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Evaluation of Remotely Monitored Battery Powered Systems for Cathodic Protection of Reinforced Concrete

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16. Abstract

This report discusses the performance of a remotely monitored battery power supply system designed to provide cathodic protection to reinforced concrete structures. The modular cathodic protection power supply consists of a conveniently sized battery pack provided with an output control device and electronics that transmits the system condition to a Base Unit. The system uses radio signals to communicate the status to the Base Unit which is connected to a remotely monitored data logger.

The system was tested under controlled laboratory conditions and at an actual cathodic protection field site. The field site was a bridge owned and operated by the Florida Department of Transportation in Jacksonville, Florida.

Reliability of the radio transmissions between Modular Cathodic Protection System (MCPS) components was evaluated in the laboratory as well as in the field. Communication between the MCPS and a third party data logger was also evaluated. The accuracy of the configured output voltage was checked to ensure proper cathodic protection voltage could be provided to a reinforced concrete structure.

The findings indicate that the MCPS has the ability to provide adequate cathodic protection to concrete structure components and can provide information on the status of the cathodic protection system wirelessly. Equipment modifications recommended to enhance the dependability of the system include the use of two-way communication. Improvement of the circuitry efficiency is needed to minimize current drain on the batteries and achieve practical operating periods.

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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

US Customary and SI Conversions for Typical Corrosion Units

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

Table of Contents

DISCLAIMER

The opinions, findings, conclusions, and/or recommendations expressed in this report are those of the authors and do not necessarily represent those of the Florida Department of Transportation or the Federal Highway Administration.

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Executive Summary

In a previous study conducted by FDOT, the feasibility of using compact, long-life batteries as power supplies to provide cathodic protection (C.P.) to reinforced concrete bridge substructures was demonstrated. The study concluded that it would be desirable to remotely determine system condition to allow for quick replacement of the batteries with minimal interruption to the application of C.P. This investigation intended to evaluate the basic performance of a wireless Modular Cathodic Protection System (MCPS) and to identify needs for future development. The system uses radio signals to communicate the C.P. operation status to a Base Unit which is connected to a remotely monitored data logger. To that end, developers of the system were provided with detailed input on desired features; based on that input system prototypes were created. Evaluation procedures were developed, field installations were implemented and the resulting performance was analyzed.

The system was tested under controlled laboratory conditions and at an actual cathodic protection field site. The field site was the Dunn's Creek Bridge owned and operated by the Florida Department of Transportation in Jacksonville, Florida. The field test involved two remote units and one base unit. After initial field and laboratory testing, an improved MCPS design was implemented and field testing continued for a period of seven months.

The two remote units performed equally as well regarding communications, even though Unit 2 was positioned in a highly adverse location to successfully transmit data to the Base Unit. This suggests that the distance between the Remote and Base Units can be increased if necessary, provided the units are kept in as close to direct line of sight as possible. The findings indicate that the MCPS has the ability to provide adequate cathodic protection to concrete structure components and can provide information on the status of the cathodic protection system wirelessly. Extended testing is necessary to ascertain performance over a time frame representative of actual applications.

Improvement of the circuitry efficiency is needed to minimize current drain on the batteries and achieve practical operating periods. It is also recommended to enhance the dependability of the system by the use of two-way communication. Compatibility of the MCPS with data loggers and other support equipment is essential. It is also recommended that the manufacturer investigates the use of more robust switches and other electronic components than those provided with the prototype. Under normal use, these devices will be mostly used in aggressive marine environments which are extremely severe on electronic components.

Introduction

Corrosion is a naturally occurring process in which metal oxidizes, usually with detrimental effects on the physical properties of an engineering component. When this happens in a concrete bridge, the steel reinforcement inside the concrete forms a corrosion product which effectively increases the volume of the steel bars thus leading to an increase in internal tensile forces, cracking the concrete and compromising the bridge structural integrity. There are many factors that may prompt or influence the occurrence of corrosion. Some of these factors include but are not limited to: increased temperature, moisture, chloride concentration, and oxygen availability[1]. The bridges along Florida's coastline are highly susceptible to corrosion due to the high chloride concentration of the water and the sub-tropical climate. While Northern states are only exposed to high salt concentrations (road salts) during the winter months, Florida's bridges are continuously exposed to chlorides promoting a continuous diffusion of chloride ions inside the concrete. This exposure to chlorides and some of the above factors contribute to a large incident of corrosion induced damage on many structures resulting in the expenditure of millions of dollars in yearly maintenance repairs in Florida as well as nationwide. It is estimated that the annual cost of corrosion related repairs on highway bridges in the United States is around 8.3 billion dollars[2].

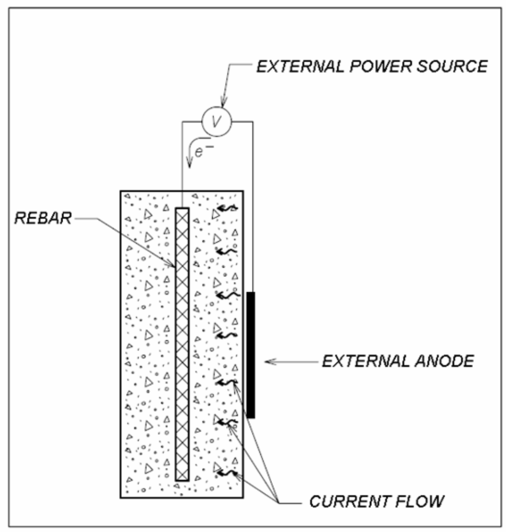

Figure 1: Typical mechanism of an impressed current cathodic protection system with external power supply.

Experience as well as many research investigations have shown that conventional repairs such as concrete replacement or encapsulation do not control the corrosion activity in chloride contaminated concrete once it has begun. Even after repairs, additional corrosion damage is produced in many instances, further compromising the structural stability of the bridges. An alternative to these short life repairs is the use of "cathodic protection" to halt the corrosion.

Cathodic protection is a means by which the corrosion process can be controlled and even stopped. Although cathodic protection has been practiced since the 1820's, it was not until around 1945 that it began to be widely used in the United States[3]. The most common use of cathodic protection in the U.S. is for corrosion control of submerged or buried pipe lines but it is also used to protect the reinforcing steel on concrete structures. Through cooperative research with industry and states in the development of durable anodes, monitoring devices, installation techniques, and other components, application of impressed-current cathodic protection systems on bridge decks has become a routine rehabilitation technique[4]. To a lesser extent, but with much success, it is also used in marine bridge substructures.

There are two basic types of cathodic protection: 1) sacrificial and 2) impressed current. Cathodic protection stops the corrosion activity by converting all the anodic areas within a corrosion cell into cathodes by establishing a current flow from an externally placed anode onto the surface of the corroding metal (Figure 1).

