. Two types of cathodic protection systems exist. These are: 1) galvanic and 2) impressed current systems. On a galvanic system the current is provided by a metal with a higher energy than that of the one being protected. These systems are typically of simple construction and require low maintenance. However, galvanic systems have a limited service life. An impressed current system utilizes an external power supply to provide the cathodic protection current. By properly adjusting the power source on the system, the entire surface of the steel becomes cathodic in relation to the externally placed anode. The anodes used are noble in relation to the metal being protected and have a significantly greater service life than the galvanic anodes. Several types of impressed current systems are available in the market.

For years, impressed current cathodic protection systems have been used successfully on underground pipelines and marine concrete structures. The most common power supply for impressed current systems is the rectifier. This device converts AC current into DC current and establishes the direction of the current flow. Another common power supply is the photovoltaic generator (solar panel). This device converts solar energy into DC electricity and also establishes the direction of the current flow. Both of these power supplies are readily available in most markets. Both systems have their advantages and limitations

SCOPE

Figure 3: Corrosive marine environment at Howard Frankland Bridge (Field Site 3 of this study).

This report discusses the findings of an evaluation study conducted to measure the performance of an air cathode battery developed specifically as a power supply for impressed current cathodic protection systems. Even though this battery system has a more limited service life when compared to rectifiers and photovoltaic generators, the initial cost savings and the long term maintenance costs may give the batteries an economic advantage over the other two systems. The evaluation study was conducted in cooperation with the University of South Florida (USF). The batteries were monitored for a period of approximately 17 months (70 weeks).

In general, rectifiers and photovoltaic generators are proven effective and reliable power sources for cathodic protection systems. However, the costs associated with providing electric (AC) power to the rectifier or the periodic maintenance of a photovoltaic generator and the current storage cells, often significantly impact the overall cost of the cathodic protection system. In this study, the Florida Department of Transportation evaluated the performance of the alternate battery power supply for the impressed current cathodic protection systems. The battery has a predictable service life and will require replacement after a period of time. As such, in addition to evaluation of the ability of the batteries to produce cathodic protection, the study also addressed the service life of the batteries as this is necessary to properly understand the economic factors involved in selecting the battery system over the other two systems as the power supply for a specific cathodic protection system.

To evaluate the performance of the battery, two approaches were used. The first approach measured the battery performance under controlled laboratory conditions at normal and below normal current outputs. This test was conducted in the facilities of the Florida Department of Transportation – Corrosion Research Laboratory. The test se-up was designed and monitored by laboratory personnel. The second approach observed the performance of the battery under typical field applications on actual bridges with existing cathodic protection systems.

A total of twenty nine (29) batteries were used for this study. Two (2) of the batteries were evaluated in the laboratory while the other twenty seven (27) were evaluated on the actual bridges. The first field test (Ribault River Bridge) was installed by FDOT –

Corrosion Research Lab personnel. The other two test sites (Dunn's Creek Bridge and Howard Frankland Bridge) were installed by a corrosion specialty contractor under contract with the University of South Florida in accordance with plans and specifications provided by FDOT Corrosion Research Laboratory. Personnel from the Florida DOT provided quality assurance inspection for the work.

All the field sites selected were located in corrosion aggressive marine environments. In addition, two of the sites were located in north Florida where the seasonal temperature changes are more noticeable than in the rest of the State. Temperature probes were also installed at two of the field sites such that battery performance could be measured as a function of temperature.

TABLE 1: Location of Field Tests

Site Number	Location	Date of Initial Data
Site 1	Ribault River Bridge on S.R.115 in Jacksonville, Florida	May, 1999
Site 2	Dunn's Creek Bridge on S.R.105 in Jacksonville, Florida	July, 1999
Site 3	Howard Frankland Bridge on I-275 in Tampa, Florida	July 1999

The field evaluation consisted of installing several batteries as replacements for rectifiers on existing operational cathodic protection systems at the three different bridge locations. All of the sites provide impressed current cathodic protection to bridge substructure pilings as this type of substructure support is the most common on bridges built between the late 50's and the early 80's. Prior to connecting the batteries, specific zones (circuits) of the existing cathodic protection system were selected for the test. The selected circuits were disconnected from the existing system for a period of two weeks (minimum) to allow depolarization of the structure.

The initial scope of this project only included the evaluation of the battery system at two field sites as some preliminary laboratory evaluation had been conducted. However, due to significant changes to the physical characteristics and design rating of the basic battery made by the manufacturer, the Department conducted additional laboratory evaluation and implemented one additional field test site. The added field site evaluated the battery system using a cathodic protection anode different from that existing at the originally planned sites. Anodes and general system characteristics are discussed in the Evaluation Procedure section of this report.

An onsite data logging system was installed at all sites to obtain the evaluation measurements. Each data logging system was provided with digital communication capabilities for remote monitoring. The data logger measured the output current and voltages as well as the voltage potentials of the protected reinforcing steel.

EVALUATION PROCEDURE

Laboratory Test

For the laboratory evaluation, one battery was connected to two small cathodically protected reinforced concrete specimens which were placed in a saltwater tank. This arrangement provided a very low current output and was designed to assess the service life of the battery under long term current output levels well below the design parameters.

Figure 5:Battery arrangement with mounting brackets for the Multiple Piles Test at Site 2. Number of batteries differ per site.

The second battery was connected to a 40 ohm constant load device placed on the outside of the tank to produce a current output similar to what was expected for a single pile in the field. The typical laboratory conditions were around 75^{o} F (24^{o} C) and 60% relative humidity. Both batteries were attached to the inside walls of the tank above the water level to create exposure to the salt sprays from the tank's aeration system (Figure 4).

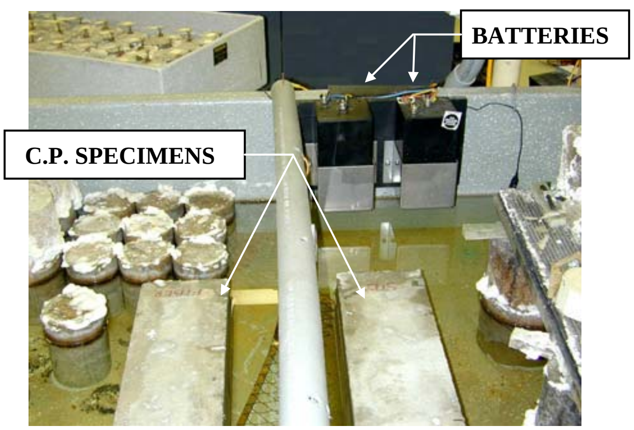

Figure 4: Batteries placed inside a saltwater tank for the laboratory evaluation.

The output of both batteries and other pertinent measurements were obtained at 6 hour intervals by an automated data-logger connected to the test specimens.

Field Test

At the first field site (Site 1 – Ribault River Bridge) the cathodic protection system consisted of conductive rubber anode panels[5] attached to all faces of the piles at splash zone elevation (Figure 1B – Appendix B). This was the field site added to the original scope of the study. At the other two sites (Site 2 – Dunn's Creek Bridge, and Site 3 – Howard Frankland Bridge), the cathodic protection system consisted of cathodic protection pile jackets with an embedded titanium mesh anode[6] (Figures 3B, 4B). Four different battery combinations were installed. Table 1A – Appendix A shows the test configuration of the battery system used at each site.

The first arrangement (Multiple Piles) consisted of several batteries installed in a combination of parallel and serial connections to provide cathodic protection current to one pile bent comprised of four, five, and six piles respectively for sites 1, 2, and 3. Table 1A also shows the number of batteries used per test and the area cathodically protected by each battery arrangement. The nominal output was 3 volts. This arrangement was installed at all three sites. At Site 3, the arrangement was provided with a 0-100 ohm circuit voltage regulator device to provide output adjustment control. This was implemented assuming the possibility of excessive currents at 3 volts which could cause over-protection. The protected surface areas were 96, 180, and 192 square feet (9.0, 16.7, and 18.0 m^2) for Sites 1, 2, and 3 respectively.

The second arrangement (Single Pile - 1.5V) consisted of one battery directly connected to a cathodic protection system for corrosion protection of one pile. The nominal voltage output for this test was 1.5 volts. This test was implemented at Sites 2 and 3. The cathodically protected surface area for this test was 36 and 32 square feet (3.3 and 3.0 m^2) for Sites 2 and 3 respectively.