A sacrificial (or galvanic) cathodic protection system utilizes a metal with a higher propensity to corrode than the steel as the anode. This sacrificial metal produces the direct current (DC) needed for protection and corrodes preferentially to the steel, therefore protecting it from further damage. This type of system is somewhat less expensive and easier to install than the impressed current type. However, it does have a limited design life and limited output power. Because of this, its application is limited.

An impressed current cathodic protection (ICCP) system on the other hand, requires an external source of direct current to halt the corrosion process. The external current can typically be obtained from several different sources. The most common source of cathodic protection current is a rectifier which converts alternating current (AC) into direct current (DC). Other sources of external current are photovoltaic cells and wind generators which convert solar or wind energy into DC power to provide the cathodic protection. Photovoltaics and wind generators can be practical in some instances but require complex wiring because the main components require installation at specific locations to maximize the use of sunlight or wind. They also require the installation of temporary current storage batteries to provide the power during periods of no sunlight or wind. All of these sources of current require complex conduit and wiring systems to route the power to the component being cathodically protected. In addition, some require close monitoring to avoid overprotection in the event of a malfunction that sends excessive current to the component.

A fourth option to the above is DC power obtained directly from replaceable low power, long-life batteries. When the batteries are discharged and exhausted of power, they are simply replaced with new ones. This allows installation of the power supply at a short distance from the component being protected, thereby eliminating complex wiring systems. A low power battery also reduces the risk of overprotection since high voltages would not be available. A battery system as such would be an excellent alternative as long as a reasonable service period is achieved.

Background

In a previous study conducted by the Florida Department of Transportation (FDOT), the feasibility of using compact, long-life batteries as power supplies to provide cathodic protection to reinforced concrete bridge substructures was investigated[5]. The study concentrated on the use of the batteries for bridge pilings. However, with the correct combination of batteries, the method could be used for other concrete impressed current cathodic protection applications. Even though the batteries were specifically designed for cathodic protection, other uses are considered possible.

The results from this earlier work showed that the compact batteries were capable of providing cathodic protection to the piles maintaining an acceptable service period of four to five years as long as the battery output could be controlled within design parameters. The study also indicated that some means of adjusting the output voltage was needed to help make the battery system more practical and provide better control of the cathodic protection parameters. The report also concluded that it would be desirable to remotely determine when the batteries could no longer provide sufficient voltage and/or current to protect the reinforced concrete structure. This feature would allow for quick replacement of the batteries with minimal interruption to the application of the cathodic protection. The report recommendations assumed that these enhancements could be made as an accessory to the batteries using low voltage electronics and without deviating from the concept of a "compact, portable system" with a reasonable service life.

Following the recommendations of the above referenced report, Innovative Business Solutions inc. (IBSi) began development of a Modular Cathodic Protection System (MCPS) that incorporated the recommendations of the report using the already tested batteries.

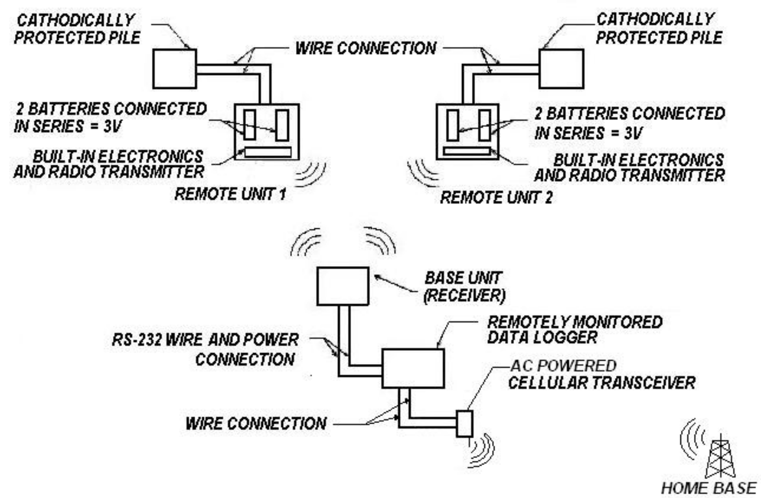

Figure 2: Basic schematic of the Modular Cathodic Protection System (MCPS) evaluated with data logger connection.

Objectives

This investigation intended to evaluate the basic performance of the wireless modular cathodic protection system and to identify needs for future development. To that end, developers of the system were provided with detailed input on desired features; based on that input system prototypes were created. Evaluation procedures were developed, field installations were implemented and the resulting performance was analyzed. Activities were conducted by the University of South Florida in conjunction with the Florida Department of Transportation while sponsored by the Federal Highway Administration under Federal Aid Project 20.205.

Electronic Units

The MCPS consists of a single Base Unit that communicates with up to four Remote Units using radio transmissions to relay the general status of the batteries. At the same time, it provides cathodic protection current through a pair of the batteries included as part of each Remote Unit (Figure 2).

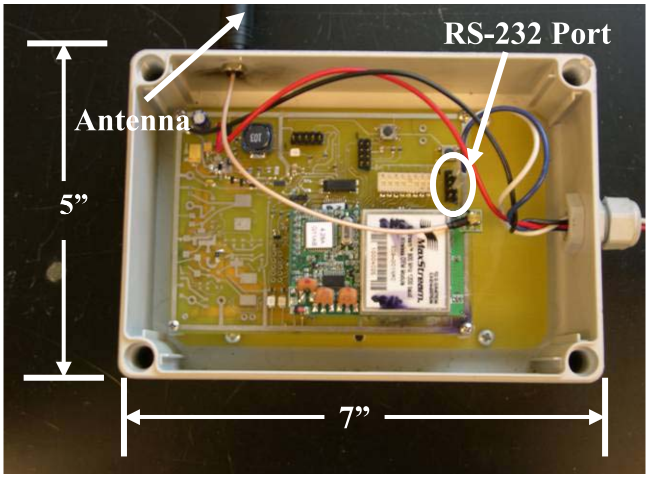

Figure 3: Modular Cathodic Protection System - Base Unit. Its primary function is to receive wireless transmissions form the Remote Unit(s) and relay the status of the batteries to a data logger through a standard RS 232 port.

The Base Unit is designed for installation at a central location on the bridge or structure where communication with a remotely operated, third party data logger needs to be provided via a direct wire connection. The Base Unit requires externally supplied DC power of a nominal 2.7 volts and relays information received from the Remote Unit(s) to the data logger using standard RS 232 transmission protocols (Figure 3). Up to 4 Remote Units can be used with a Base Unit. Each Remote Unit can be configured with its own address as unit 1 through unit 4. However, the Base Unit is not addressable, therefore limiting the number of systems that can be connected to the third party remote data logger to a single base unit and 4 remote units.

The Remote Unit is designed to be installed on or near the component (pile) receiving cathodic protection and then connected to the component's cathodic protection anode system to provide the protection current. Each Remote Unit is powered by 2 self-contained batteries connected in series in order to provide a maximum output of up to 3 volts at 1200 amp hours of service. Adjustments to the output voltage are achieved through dual in-line package (dip) switches built into the unit. The batteries provide power to operate the remote transmission electronics portion of the unit as well as to provide power to cathodically protect the structure (Figure 4). Because of the power consumption of the cathodic protection (C.P.) system, installation must be carefully designed such that

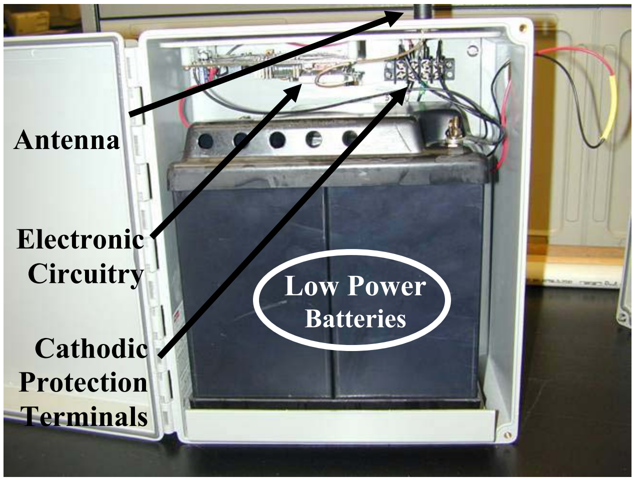

Figure 4: Modular Cathodic Protection System - Remote Unit. The Remote Unit provides and controls the voltage output for the cathodic protection system and transmits the status of the system to the Base Unit.

the demand of the C.P. system is not excessive (e.g. not much above ~50 mA). Otherwise, frequent replacement of the batteries would be necessary.

Each Remote Unit can be configured to apply a cathodic protection voltage between 1.0 and 2.5 volts in 0.1 volt increments to satisfy the requirements of the C.P. system (Appendix C, Table 1). The Remote Units are designed to transmit a status message to the Base Unit connected to the data logger.

The Remote Units are provided with two modes of operation: 1) test mode, which transmits continuously at one minute intervals and, 2) normal mode, which sends a transmission every five days. The test mode is provided mostly for troubleshooting and performance evaluation after installation. The mode of operation selection is also established via the built-in dip switches.

The voltage output, unit ID number, and the operation mode are user configurable by properly setting 8 dip switches. The message sent by the Remote Unit provides information on the condition of the system output (voltage and current), mode of operation, and Unit ID. Date and time information is not sent by the Remote Unit. This information must be provided by the data logger.

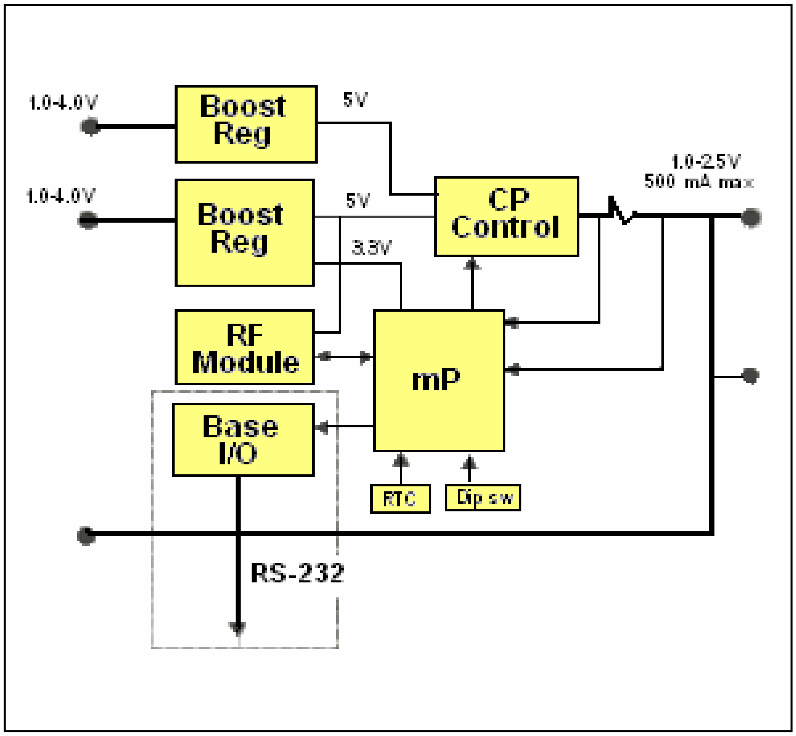

Figure 5: Basic schematic of the MCPS Remote Unit electronics.

The electronics for the Remote Unit are designed with two voltage boost regulators with an estimated design efficiency of 92%. The regulators allow an output to the cathodic protection system of up to 2.5 volts even when the input battery voltage is lower than the output. One of the voltage boost devices also provides 3.3 volts to a built-in micro processor that controls the reporting mode and the RS 232 port. Basically, the boost regulators provide a voltage boost higher than the available input voltage so that the proper C.P. output voltage can be maintained as the batteries weaken and also to provide the proper power to the electronic components. A 1200 baud RF module is also provided for transmission of the status data to the Base Unit (Figure 5).

Three Base Units and three Remote Units were delivered for evaluation by the manufacturer. Due to logistics, a two Remote Unit – one Base Unit system was evaluated, although a second Base Unit was used for troubleshooting as later discussed.

Evaluation Procedure

The scope of the evaluation study was to determine the precision of the new built-in remote monitoring electronics, output control, and to determine the service life of the batteries while providing power to the new devices as well as the cathodic protection current.

Evaluation of the Modular Cathodic Protection System was carried out in two phases. The first phase consisted of laboratory testing under controlled environmental conditions for verification of satisfactory performance of the new features. Once Phase 1 was completed, the system was installed on a real bridge cathodic protection system and evaluated under Phase II.

Laboratory Procedure:

The first step in the laboratory evaluation was to determine if the Remote Units of the MCPS could properly regulate the voltage output to a C.P. system as per design. For that purpose and with the batteries disconnected from the Remote Unit, a 67 ohm-¼ watt resistor was connected across the C.P. output leads to simulate a load and monitor the output. Next, the dip switches were configured to generate the desired voltage following the manufacturer's instructions. The batteries were then connected to activate the Remote Unit and the output voltage was measured at the output terminals using a hand held digital volt meter. This was repeated on both of the units tested until all 16 possible voltages had been configured and measured.