The third arrangement (Single Pile – 3V) consisted of two batteries connected in series to provide a nominal output of 3 volts and was connected to the cathodic protection system to protect one pile. This test was implemented at Sites 2 and 3. At Site 3, the circuit was also provided with a 0-100 ohm voltage regulating device to control the current output. The protected surface area for this test was 36 and 32 square feet (3.3 & 3.0 m^2) for Sites 2 and 3 respectively.

The fourth field arrangement (Constant Load Test) consisted of moving a current through a constant resistance device under actual field conditions. This test was implemented at Sites 2 and 3. At site 2, the connection arrangement provided 3 volts (two batteries) and was initially connected to a 25 ohm load. The load was later changed to 40 ohms. At site 3, the output voltage was 1.5 volts (one battery) and was connected to a 25 ohm load. The test matrix for this arrangement is also shown in Table 1A.

At all field sites, the arrangements were monitored using the remote data acquisition unit and through periodic field visits. The initial circuit resistance, depolarized structure potential, and open circuit battery voltage for each of the field tests are shown in Table 2A (Appendix A). The potential of the steel reinforcement was measured using a silver/silver chloride (Ag/AgCl) reference electrode embedded in the concrete at each test arrangement. During field visits, the potentials were measured using a copper/copper sulfate CuSO4 electrode. The measurements obtained with this electrode were later converted to Ag/AgCl values for proper comparison.

The collected data were used to measure the cathodic protection performance under the battery output and to compare the values to those previously achieved using the current rectification systems. Standard guidelines established by the National Association of Corrosion Engineers (NACE) were used to determine if cathodic protection was being properly provided. The selected criterion was the 100 mV polarization test. This criterion suggests that a polarization in the negative direction of at least 100 mV indicates satisfactory cathodic protection.

The polarization was calculated mathematically by subtracting the instant-off potential (measured versus the reference electrode) from the static potential (measured prior to applying the cathodic protection current).

BATTERY SPECIFICATIONS

The evaluated batteries are manufactured by Enser Corporation of Pinellas Park, Florida. The battery is a modified zinc anode - aerated cathode based unit with a gelled electrolyte (Figure 6). It was specially designed for cathodic protection of independent structure components such as bridge piles.

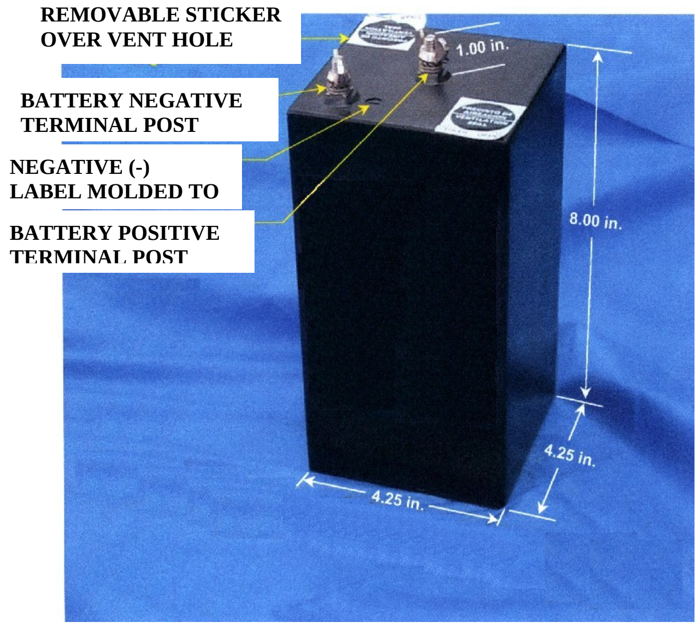

Figure 6: Typical configuration of the evaluated battery.

Based on the manufacturer test data, the overall output rating is 1,200 Amp-Hours. By design, the output capacity should be sufficient to supply an initial current output of 100 mAmp sustained for a period of 30 to 60 days to provide the initial polarization of the structure component followed by a steady-state current of approximately 30 mAmp for up to five years. Currents above the design output will reduce the service life of the battery. However, a number of batteries can be combined if necessary to compensate for the above design current outputs. Two batteries connected in parallel will linearly increase the overall rating to 2,400 Amp-Hours.

The battery is provided in a 4.25 X 4.25 X 8.0 inches (108 X 108 X 203 mm) casing. The connection posts are nickel plated provided with wing-nuts, and are located on the upper lid of the battery casing. The casing is constructed of black polyvinyl chloride and is provided with a two piece stainless steel mounting bracket which also serves as a weather shield. The nominal weight of the battery is 9 lbs. (4.1 kg), not including the stainless steel bracket (Figure 3B, 4B). The battery has two small air intake orifices at the top lid to allow oxygen to enter the cell. Should the openings become obstructed, the battery will not function. In addition, the vent orifices should be weather protected as to prevent any water intrusion which could contaminate the electrolyte.

From the factory, the battery is provided with a self adhesive plastic tab sealing the air intakes. This tab is removed when the battery is put in service.

RESULTS AND DISCUSSION

Laboratory Evaluation:

The battery connected to the cathodic protection specimens had an initial current output of 13 mAmp decreasing to a nominal output between 4 and 5 mAmp after three weeks when the specimens stabilized to steady-state condition (Figure 9B). The relatively low output was expected due to the small size of the specimens. This output has been maintained for a period of 67 weeks at very stable levels. The output voltage of the battery changed from an initial 1.51 volts to around 1.46 volts.

TABLE 2: Circuit Characteristics of Laboratory Constant Load Test

	Battery 1 CP Test	Battery 2
System Resistance	2.2 ohms	1.5 ohms
Load		40 ohms
Anode-Structure Voltage	0.643 v	---
Battery Voltage OC	1.51 v	1.50 v
Battery Voltage CC	1.49 v	1.46 v
Initial Rebar Potential Specimen A/B	-0.016 v/ -0.099 v	---

The voltage potential of the specimens achieved cathodic protection levels shifting from an average static of –0.086 volts to an average polarized potential of -0.265 volts.

The second battery (connected to a constant load) had an initial current output of 37 mAmp. This value has been maintained with only minimal variations throughout the test. The general circuit characteristics for this test are shown in Table 2. The test has been in progress for a period of 66 weeks with no observed changes in the battery's ability to deliver current (Figure 7 - lab test).

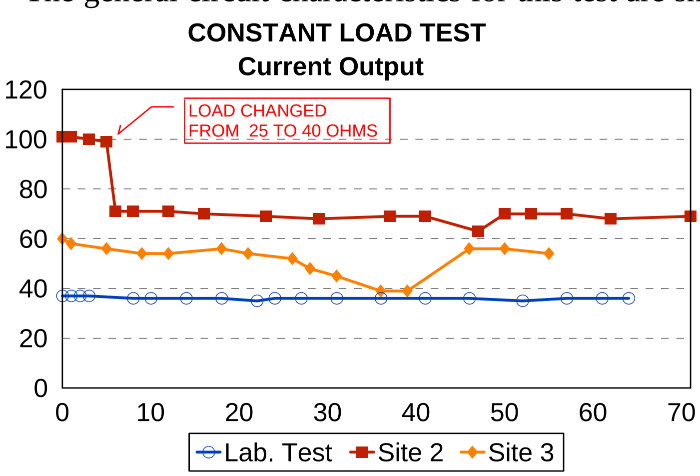

Figure 7: Current output behavior of batteries tested under a constant load.

On both tests the general output has been at or below the manufacturer design operational range. At this time none of the batteries evaluated in this test have shown any significant decrease in voltage or any other indication that may suggest depletion of the battery anode or deterioration of any other battery component.

Field Evaluation:

Multiple Piles Test:

Site 1: Upon connection, the voltage potential of the reinforcing steel shifted from a static (depolarized) potential of -0.333 V to -1.09 V with an open circuit (instant 0ff) potential (measured next day) of -0.623 V. The initial current was 301 mAmp. After 9 days the system stabilized to a near steady-state current of around 180 mAmp or 1.0 mAmp/ft^2 (10.76 mAmp/m^2).

The system has been continuously operational for a period of 67 weeks. At this time the steady-state current is around 115 mAmp and the voltage potential of the steel has polarized to an open-circuit value of approximately -0.625 V. It was also observed that occasionally, at periods of extreme high tides, the output current was significantly increased producing voltage potentials as high as -.825 volts. However, this had also been observed with the previous rectifier system as the resistance of the anode employed at this site is somewhat affected by the tidal changes (Figures 8 & 9).

The average current output over the test duration is 0.160 Amp. After 68 weeks of operation the system has consumed 1,828 Amp-h. With a total of 2400 Amp-h (originally available from 2 batteries), approximately 24 percent of the total output capacity should remain available (Table 13A).