The ability of the Base Unit to transfer data to a third party data logger was also evaluated. The selected data logger was an Environmental Data Systems (EDS) model CPM8x8 as these are the standard units used by FDOT for monitoring cathodic protection systems. The Base Unit and the data logger were connected using the provided RS 232 ports. Communication was checked between the data logger and the MCPS Base Unit (fitted again with a 67 ohm resistor to simulate a load). The distance between the Base and the Remote Units for this test was approximately 45 feet.

Following the above, a Base Unit with 67 ohm load was left connected to the data logger at a static location. The remote unit was first placed in test mode, which transmits every minute, such that continuous testing could be performed. Testing the reach of the radio communication signal was performed by moving the Remote Unit further away from the base. For this test, the initial distance was again around 45 feet. The separation was then gradually increased until the separation distance was around 300 feet. This was the maximum distance allowed by the testing facility without any obstruction between the

Remote and Base Units. At 300 feet, the signal reception was determined satisfactory based on confirmation that all of the transmissions were received and recorded by the data logger. After completing the long distance testing, the separation distance was returned to 45 feet and the remote unit was set to normal mode (transmission every 5 days) to complete the communication testing in the laboratory. This testing was conducted for several weeks during which consistent results were obtained.

Field Procedure:

After verifying performance under controlled laboratory conditions, the system was installed in the field. The field evaluation was performed by installing the MCPS units (one base unit and two remote units) to actual bridge piles with cathodic protection to evaluate operation. The chosen location for this phase of the project was the Dunn's Creek Bridge in Jacksonville, Florida (Figure 6). The primary reasons for this location were the relatively close proximity to the FDOT State Materials Laboratory which would allow prompt response from the laboratory personnel for troubleshooting in the event of any problems or malfunctions, and the fact that the bridge was used in the previous study involving the batteries. Because of that, the bridge had several piles already equipped with a battery power supply system allowing quick installation of the MCPS Remote Units. The cathodic protection on the piles consisted of titanium mesh anode embedded in standard, mortar filled, pile jackets[6].

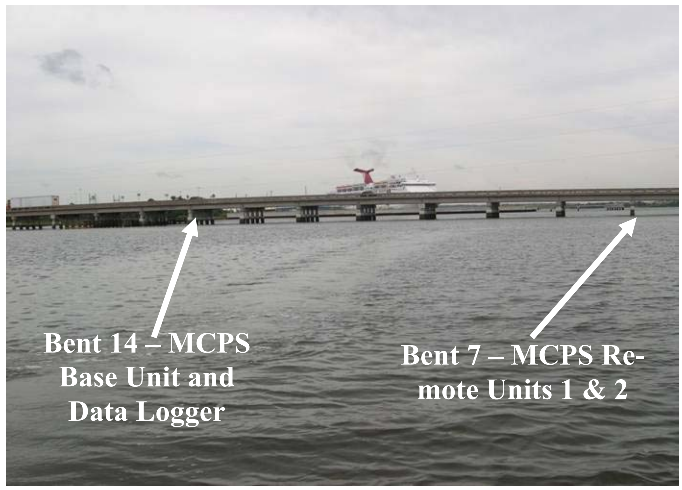

Figure 6: Dunn's Creek Bridge, Jacksonville Florida Field Evaluation Site.

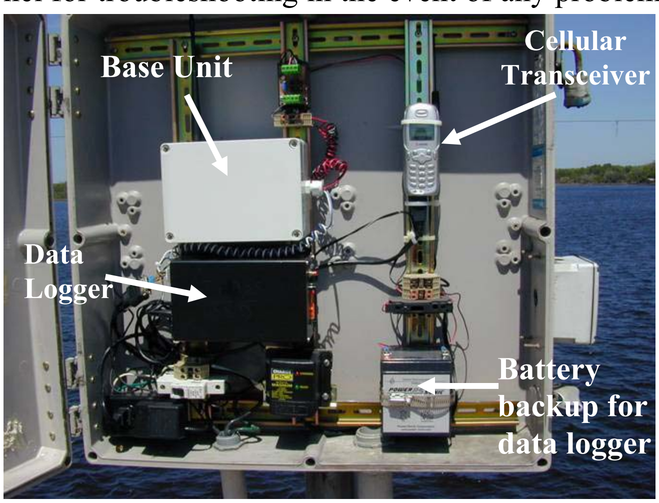

Figure 7: EDS data logger and MCPS Base Unit installed on Dunn's Creek Bridge, prior to relocating the Base Unit below the bridge deck.

The Base Unit was initially installed inside an existing Nema 4 enclosure located four feet above the bridge deck, directly over Bent 14 (Figure 7). Also installed in this enclosure were the selected third party data logger and the associated cellular communication equipment for remote access from the office. This location was primarily selected because of the existing enclosure and good reception of the cellular equipment.

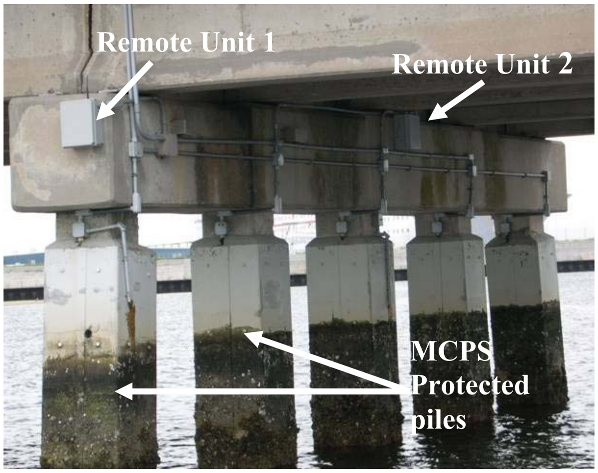

Figure 8: Modular Cathodic Protection System: Remote Unit 1, located on the North end of the pile cap of Bent 7 and Remote Unit 2 located near the center of Bent 7.

Remote Unit 1 was installed on the north end of the pile cap at Bent 7, approximately four feet below the bridge deck. This placed the Base Unit and Remote Unit 1 approximately 310 feet apart. They were not however in a direct line of sight to each other as this was not considered a factor at the time (Figure 6). This location was considered acceptable and expected to be appropriate to achieve successful communication between the Base Unit and the Remote Unit without having to install new wiring and conduit. Remote Unit 2 was installed on Bent 7 but on the west face of the pile cap, approximately 16 feet from the outer edge of the bridge (Figure 8). This location was intentionally chosen because it represented one of the worst possible locations (apart from distance) for communication to occur since there was not a clear path of the radio signal to the Base Unit. Any signal transmitted would have to reflect around the surrounding beams and bridge substructure components to reach the Base Unit on top of the bridge.