Under the previous rectifier power supply, the system was operating at a current density of 0.67 mAmp/ft^2 (7.21 mAmp/m^2) at 2.0 volts producing an open circuit potential of -0.659 V (Table 3A).

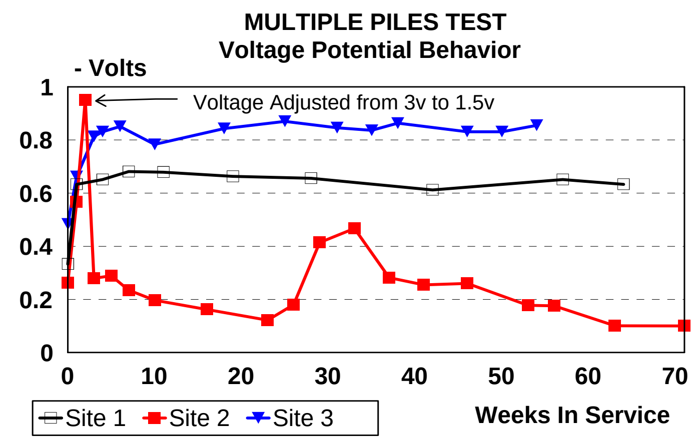

Figure 8: Voltage potentials of the steel at the Multiple Piles test.

Site 2: Upon initial connection, the voltage potential of the reinforcing steel shifted from a static of -0.263 V to -0.611 V with an open circuit potential (after one day) of -0.566 V. The initial current was 1.6 Amp or 9 mAmp/ft^2 (96.9 mAmp/m^2). After five days the open-circuit voltage potential had shifted to -0.950 V. Because of the high potential within a relative short period, the batteries were re-wired to produce a 1.5 V output instead of the 3.0 V originally scheduled. Under the lower voltage, the current output was 74 mAmps or 0.5 mAmp/ft^2 (5.38 mAmp/m^2) and the open circuit potential was -0.279 V. At week 26 the voltage potentials began to move in the negative direction to –0.425v suggesting satisfactory polarization levels. However, this trend did not continue. After 71 weeks of operation at the lower voltage, the current has fluctuated between 125 and 26 mAmp (Figure 9–Site 2) producing voltage potentials meeting cathodic protection criteria only for a short period of time as determined by the level of polarization from the static of the steel (Figure 8-Site 2).

The average current output over the duration of the test is 0.228 Amps including the initial period of operation above 1.0 Amp. After 71 weeks of operation the system has discharged a total of 2,720 Amp-h. The four power packs used on this test should be able

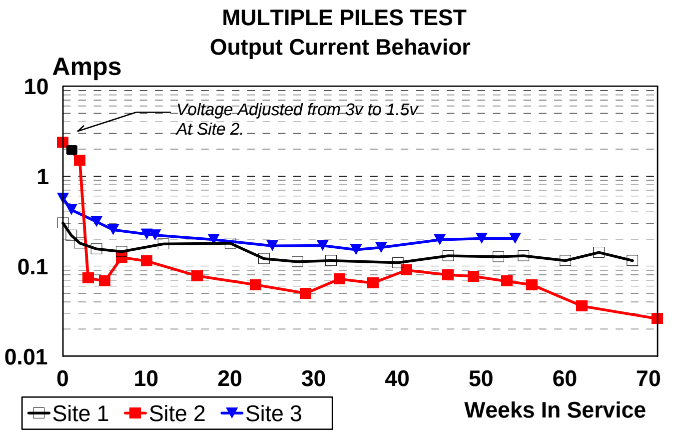

Figure 9: Current output of the battery arrangement on the multiple piles test.

to provide 9,600 Amp-h since the battery arrangement was re-wired to set all the batteries in parallel. The available output is estimated to be around 6,880 Amp-h.

Under the previous rectifier power supply the system was operating at a current density of 1.1 mAmp/ft^2 (11.84 mAmp/m^2) at 1.7 volts with an open circuit potential of -0.804 V (Table 3A).

Since cathodic protection is not being achieved, these units are scheduled for further modifications to bring polarization levels into the proper ranges. It is estimated that the available output after modifications will be 3,440 Amp-hours and that the current output will be around 0.450 Amp. Based on these estimates the remaining service life is around 45 weeks.

Site 3: Upon initial connection, the output voltage was adjusted to 2.0 V using the 0-100 ohm regulator. The voltage potential of the reinforcing steel shifted from a static of -0.483 V to -0.713 V with an open circuit potential (after one day) of -0.662 V. The initial current was 567 mAmp or 2.9 mAmp/ft^2 (31.22 mAmp/m^2). At week 10 the steady state current stabilized to approximately 250 mAmp or 1.3 mAmp/ft^2 (13.99 mAmp/m^2) with an open circuit voltage potential of around -0.800 v. After 54 weeks of operation the current output was around 200 mAmp producing an open circuit potential on the steel of –0.855 volts satisfactorily meeting cathodic protection requirements.

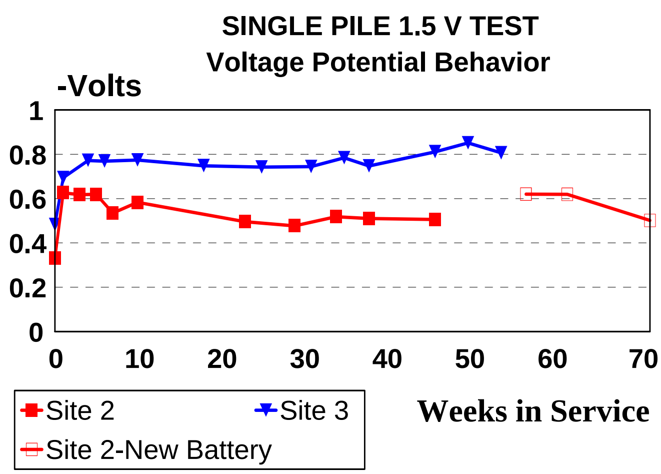

Figure 10: Voltage potential behavior of the reinforcing steel at the two Low Voltage (1.5v)-Single Pile tests.

The average current over the test period is 0.222 Amp with a current consumption of 2,014 Amp-h. The battery arrangement at this site should provide a total of 3,600 Amp-h. Based on the above, 44 percent of the total capacity should remain available.

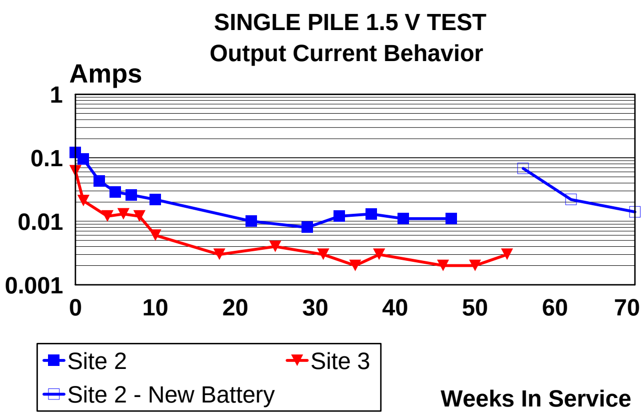

Figure 11: Current output behavior of Low Voltage (1.5V) - Single Pile test.

Under the previous rectifier power supply the system was operating at a current density of 0.81 mAmp/ft^2 (8.72 mAmp/m^2) at 1.5 volts with an open circuit potential of -0.664 V. At this site also, the higher voltage of the battery increased the polarization. However, the level of polarization is within acceptable limits and is readily controllable through the voltage regulator if necessary.

<u>Single Pile - 1.5 V</u>:

Site 2: Upon connection, the voltage potential of the reinforcing steel shifted from a static of -0.330 V to -0.638 V with an open circuit potential (after one day) of -0.626 V. The initial current was 121 mAmp or 3.6 mAmp/ft^2 (38.75 mAmp/m^2). At week 10 the steady state current was around 25 mAmp or 0.7 mAmp/ft^2 (7.53 mAmp/m^2). The open circuit potential was maintained at around -0.600 V (Figures 9 & 10). After 46 weeks of operation the current had further dropped to 11 mAmp while maintaining an open circuit potential of –0.506 volts meeting cathodic protection criteria.

At around week 48 the battery suddenly stopped producing current. The battery was removed and returned to the manufacturer who determined that the malfunction was a result of water intrusion through the vent orifices. A new battery was provided to replace the failed one. The new battery produced a current output of 68 mAmp with an open circuit potential of –0.603 volt. After 15 weeks of operation the current stabilized to 14 mAmp and a voltage potential of –0.568 volts similar to the previous unit.