Before permanently attaching Unit 2 to the pile cap, a quick test was performed to make sure that communication could be achieved from this location. To accomplish this task, the unit was placed in test mode and temporarily held in position against the pile cap. A 67 ohm resistor was used to simulate a load as it was previously done in the laboratory tests. At the same time, a laptop computer provided with cell phone communications was used to wirelessly connect with the data logger to determine whether data transmissions were being received by the Base Unit located above the bridge deck and connected to the data logger. Once satisfactory communication was verified, the Remote Unit 2 was securely attached to the pile cap for permanent operation.

With both Remote Units and the Base Unit permanently installed, the transmission mode was initially set to test mode. The C.P. outputs terminals of the MCPS remote units were then connected to the existing cathodic protection systems on two piles, each adjacent to the location of each Remote Unit. This setup was considered representative of the intended typical usage conditions.

As later explained in the Field Evaluation Section, following additional initial tests the Base Unit was relocated from the top of the bridge to below the bridge deck, on the end of the pile cap on Bent 14 to improve the line-of-sight alignment between the Base and the Remote Units (Figure 9). This new location put the Base Unit and Remote Unit 1 in a direct line-of-sight, separated by approximately 308 feet which was about half of the manufacturers' design reach. The unit stayed at that location for all future tests.

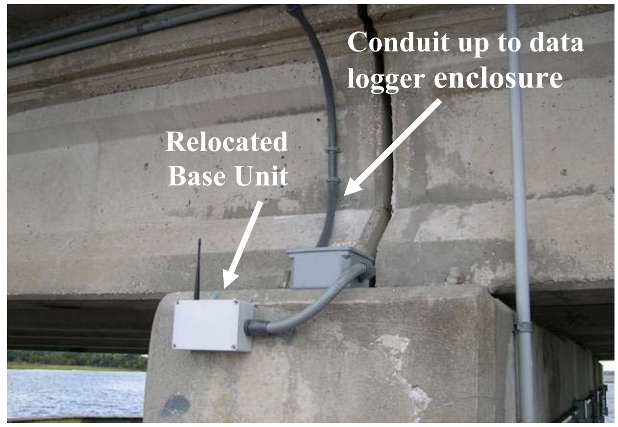

Figure 9: Modular Cathodic Protection System, Base Unit (Re-located to the North end of the pile cap of Bent 14). Conduit was installed from the data logger above the bridge deck in order to supply power and communication down to the Base Unit.

After modification of the units by the manufacturer to resolve malfunctions (see Field Evaluation Section), the Remote Units were placed back on the bridge to re-initiate the field tests.

Upon re-initiation successful transmissions in test mode on the bridge for two weeks were obtained, which allowed the final phase of the field test to begin. The two Remote Units were each placed in normal mode to verify transmission reception and cathodic protection of the bridge components under expected normal operating conditions. The system was then monitored for seven months.

In general, the initial scope and schedule of the evaluation study was significantly delayed by the malfunction of the MCPS and other problems detected on the communication between the MCPS Base Unit and the third party data logger. It is important to note that although some additional time was spent to correct the found problems, both the MCPS and data logger manufacturers were very cooperative in the resolution of the problems.

Evaluation of Results and Discussion

Laboratory Evaluation:

The laboratory testing focused primarily on the MCPS units' ability to apply the proper cathodic protection voltages and secondarily to verify that data indicating the general conditions of the system could be transmitted and received reliably at least in a controlled environment.

Remote Units 1 and 2 were evaluated for the accuracy in voltage regulation. A third remote unit provided, "Unit 3", was not used in the evaluation because the dip switches were defective.

On Units 1 and 2, the accuracy of the voltage output was acceptable on most of the settings when tested with the resistor. The largest amount of error for each unit was seen when they were configured to output 1.0 volt and 1.1 volts. The error (as percentage offset from the set value) recorded at this setting reached up to 15 % for Unit 2 with an error difference between the two units of 7.1% on average and as high as 9% (Table 1), suggesting an appreciable performance difference between the 2 units.

Table 1. *Measured voltage output of Modular Cathodic Protection System (MCPS) for Unit 1 and Unit 2 across a 67 Ohm resistor using a digital volt meter (Laboratory Evaluation).*

DIP Switch Setting	Configured Value (V)	Unit 1		Unit 2		Difference Between Units 1 & 2
		Actual (V)	% off	Actual (V)	% off	
0000	1.0	1.058	5.8%	1.151	15.1%	9.3%
0001	1.1	1.132	2.9%	1.229	11.7%	8.8%
0010	1.2	1.207	0.6%	1.314	9.5%	8.9%
0011	1.3	1.293	0.5%	1.405	8.1%	7.6%
0100	1.4	1.385	1.1%	1.502	7.3%	6.5%
0101	1.5	1.476	1.6%	1.600	6.7%	5.1%
0110	1.6	1.577	1.4%	1.708	6.7%	5.3%
0111	1.7	1.679	1.2%	1.816	6.8%	5.6%
1000	1.8	1.784	0.9%	1.933	7.4%	6.5%
1001	1.9	1.899	0.1%	2.046	7.7%	7.6%
1010	2.0	2.007	0.4%	2.161	8.1%	7.7%
1011	2.1	2.113	0.6%	2.271	8.1%	7.5%
1100	2.2	2.221	1.0%	2.383	8.3%	7.3%
1101	2.3	2.327	1.2%	2.491	8.3%	7.1%
1110	2.4	2.429	1.2%	2.595	8.1%	6.9%
1111	2.5	2.533	1.3%	2.697	7.9%	6.6%
		Average % Error	1.4%	Average % Error	8.5%	7.1%

The output current control of the system was also acceptable at most settings. However, some fluctuations on the current levels were initially recorded. It was most noticeable that the higher current fluctuations were always observed at the beginning of the evaluation period when these were in test mode. It appears that once the batteries stabilized after approximately 30 days of operation, the output currents became more stable. However, it was evident that the system electronics were adequately controlling the current as the fluctuations remained within a 6 mA band. Figures 10, B1 and B2 show the voltage and current relationship for the three Remote Units provided.

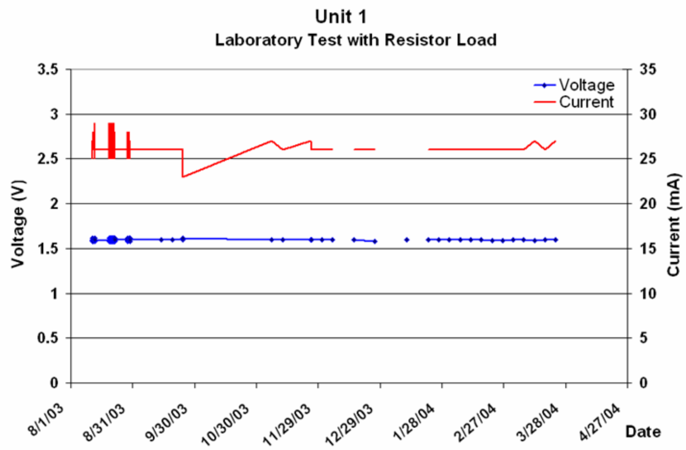

Figure 10: Voltage and current relation for Remote Unit 1 during several laboratory evaluation tests. Voltage set at 1.6 volts.

The communication test between the MCPS and the EDS data logger was positive in test mode (1 minute interval). However, the data recorded under normal mode operation was not initially considered satisfactory due to the high incidence of missing transmissions. In addition, normal mode transmissions actually occurred every 124 hours (5 days and 4 hours) rather than at the 120 hour (5 day) interval as designed. The long duration between transmissions made evaluation and troubleshooting very difficult and time consuming. Every adjustment or change made required a week to see whether the adjustment was successful. To diagnose the missing communication between the Base Unit of the MCPS and the data logger during the laboratory evaluation, a second Base Unit was installed directly connected to a lap top computer. The intent was for the second unit to also receive the signal from the Remote Units such that the data collected from the data logger (connected to Base Unit 1) could be compared to that received by the lap top computer connected to the second Base Unit. This would isolate the problem to either Remote Unit to Base Unit communication or Base Unit to data logger communication.

It was finally determined that the third party data logger was the cause of the missed transmissions in normal mode. The data logger was initially designed so that it would go into a sleep mode to conserve power if no communication was detected for a period of time and restart when activity was detected. This is an especially important feature for solar powered cathodic protection systems. However, for communication with the MCPS, the data logger must always be in a state ready to receive data. This was known prior to the start of this project and the manufacturer of the data logger made some changes to the data logger software so it would always be ready to receive data. However, a second feature of the data logger was that it would reboot itself when inactivity was sensed on the input channels after a period of time. This additional reliability routine was built into the hardware and software of the data logger to prevent the system from locking up. As a result, it appeared the data logger would be in the process of the rebooting sequence due to the long period of inactivity when many of the transmissions were sent. This led to frequent missed data by the time the data logger was ready to record the transmissions. In order to work around this problem, the data logger software and hardware settings were modified to eliminate these routines. The major drawback to this resolution is that when the data logger locks up it will not be able to automatically re-set itself.

As described in the Evaluation Procedure Section, after resolving the communication conflict with the data logger, the initial communication testing was performed over a relatively short distance of approximately 45 feet. This distance represents the distance between spans of the field evaluation site which would be the closest distance that the units would need to be installed in actual field applications. In order to test the range of the radio transmitter, a remote unit, in test mode, was moved progressively farther away from the base unit at 30 feet intervals up to a distance of 300 feet. Throughout this procedure, the units were kept aligned in a straight path and any obstructions were moved. All transmissions that were sent by the Remote Unit during the test were received by the Base Unit and recorded by the data logger at every location that was checked.

Test performed in one of the laboratory MCPS units and in Unit 1 of the units used in the field showed that (in the absence of radio transmission) the current drain on the batteries was ~2.6 times greater than the current delivered onto a 67 ohm load when output voltage ranged from 1V to 2.5 V. If the load was disconnected, the idle battery current drain was ~20 mA.

Field Evaluation:

The purpose of the field evaluation was to determine if the MCPS units could properly provide cathodic protection and transmit the data reliably in actual field applications.

Initial Tests

Initially it was intended to obtain some data in test mode for a short period of time and move directly into the final phase of the evaluation in normal mode. However, all transmissions stopped shortly after connecting Remote Units 1 and 2 to their respective cathodic protection piles on the bridge to initiate the test, even though data transmission had been observed prior to permanently affixing the Remote Units to the bridge cathodic protection system. Measurements obtained manually at each Remote Unit indicated that sufficient cathodic protection current was being applied to the piles by the batteries. Therefore, it was assumed that the malfunction was only limited to the reporting and/or transmitting portion of the electronic devices.

It was first thought that, despite the initial success, this problem stemmed from not having a line-of-sight installation between the Base and Remote Units as recommended by the manufacturer. After consulting with the manufacturer, the Base unit was relocated as indicated in Figure 9. The intent was to provide a clearer path for the radio signals from

Remote Units to the Base Unit. Unit 2 was still not in a direct line-of-sight, however the new Base Unit location was considered an improvement from its initial location. It was expected that if the location was the problem, the line-of-sight location would most likely allow communication with Unit 1. If communication was improved with Unit 1 but not Unit 2, then Unit 2 could also be relocated to a line-of-sight location.

However, data reception did not take place even after relocating the Base Unit to under the bridge deck. To troubleshoot this problem, a second Base Unit connected to a lap top computer was set up in a boat that was positioned directly in front of the Remote Units such that the signals would be unlikely to be missed due to obstructions. It was found that transmissions were actually not being sent out by either Remote Unit. The Remote Units were then disconnected from the pile's cathodic protection system. Using the 67 ohm resistor to simulate the magnitude of the cathodic protection load resulted in immediate return of transmissions being sent from both Remote Units 1 and 2. From these findings, it was apparent that the MCPS units stopped properly sending the status signal when connected to the piles' cathodic protection system. The units were then removed from the field and brought back to the laboratory for further testing and modifications in coordination with the manufacturer.

Additional laboratory testing was performed on the two MCPS Remote Units originally delivered by the manufacturer and connected to the second Base Unit. This diagnostic testing involved connecting the MCPS Remote Units to a built-to-scale concrete pile with a cathodic protection jacket located in an indoor seawater tank used to simulate the performance of cathodic protection systems (similar to the field system). The cathodic protection system on the test pile served to simulate as much as possible (although at a smaller magnitude) the load and conditions that would be prevalent by the units in actual service. Once connected to this load, communication testing was performed as previously described to determine why transmissions were not being sent. It was observed that once a real cathodic protection system was connected to the Remote Unit, it stopped sending the transmissions. When Remote Unit 1 was connected to the built-to-scale cathodic protection test pile in the lab, transmissions occurred normally for about 12 hours and then became intermittent. After approximately 37 hours, all transmissions stopped (Figure B3).

It was finally determined that the original design was based on modeling the cathodic protection output as a pure ohmic load when in reality, once the steel polarizes, the protected component develops a significant back voltage disturbing the overall operation of the unit. At the completion of this additional round of diagnostic testing, the units were returned to the manufacturer, so they could be modified to correct the problem.