Under the previous rectifier power supply the system was operating at a current density of 0.90 mAmp/ft^2 (9.69 mAmp/m^2) at 1.6 V with an open circuit potential of -0.804 V. In this test, the lower voltage of the battery reduced the steel polarization although it is still maintaining acceptable cathodic protection values.

Site 3: The voltage potential of the reinforcing steel shifted upon connection from a static of -0.452 V to -0.766 V with an open circuit potential (after one day) of -0.694 V. The initial current was 62 mAmp or 1.7 mAmp/ft^2 (18.3 mAmp/m^2). At week 10 the steady state current was around 15 mAmp or 0.5 mAmp/ft^2 (5.38 mAmp/m^2) with an open circuit potential around -0.770 V. After 54 weeks of operation the steady-state current is around 0.003 Amp with an open circuit potential of the steel of –0.798 volts meeting established cathodic protection criteria. In this case a very small current output is sufficient to maintain cathodic protection. Occasionally on piles, small amounts of current are sufficient to sustain cathodic protection levels. However, this should not be considered as the norm, The average current output over the test period is 0.010 Amp. The actual battery consumption up to week 54 was around 91 Amp-h leaving around 1,109 Amp-h available.

Under the previous rectifier power supply the system was operating at a current density of 0.4 mAmp/ft^2 (4.31 mAmp/m^2) at 1.1 V with an open circuit potential of -0.644 V. At this site the polarization increased by 154 mV above that with the rectifier system.

<u>Single Pile - 3 V</u>:
Site 2: Upon connection, the voltage potential of the reinforcing steel shifted from a static of -0.276 V to -1.127 V with an open circuit potential (after one day) of -0.926 V. The initial current was 811 mAmp or 22 mAmp/ft^2 (236.8 mAmp/m^2). Because of the high current density and potential shift of the reinforcement, the batteries were re-wired to produce 1.5 V. At the lower voltage, the closed circuit potential shifted to -0.543 V. At week 10 the steady state current was around 40 mAmp or 1.1 mAmp/ft^2 (11.84 mAmp/m^2) with the open circuit voltage potential of the steel of around -0.490 V still achieving cathodic protection levels (Figures 11 & 12). After 71 weeks of service the current output has decreased to around 23 mAmp with an open circuit potential of the steel of –0.462 meeting cathodic protection parameters (Figures 12 & 13).

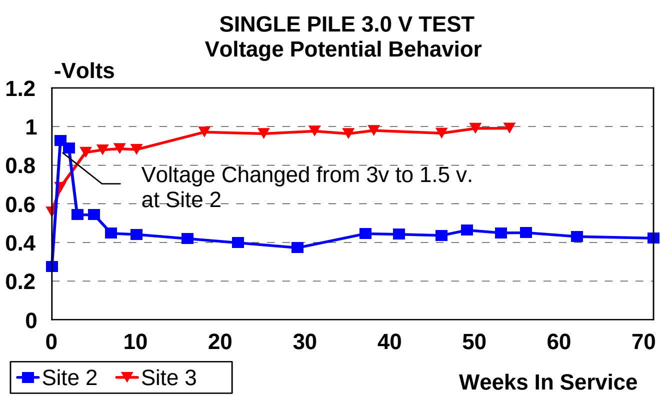

Figure 12: Voltage potential behavior of the High Voltage (3v) - Single Pile test

The average current during the test period is 88 mAmp with a total battery consumption of 1,049 Amp-h. With an initial current availability of 2,400 Amp-h (2 batteries connected in series but later re-wired in parallel), these batteries should still have around 52 percent of the original capacity.

Site 3: At this site the voltage potential shifted from a static of -0.557 V to -0.736 V with an open circuit potential (after one day) of -0.685 V. The initial current was 27 mAmp or 0.84 mAmp/ft^2 (9.04 mAmp/m^2). The steady state current promptly stabilized to around 13 mAmp or 0.4 mAmp/ft^2 (4.31 mAmp/m^2). At week 10 the open circuit potential was around -0.959 V. After 54 weeks of operation the steady-state current is still holding at 12 mAmp with an open circuit potential of –0.991 volts satisfying the cathodic protection criteria.

The average current output over the test period is 0.013 Amp with a total current consumption of 118 Amp-h. With a total capacity of 1,200 Amp-h, this battery has only consumed around 10 percent of the originally available power.

At both sites, the previous operation (voltage & current output) under the rectifier power supply was similar to that of the single pile (1.5 V) arrangement since the piles used for the 3.0 V test were previously connected to same circuit as those for the 1.5 V test. Table 3A compares the structure voltage potentials and the current density for each test at all test sites.

<u>Constant Load:</u>
Site 2: At this site the initial connection was made to the constant load device with a resistance of 25 ohms. Upon connection, a 3.021 volt output (battery O.C.) produced a current of 101 mAmp with a closed circuit voltage of 3.019 V. Because this current output level was excessively above design limits, the resistance was changed to 40 ohms at week five. With this change, the current output dropped to 71 mAmp holding constant for the following 66 weeks observed. Notice that this output is still 2.8 times above the design capacity for a service life of 5 years.

The average current for the evaluated period, including the initial five weeks at a higher output, is 0.071 Amp with a total current consumption of 870 Amp-h. The initial current availability was 1200 Amp-h (two batteries connected in series).

Site 3: Upon connection to the 25 ohm load, the 1.507 volt of the battery (battery OC) produced an output current of 60 mAmp with a closed circuit voltage of 1.487 V. With some variations of around 15 mAmp, after 54 weeks the current is holding around 54 mAmp (Figure 7).

The average current for the evaluated period is 0.05 Amp with a total current consumption of 463 Amp-h. The initial current availability was 1200 Amp-h (two batteries connected in series).

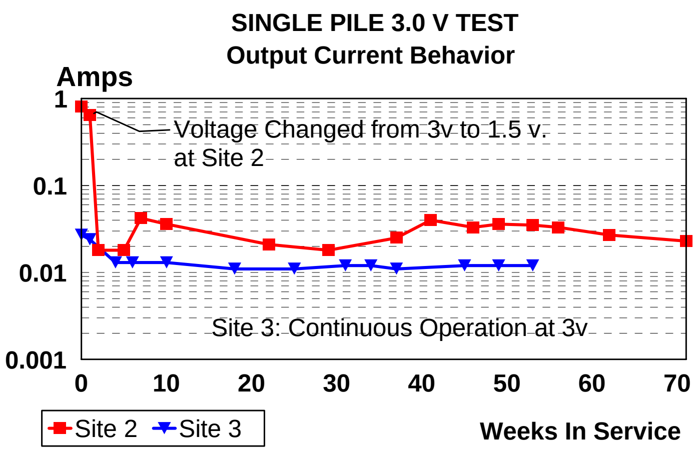

Figure 13: Current behavior of High Voltage (3v) – Single Pile test.

It was also observed that in almost every test, the difference between the closed and open circuit voltage of the batteries was somewhat reduced over the service period (Figures 7A, 8A, 10A). This observation was made based on the battery instant (on) measurements obtained by the data loggers. This measurement was obtained at approximately 100 milliseconds after circuit interruption. However, at this time no significant reduction of the nominal voltage has been observed.

ECONOMIC FACTORS

This battery system has a highly reduced initial installation cost when compared to other types of power supplies. It is expected that the overall costs of the battery power supply system will favorably compare with rectifier power supply units. However, the actual cost of the battery has not been disclosed by the manufacturer at the time of this report.

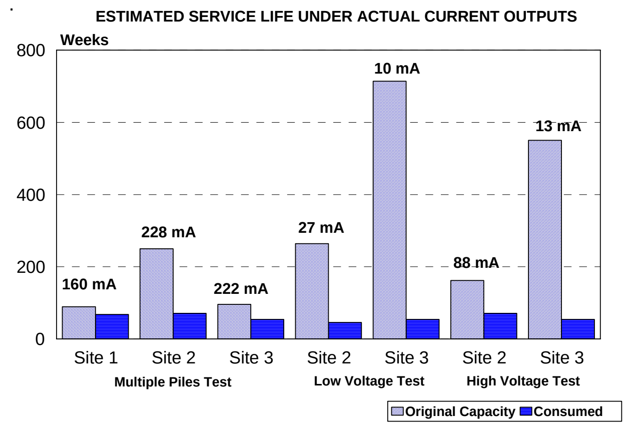

Figure 14: Original capacity and actual power consumption of each cathodic protection test at all sites. The recommended output for a service life of 5 years is 25 mAmp.

The use of batteries will eliminate the initial installation costs associated with rectifier installation such as mounting posts, housing cabinets and/or concrete slabs or platforms. It will also eliminate the costs associated with providing AC power to the rectifier, and will minimize the costs of conduit and wire runs necessary to transfer the cathodic protection current from the power supply to the protected structure components.

Long term expenses associated with routine monitoring and maintenance are also expected to be lower than those of the rectifier systems as these batteries are expected to be basically maintenance free and not as susceptible to current surges, lighting, or power failures. The period between battery replacement will mostly be governed by the general system output and the initial battery arrangement per protected structure component. Designing the battery arrangements for specific cathodic protection systems will need to be done on a case by case basis. The system current demand should be carefully calculated and an adequate safety factor should be included. In this study the current demand of the protected structure components significantly affected the service life of the battery systems (Figure 14). The extent of the service life reduction will be determined when the batteries fail to produce current.

Selection of the battery system over rectifiers should also consider the expected service life of the cathodic protection to determine how often the batteries would require replacement over the expected service life of the system.

In addition, the selection criteria should also consider the amount and the location of the piles or other components to be protected within the structure. For bridge structures, it is expected that the number of pilings to be protected will significantly influence the economic analysis to determine the cost advantage of one system versus the other.

CONCLUSIONS

1. The initial performance measurements indicate that the batteries have the ability to provide and maintain adequate cathodic protection current for bridge concrete piling systems which normally operate at nominal voltages between 1.5 and 3.0 volts. This was demonstrated through the current output and polarized potential measurements which were comparable to previous values obtained under a rectifier power supply system. The batteries could also be used for larger systems but the economics for those applications should be further studied.

2. The batteries can be conveniently arranged as battery banks to supply the protective current based on the specific cathodic protection system needs. The batteries can be combined in series to increase the output voltage or in parallel to extend the service life. Because of the small size of the batteries, each arrangement can be designed to provide the required current to localized areas (C.P. component or zone) such that in the event of system malfunction, only isolated areas would be affected. Based on the results of this study it appears that the one pile – one battery arrangement will be the most efficient installation as well as the most economical.

3. When combining two or more batteries in series, it will be necessary to install a voltage regulation device within the circuit to adjust the output voltage when the cathodic protection system requirements fall between the 1.5 V step increments. Because of the mechanism of the cathodic protection process, the voltage requirements will sometimes be such that a 3.0 volts output is too large but a 1.5 V is not sufficient to provide adequate protection. This was the case observed on the Multiple Piles Test at Site 2.

The device suggested above should be provided within a suitable size NEMA enclosure for long term weather and environment protection. In addition, a circuit interruption switch could be added inside the enclosure to facilitate turning the system "on" and "off" as this is necessary to properly monitor the cathodic protection levels of the protected structure. Such device should be marketed as an optional accessory to the batteries and should be readily available.

4. Based on the failed battery at Site 2, it seems that it will be necessary for the batteries to be better protected from water intrusion as this will destroy the battery. The manufacturer should provide a device such as a vent cap or a breathing tube that will allow adequate air intake while better preventing the entrance of water. In addition, the cathodic protection designer should provide for the installation of the batteries at locations where the possibilities of a battery coming in contact with water are minimized. Caution should be observed as location of the batteries too far from the piles may generate a significant cost increase which will need to be considered during the power supply selection process.

Even though it was not observed on any of the tests, it was not conclusive if moisture accumulation due to high humidity and condensation would produce sufficient water to generate a battery failure. Further evaluation of this process is needed.

5. It was clearly concluded that the batteries are able to satisfactorily provide and maintain cathodic protection currents. However, selection of the most practical arrangement for specific cathodic protection systems should be made based on the system current requirements. First, the cathodic protection designer should carefully estimate the system current requirements and design the battery arrangement based on this.

It is clear that under a constant load the current consumption can be easily determined and the service life calculated. However, in a cathodic protection system, the system itself polarizes producing a changing voltage at the load (the C.P. component). This voltage significantly affects the current output from the battery making the process of estimating the service life of the battery more difficult. On concrete structures, polarization occurs at different levels and after different time periods. Preliminary testing of the polarization characteristics may be necessary in order to design the proper battery arrangement based on the required service life of the system.

6. When selecting the battery power supply over a rectifier system, an economic analysis should be performed taking into consideration the estimated service life of the batteries as previously discussed. It is expected that due to the recurring costs, for a typical cathodic protection system with a service life of 25 to 30 years, and a moderate number of required batteries, the battery system should have an economic advantage.

7. From the study conducted, it can be determined that the batteries perform as per manufacturer specifications under a current output of 25 to 35 mAmp. However, further evaluation will be required to determine the service life at lower current outputs. At this time it is unknown if the electrolyte or other of the battery components will deteriorate over a period of five years or more regardless of the low battery anode consumption.

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APPENDIX A

TABLE 1A: Schedule of Field Tests		
Site	Tests Implemented	Protected Area *
Site 1 Ribault River Bridge	1. Multiple Piles - 3 volts nominal output. Four batteries in series & parallel connections.	4 piles – 96ft^2
Site 2 Dunn's Creek Bridge	1. Multiple Piles - 3 volts nominal output initially, later re-wired to 1.5 volts. Four sets of two batteries each (3v). All sets connected in parallel. 2. Single Pile - 1.5 volts (one battery) 3. Single Pile - 3 volts nominal output (two batteries in series), later re-wired to 1.5 volts. 4. Constant Load Test - 3 volts nominal output (two batteries connected in series).	5 piles -180ft^2 1 pile - 36 ft^2 1 pile - 36 ft^2 40 ohms load
Site 3 Howard Frankland Bridge	1. Multiple Piles - 3 volts nominal output. Three sets of two batteries each (3 v). All sets connected in parallel. Circuit provided with voltage regulation 2. Single Pile - 1.5 volts (one battery) 3. Single Pile - 3 volts nominal output (two batteries in series) provided with voltage regulation 4. Constant Load Test - 1.5 volts nominal output (one battery).	6 piles -192ft^2 1 pile - 32 ft^2 1 pile - 32 ft^2 25 ohms load

** Cathodically protected area is typically located around the tidal area and the splash zone*

TABLE 2A: Initial Circuit Measurements at Field Test Sites				
Site 1				
Measurement	Multiple Piles	Low Voltage Test (1.5v)	High Voltage Test (3.0v)	Constant Load Test
System Resistance	1.1 ohms	---	---	---
Anode-Structure Voltage Difference	0.691 v	---	---	---
Battery Open Circuit (V)	3.27 v	---	---	---
Battery Closed Circuit (V)	2.90 v	---	---	---
Initial Rebar Potential (Ag/AgCl)	-0.330 v	---	---	---
Site 2				
System Resistance	0.33 ohms	1.3 ohms	1.5 ohms	40 ohms
Anode-Structure Voltage Difference	0.754 v	0.619 v	0.631 v	---
Battery Open Circuit (V)	3.012 v	1.508 v	3.021 v	3.021 v
Battery Closed Circuit (V)	2.851 v	1.482 v	2.819 v	3.019 v
Initial Rebar Potential (Ag/AgCl)	-0.263 v	-0.330 v	-0.276 v	---
Site 3				
System Resistance	0.47 ohms	19 ohms	6.6 ohms	25.0 ohms
Anode-Structure Voltage Difference	0.594 v	0.552 v	0.895 v	---
Battery Open Circuit (V)	3.015 v	1.509 v	3.017 v	1.507 v
Battery Closed Circuit (V)	2.256 v	1.503 v	2.902 v	1.487 v
Initial Rebar Potential (Ag/AgCl)	-0.483 v	-0.482 v	-0.557 v	---

1. *System resistance = anode to cathode or load resistance*
2. *Circuit resistance = System resistance + voltage limiting device*
3. *Battery closed circuit includes C.P. or load resistance + voltage limiting device when applicable.*
4. *Initial rebar potential = Potential after depolarizing from previous C.P. system. Some of the systems may not have completely depolarized to its natural potential during the allowed disconnection period.*

Table 3A:Comparison of Current Density and Rebar Potentials with Rectifier and Battery Power Supplies for Multiple Piles Test				
Test Site	Battery Power Supply		Rectifier Power Supply	
Multiple Piles Test	Steady-State Current (mA/ft^2-mA/m^2)	Polarized Potential * (volt)	Steady-State Current (mA/ft^2-mA/m^2)	Polarized Potential * (volt)
Site 1	1.0 - 10.76	-0.625	0.67 - 7.21	-0.659
Site 2	9.0 - 96.8	-0.950 ***	1.1 - 11.84	-0.804
Site 2 **	0.5 - 5.38	-0.279	----	----
Site 3	1.3 - 13.9	-0.800	0.8 - 8.61	-0.644