The manufacturer completed hardware and firmware changes to the MCPS Remote Units and returned them to the FDOT for continued evaluation. The manufacturer reported that the following changes had been made: 1) The firmware functions that disabled the unit when no load was detected were removed. 2) Signal filters were added to reduce noise in the sense circuitry. 3) Additional filtering routines were added to the firmware. 4) The sense resistor was changed to increase the range in the reported current. 5) C.P. voltage control circuits were fine tuned to work better in a current range between 0 and 210 mA.

In addition to the data transmission problems, a voltage control problem not previously observed in the field was determined as well. The remote unit was configured at this time to output 1.5 volts, but the actual voltage applied to the pile was measured over 3.7 volts forcing excessive current to the C.P. test pile. This voltage output problem was resolved when the MCPS remote unit was reset by disconnecting and then reconnecting the battery. This voltage irregularity was not seen again during any other phase of the testing. The MCPS was returned to the manufacturer for these issues to be fully investigated and resolved.

After 2 months of testing and modifications by the manufacturer, the MCPS units were returned to the FDOT for continued evaluation. Remote Unit 1 was reconnected to the laboratory test pile in test mode. Results obtained this time were very promising. There were only two instances where transmissions were not received for a period of time (Figure B4). We were not able to determine with certainty why these transmissions were missed but it was suspected to possibly be due to a data logger malfunction.

Tests with Improved Units

After the manufacturer's modifications, Remote Units 1 and 2 were placed back in the field, reconnecting them to the same piles as before. The Base Unit was left located below the bridge deck. After a two week evaluation period in test mode, significant improvement was observed in the number of recorded transmissions as well as maintaining the pre-set voltage output.

Both units exhibited similar maximum percentage of transmissions, recording approximately 75% of the scheduled transmissions (Figures B5 and B6). The average percent of recorded transmissions was 57% for Unit 1 and 47% for Unit 2. The maximum, minimum, and average percentages for each unit are shown in Table A1 on Appendix A. During the two week evaluation in test mode the data logger locked-up once and did not record any data for approximately three days. It was necessary to physically reboot the data logger in order to resume recording the data transmissions received and relayed by the Base Unit. It should be noted that this data logger is not part of the evaluation, but it was the cause of some lost data transmissions because of poor compatibility with the Base Unit design.

Table 2. *Percentage of transmissions received and recorded hourly over a 2 week time frame from Remote Units 1 and 2, each unit configured in test mode, connected to the cathodic protection system on Dunn's Creek Bridge after manufacturer modifications.*

Remote Unit	Maximum Hourly (%)	Minimum Hourly (%)	Average Hourly (%)
1	78.33	1.67	56.86
2	75.00	0.00	46.61

The final phase of testing began once the two Remote Units were placed in normal mode and fresh, new batteries were installed in the Remote Units. The MCPS was evaluated for a total of 7 months in this phase of the testing. Four months into the test, the battery pair in Unit 2 suddenly failed. The batteries were replaced and the unit returned to normal operation. No moisture or other conditions that could have damaged the batteries were observed inside the enclosure, indicating (together with the considerations indicated below) that the failure represented genuine exhaustion during operation. One concern generated by this event was that the system did not show any indication of debilitating power prior to failure. As discussed with the manufacturer, no indication is given as the output voltage is generated by a voltage boosting device which is functional as long as the batteries have a voltage of 0.85 volts and the required current. Below this voltage, the system shuts down. It was learned that the condition of the batteries itself can not be detected by the system unless it falls below the 0.85 v threshold and shuts down. Another important observation is that the failure occurred with an apparent consumption at the load of only 45 % of the nominal batteries' capacity (based on the recorded output data from the last and previous operating periods of those particular batteries). This observation is in approximate agreement with the low current efficiency (battery current demand about 2.6 times greater than output current in the range evaluated) noted earlier for companion units[A]. While the prototype units have been adequate for the purposes of evaluating radio range and reliability, it is essential that future development units have substantially improved efficiency in order to attain reasonably long periods of operation without battery replacement.

There were 40 transmissions expected from each unit during the final evaluation period. For Remote Unit 1, successful transmission reception occurred 42.5% of the time, while for Remote Unit 2 successful transmissions occurred 37.5% of the time. Given enough redundancy in the number of scheduled transmissions, the success ratios observed may be adequate for practical monitoring purposes. Table A1 provides the date and time a transmission was expected to be received and whether it actually was. Basically, the two units performed equally as well regarding communications, even though Unit 2 was positioned in the worst possible location to successfully transmit data to the Base Unit. This suggests that the distance between the Remote and Base Units can be increased if necessary, provided the units are kept in as close to direct line of sight as possible. Because of the limited actual time of field testing, other location configurations were not evaluated but continued evaluation is planned which would allow relocation of the Units.

A separate problem that was encountered involved the data logger which is not part of the system being evaluated but an essential component to make the MCPS operational. Without the reliability routines, which cause the data logger to reboot when inactivity is detected, the data logger would become unresponsive and miss the data sent to it by the Base Unit. For this evaluation, it was necessary to remotely call into the data logger a couple of hours prior to the expected data transmission so that the data logger would be ready to receive the transmission. Obviously there were occurrences where it was not

[A] It is noted that Unit 2 was found to be malfunctioning several months later, in a follow-up inspection conducted after the test period covered by the present report.

practical to do this, which resulted in missed data. Compatibility with other data loggers was not evaluated due to time limitations and the extended period of time spent trouble-shooting other problems.

In some instances, it also appears that transmissions were not always received by the Base Unit. These missed transmissions could possibly have been caused by conditions such as propagation affected by solar activity, electrical storms or interference. However, there is no way to verify if indeed the transmissions were actually sent from the Remote Units.

Recommendations

The basic function of the Modular Cathodic Protection System appeared to work well after the hardware revisions were made. The basic concept of a self sustained cathodic protection power supply with the ability to report its functional status was demonstrated to be possible. There are several enhancements to the MCPS units that would make them more functional without deviating from the basic concept of being a compact, portable system. The most important relates to the remote monitoring capability of the system. It would be desirable to establish two-way communication, using industry standard protocols, between the Base and Remote Units as well as between the Base Unit and third party data loggers. An essential improvement is increasing the overall current efficiency of the circuitry to allow for operation over practical time periods without the need of frequent battery replacement or installation of added batteries.