** Polarized potentials = Instant off potentials.*
*** Measurements after adjusting the output voltage to 1.5 V.*
**** Measured at day 5.*

Table 4A: Performance Data of Multiple Piles Test at Site 1				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
		3.027	---	-0.333
0	0.301	2.99	1.18	---
1	0.289	2.297	1.705	-0.623
4	0.179	2.295	1.705	-0.651
7	0.188	2.287	1.656	-0.681
12	0.176	2.276	1.592	-0.679
20	0.179	2.323	1.770	-0.663
24	0.121	2.451	1.916	-0.660
28	0.112	2.486	1.905	-0.656
32	0.115	2.477	1.794	---
40	0.109	2.481	1.932	---
46	0.130	2.425	1.798	-0.612
48	0.154	2.381	1.705	---
52	0.127	2.417	1.986	---
60	0.115	2.473	1.621	-0.651
64	0.142	2.369	1.719	-0.633
68	0.115	2.445	1.791	---
AVE	0.160			

Table 5A: Performance Data of Multiple Piles Test at Site 2				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.263
0	2.380	3.012	2.851	-0.566
1	2.250	3.010	2.800	-0.950
5	0.068	1.435	1.432	-0.235
10	0.114	1.447	1.440	-0.197
16	0.125	1.448	1.400	-0.162
23	0.062	1.446	1.441	-0.122
29	0.050	1.440	1.429	-0.414
33	0.072	1.444	1.440	-0.467
37	0.065	1.445	1.449	-0.282
42	0.108	1.438	1.439	-0.255
46	0.080	1.436	1.439	-0.260
49	0.077	1.433	1.437	-0.245
53	0.068	1.421	1.416	-0.178
56	0.062	1.403	1.398	-0.176
62	0.036	1.333	1.331	-0.099
71	0.026	1.331	1.323	-0.092
AVE	0.228			

Table 6A: Performance Data of Multiple Piles Test at Site 3				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.483
0	0.567	3.015	2.256	-0.662
4	0.237	2.834	2.805	-0.809
10	0.226	2.822	2.799	-0.783
18	0.197	2.807	2.787	-0.843
22	0.179	2.808	2.786	-0.843
25	0.168	2.810	2.691	-0.870
31	0.169	2.819	2.603	-0.846
35	0.152	2.823	2.497	-0.836
38	0.161	2.829	2.600	-0.883
46	0.196	2.820	2.680	-0.831
50	0.203	2.813	2.718	-0.831
54	0.203	2.802	2.750	-0.855
AVE	0.222			

Table 7A: Performance Data of Low Voltage - Single Pile Test at Site 2				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.330
0	0.121	1.508	1.482	-0.626
1	0.039	1.468	1.461	-0.598
10	0.022	1.436	1.431	-0.583
23	0.010	1.337	1.335	-0.494
29	0.008	1.305	1.304	-0.473
31	0.008	1.272	1.270	-0.474
37	0.013	1.319	1.320	-0.501
42	0.011	1.321	1.328	-0.499
46	0.011	1.319	1.326	-0.506
AVE	0.027			
49	Failed battery - no data			
53	Failed battery - no data			
56 New Battery	0.068	1.501	1.443	-0.633
62	0.022	1.449	1.425	-0.613
71	0.014	1.436	1.377	-0.568

Table 8A: Performance Data of Low Voltage - Single Pile Test at Site 3				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.482
0	0.062	1.509	1.503	-0.694
1	0.021	1.497	1.491	-0.772
3	0.008	1.487	1.482	-0.772
10	0.006	1.479	1.478	-0.781
18	0.003	1.476	1.475	-0.784
25	0.004	1.467	1.462	-0.742
31	0.003	1.459	1.458	-0.732
35	0.002	1.461	1.459	-0.778
38	0.003	1.460	1.458	-0.742
46	0.002	1.460	1.459	-0.805
50	0.002	1.459	1.458	-0.838
54	0.003	1.452	1.450	-0.798
AVE	0.010			

Table 9A: Performance Data of High Voltage - Single Pile Test at Site 2				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.276
0	0.811	3.021	2.819	-0.926
1	---	2.728	2.612	-0.876
10	0.036	1.444	1.437	-0.441
23	0.021	1.446	1.436	-0.398
29	0.016	1.412	1.406	-0.372
31	0.013	1.447	1.375	-0.387
37	0.025	1.445	1.438	-0.445
42	0.040	1.439	1.412	-0.442
46	0.033	1.444	1.397	-0.436
49	0.036	1.440	1.431	-0.463
53	0.035	1.440	1.129	-0.449
56	0.033	1.441	1.423	-0.450
62	0.027	1.441	1.419	-0.430
71	0.023	1.438	1.421	-0.422
AVE	0.088			

Table 10A: Performance Data of High Voltage - Single Pile Test at Site 3				
Weeks in Service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)	Potentials O.C. (V)
				-0.557
0	0.027	2.965	2.902	-0.685
1	0.013	2.965	2.965	-0.965
3	0.013	2.957	2.962	-0.958
10	0.013	2.914	2.908	-0.948
18	0.011	2.887	2.879	-0.971
25	0.011	2.895	2.883	-0.963
31	0.012	2.866	2.882	-0.976
35	0.012	2.885	2.882	-0.963
38	0.011	2.891	2.887	-0.979
46	0.012	2.866	2.852	-0.965
50	0.012	2.871	2.868	-0.990
54	0.012	2.870	2.866	-0.991
AVE	0.13			

Table 11A: Constant Load Test Data at Site 2			
Weeks in service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)
0	0.101	3.021	3.019
1	0.101	3.018	3.017
4	0.075	3.011	2.992
8	0.071	2.836	2.812
9	0.071	2.831	2.809
23	0.069	2.793	2.772
29	0.068	2.763	2.741
32	0.068	2.796	2.776
37	0.069	2.812	2.806
41	0.069	2.824	2.818
46	0.063	2.830	2.826
49	0.070	2.829	2.826
53	0.070	2.823	2.805
56	0.070	2.817	2.800
62	0.068	2.806	2.789
71	0.069	2.787	2.768
AVE	0.073		

Table 12A: Constant Load Test Data at Site 3			
Weeks in service	Current (Amp)	Battery Open Circuit (V)	System Closed Circuit (V)
0	0.060	1.507	1.487
1	0.058	---	1.437
6	0.056	1.432	1.407
10	0.054	1.424	1.401
18	0.056	1.412	1.390
22	0.050	1.412	1.390
25	0.039	1.423	1.407
27	0.048	1.418	1.396
31	0.045	1.421	1.402
35	0.039	1.423	1.407
38	0.039	1.427	1.409
46	0.056	1.419	1.394
50	0.056	1.416	1.392
54	0.054	1.414	1.392
AVE	0.051		

TABLE 13A: Power Consumption per Test					
Multiple Piles Test					
Site Number	Average Current * (Amp)	Hours per Week (K)	Weeks in Service	Used Power** Amp-hour	Power Initially Available Amp-hour
1	0.160	168	68	1,828	2,400
2	0.228	168	71	2,720	9,600
3	0.222	168	54	2,014	3,600
Low Voltage (1.5 V) – Single Pile Test					
2	0.027	168	46	209	1,200
3	0.010	168	54	91	1,200
High Voltage (3 V) – Single Pile Test					
2	0.088	168	71	1,049	2,400
3	0.013	168	54	118	1,200
Constant Load Test					
2	0.073	168	71	870	1,200
3	0.051	168	54	463	1,200

* *From Tables 4A – 11A*
** *Power consumption calculations are based on long range current averages.*

APPENDIX B

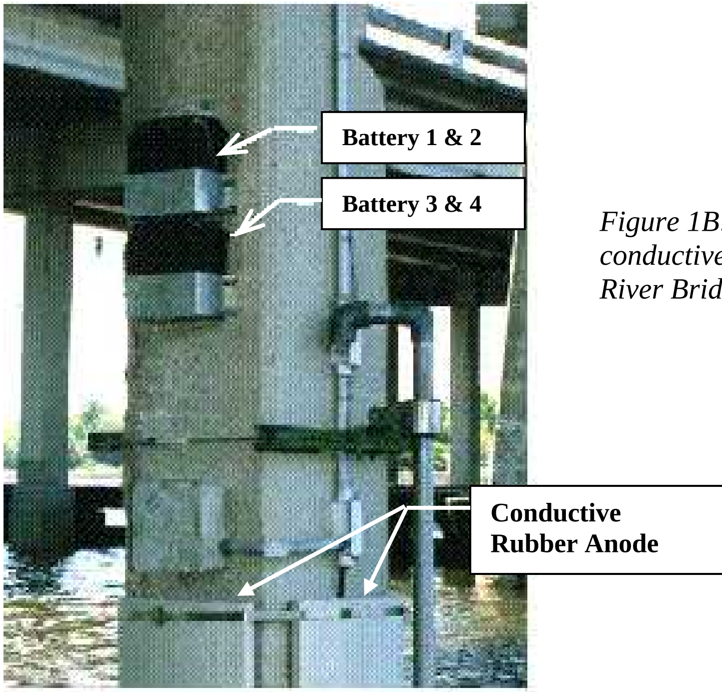

Figure 1B: Battery arrangement and conductive rubber anode system at Ribault River Bridge (Site 1).

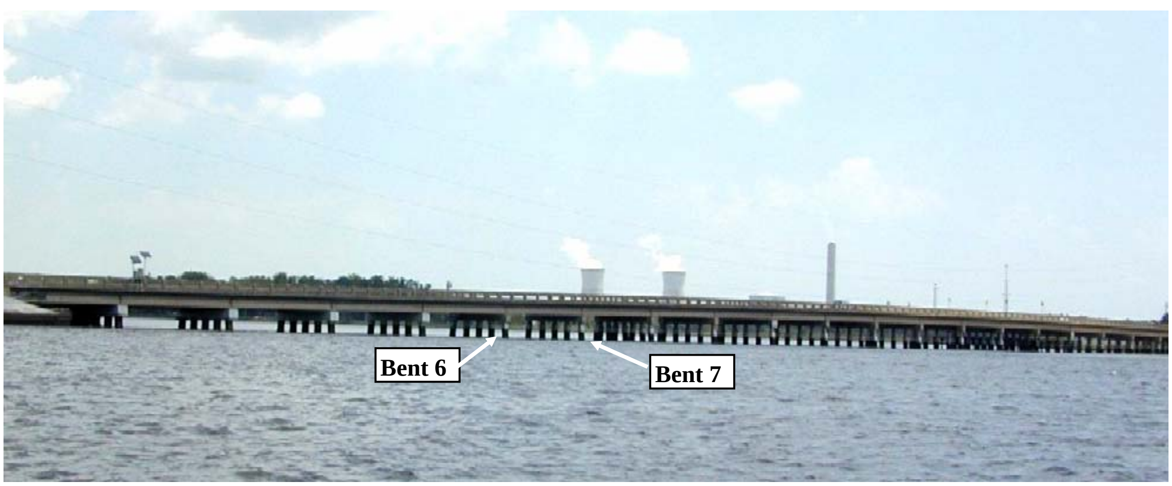

Figure 2B: Extremely corrosive environment at Dunn's Creek Bridge in Jacksonville, Florida (Site 2). Evaluation of the batteries was conducted on Bents 6 and 7.

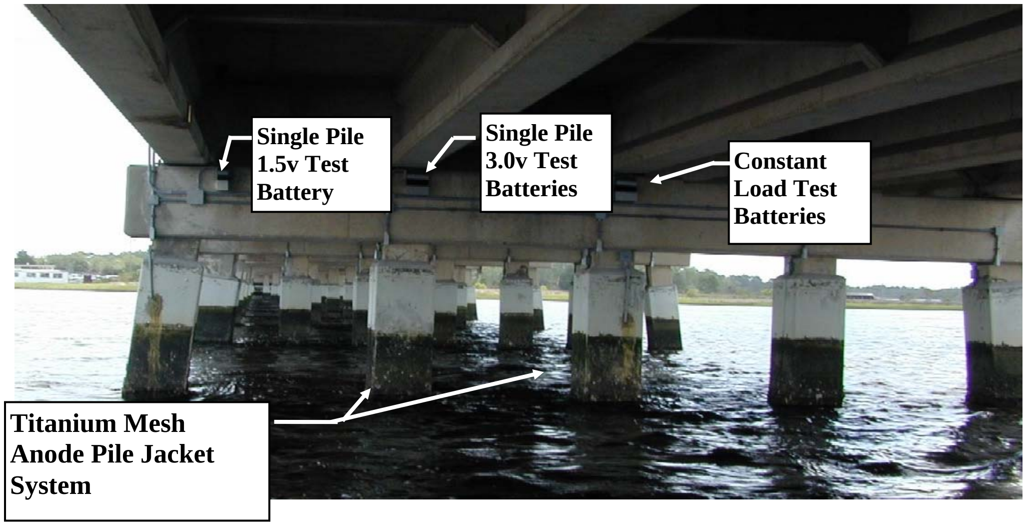

Figure 3B: Three of the battery arrangement and cathodic protection system at Dunn's Creek Bridge (Site 2). For the Bent Test, the battery arrangement protected all the piles of similar bent.

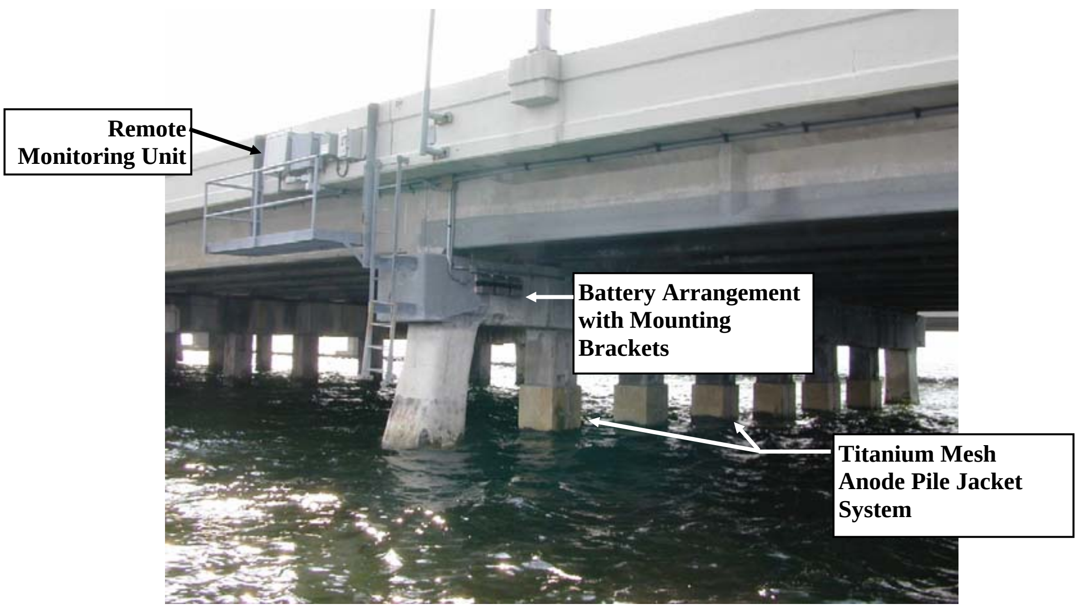

Figure 4B: Bent test at Howard Frankland Bridge in Tampa, Florida (Site 3). Three sets of 2 batteries providing a nominal output of 3V. Each mounting bracket accommodates 2 batteries.

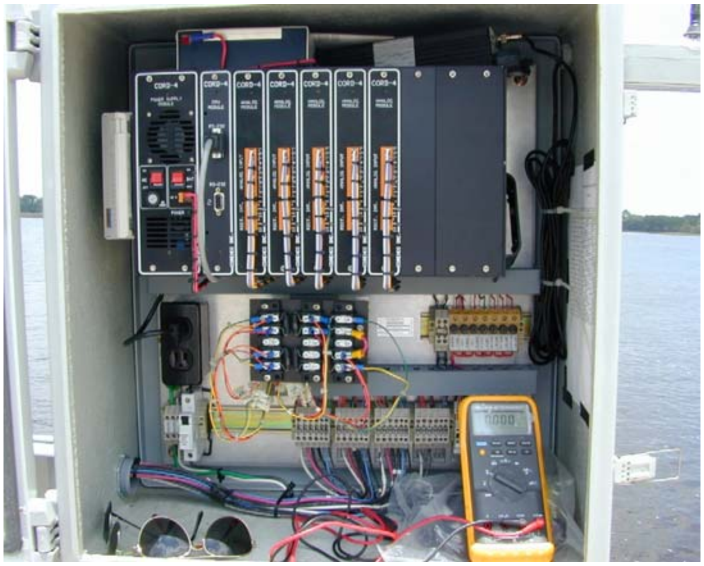

Figure 5B: Remote monitoring unit at Dunn's Creek Bridge (Site 2). A similar unit was installed at Site 3. Different units were installed at Site 1 and the Lab test.

Figure 6B: Close-up of failed battery at Site 2 after removal of upper bracket. Rusted terminals, and dirt and debris accumulated at the top of the battery suggested access of run-off water from the upper deck to the vent holes on top of the battery.

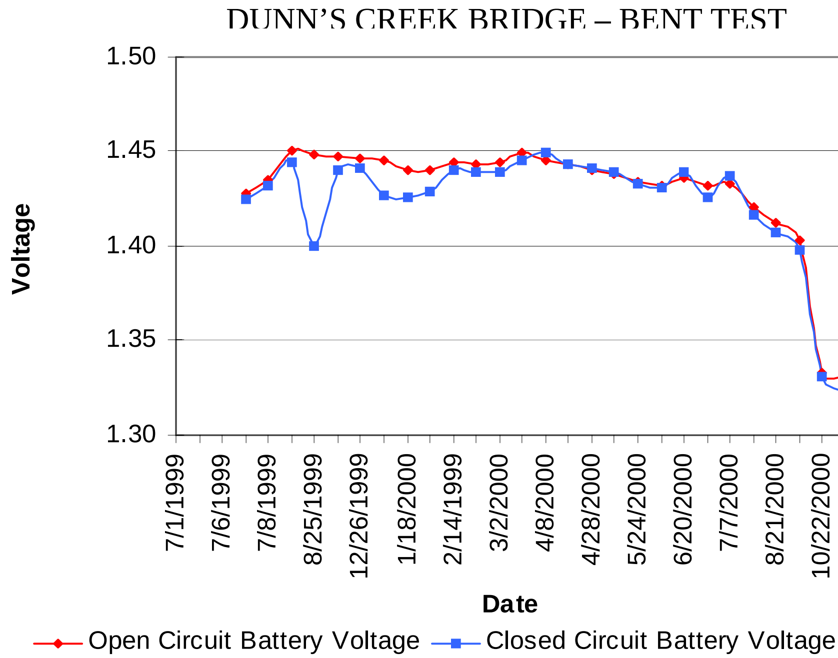

Figure 7B: Open and closed output voltage of the batteries for the Bent Test at Site 2.

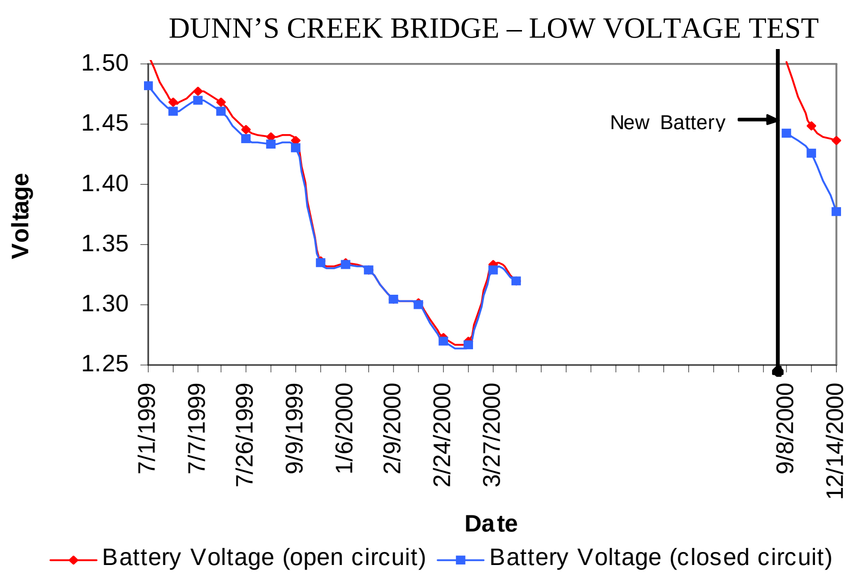

Figure 8B: Open and closed voltage of the batteries for the Single Pile-Low Voltage test at Site 2. In most instances, after a period of service, the difference between open and closed circuit voltage becomes minimal.

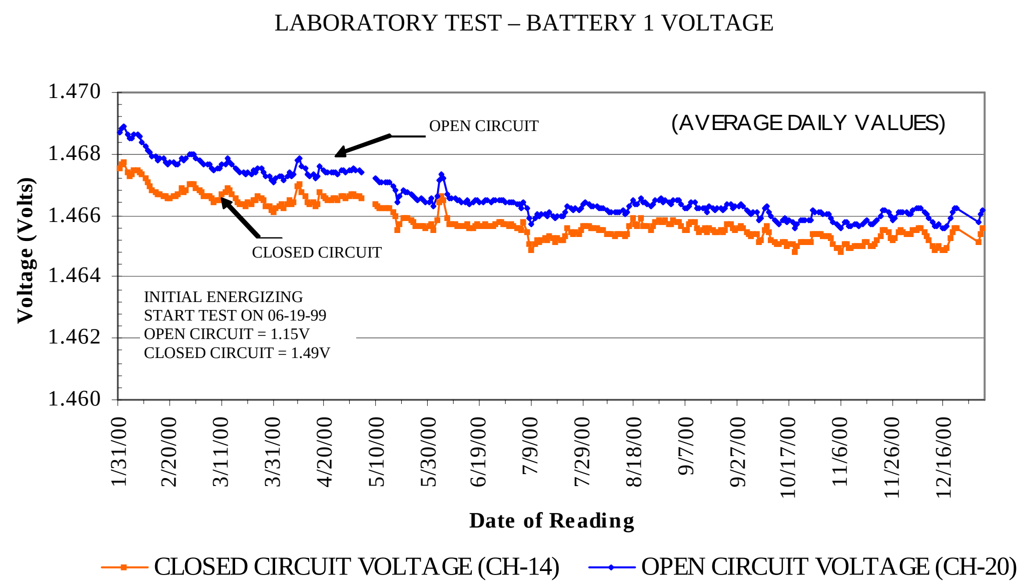

Figure 9B: One year open and closed circuit voltage of battery No. 1 of the Laboratory Test. The current output for this test is around 4 mAmp.

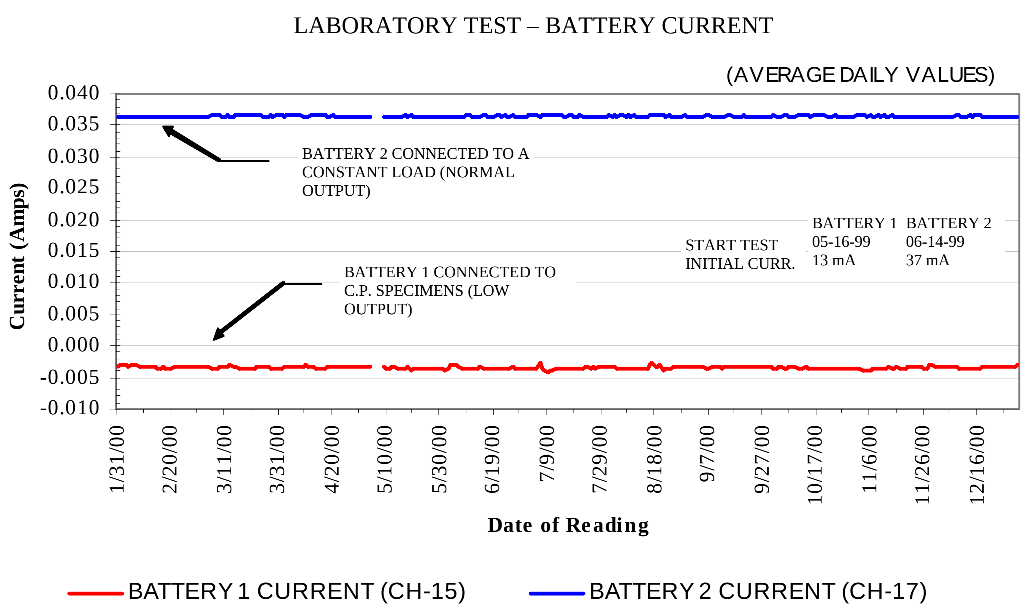

Figure 10B: One year current output of the two batteries for the Laboratory Test.