Two-way communication between the Base and Remote Units will permit two enhancements. First, a receive/acknowledgement routine could be developed so that when a transmission is received by the Base Unit, it will respond back to the Remote Unit, confirming reception of the data packet. If the Remote Unit does not receive the acknowledgement, it could then resend the packet a predetermined number of attempts or length of time. In addition two-way communication would allow the development of a control method so that the voltage output could be adjusted remotely if necessary. Currently, if the voltage output needs to be changed, it is necessary to physically go to the remote unit and reconfigure the dip switches to the appropriate value. This remote control feature would be a convenient enhancement, but it is not considered an absolute necessary change as the expected typical use would be for single piles which should not require frequent adjustments.

Two-way communication between the Base Unit and the remotely controlled data logger will allow for error checking, helping to ensure that the transmitted data is received by the data logger. At this time, the Base Unit simply relays whatever transmission it picks up through the wireless transmitter from the Remote Units and passes it along through its RS-232 port to the data logger. No consideration is given to whether the data packet was received by the data logger. This enhancement would not affect the overall service life of the system due to higher power consumption as the Base Unit is not powered by the batteries. Another benefit of two way communication between the Base Unit and the data logger would be the ability to remotely adjust the settings on the MCPS units if the Remote Units are configured to accept commands. All the variables of the MCPS system could be made adjustable remotely through the data logger, such as the mode of operation and the voltage being outputted to the cathodically protected structure. Enhanced two way communication between all components using standard protocols and specific commands would also allow for each Remote Unit to be remotely interrogated at any time in the event that transmissions are missed or it is considered necessary for other reasons.

In addition to the above, two-way communication would allow for on-demand site interrogation of the remote units by using a portable base unit connected to a lap top computer. This would eliminate the need for a third party data logger on applications where periodic site visits are feasible. Presently, the MCPS reports: the Remote Units ID (1, 2, 3, or 4); the current mode it is set to, (test or normal); and the voltage and current being applied to the structure. Additionally, it would be desirable to know the actual battery voltage. The MCPS remote units have a boost regulator that adjusts the output voltage up to the configured setting providing the batteries have a minimum of 0.85 volts and sufficient current capacity available to support the boost. Because of this, there was no warning that the batteries in Unit 2 were about to fail during the field testing phase. The last transmission received before failure indicated that the C.P. voltage and current applied was satisfactory. After several transmissions were not received, the situation was investigated and it was found that the batteries were significantly below the 0.85 volts. Not knowing in advance the actual battery voltage lead to an estimated 2 weeks with no cathodic protection.

Currently the transmission modes available are rather limited. Test mode transmits every minute, which is great for troubleshooting. Normal mode transmits approximately every 124 hrs or every 5 days and 4 hours. It may be helpful if the interval between transmissions was configurable with at least another intermediate setting. Most of FDOT's existing impressed current cathodic protection monitoring data loggers record voltages and currents every 6 hours to monitor the effect of tidal changes on the cathodic protection systems. This allows a better understanding of the operational condition of the system. Obtaining a status report on the cathodic protection system once a day would however be sufficient and definitely more adequate for troubleshooting.

Another enhancement would be to find and/or develop a stronger radio transmitter so that the units would not need line-of-sight at larger distances. The major drawback would be a possible increase in power required to operate that could be imposed on the Remote Units. Currently, transmissions are very brief and the additional load would probably be negligible. If more power is needed to operate, an additional battery (for a total of 3) could be added to the unit (package) and still maintain a size that is practical and easily installed.

Poor circuitry efficiency is the likely cause of early exhaustion of batteries as experienced with Unit 2. The large observed overburden on the batteries above current delivered to the load is excessive for practical operation. The control circuits need to be modified so under normal operation regimes the current drain on the batteries is limited to only a small fractional overburden on the current delivered to the load. The idling current of the circuitry needs to be reduced from the observed value of ~20 mA as well, otherwise battery changes would be needed frequently even in the case of piles that require only small protective currents.

Additional evaluation should also consider determining the cause of the average 7 % difference error in voltage output between Unit 1 and Unit 2. It is also recommended that the manufacturer investigates the use of more robust switches and other electronic components than those provided with the prototype. Under normal use, these devices will be mostly used on aggressive marine environments which are extremely severe on electronic components.

Conclusions

The basic function of the Modular Cathodic Protection System improved markedly after hardware revisions were made.

The results demonstrated the feasibility of the basic concept of a self sustained cathodic protection power supply with the ability to report its functional status.

Additional evaluation of the combined reliability of the batteries and the control unit is needed.

Two-way communication is recommended as a means of enhancing the dependability of the system.

It is essential to improve efficiency of the circuitry to achieve practical operation life without the need for frequent battery replacement or expensive battery additions..

References

1. N.G. Thompson, M. Islam, D. Lankard, P. Virmani, "Environmental Factors in the Deterioration of Reinforced Concrete", MP September 1995, p43; Re. Paper No. 4, CORROSION/95, in Orlando, FL.

2. G.H. Koch, J.H. Prayer, P. Brongers, N.G. Thompson, Y.P. Virmani, "Corrosion Cost and Preventive Strategies in the Unites States", Report No. FHWA-RD-01-156, Prepared for Federal Highway Administration (FHWA), Sept. 30, 2001

3. R.L. Kean, K.G. Davies, "Cathodic Protection", Report prepared for the British Department of Trade and Industry (DTI), 1981.

4. Y.P. Virmani, G.G. Clemena, "Corrosion Protection of Concrete Bridges" Report No. FHWA-RD-98-088, Prepared for Federal Highway Administration (FHWA), Sept. 1998.

5. R.G. Powers, I. R. Lasa, M. H. Duncan, "Evaluation of Galvanic Battery Power Supply for Cathodic Protection", Prepared for the University of South Florida, Report No. 01-01A, March 8, 2001.

6. B.L. Martin, C.A. Firlotte, "Protecting Substructures in Marine Environment" Materials Performance Magazine, September 1995, p26; Re. Paper No. 15, CORROSION/95, in Orlando, FL.

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Appendix A

Table A1. *Transmissions recorded during the 7 month field evaluation of the MCPS Units 1 and 2 in normal mode (every 124 hours) after hardware modifications and reconnection to Dunn's Creek Bridge.*

Time of Expected Transmission		Transmission		Notes
Unit 1	Unit 2	Unit 1	Unit 2	
11/27/2004 4:28 PM	11/27/2004 4:18 PM	unknown	unknown	RMU not responding
12/2/2004 8:16 PM	12/2/2004 8:06 PM	none	none	reset RMU on 11/29/04
12/8/2004 12:04 AM	12/7/2004 11:54 PM	yes	yes	
12/13/2004 3:53 AM	12/13/2004 3:43 AM	yes	yes	
12/18/2004 7:41 AM	12/18/2004 7:31 AM	yes	none	
12/23/2004 11:29 AM	12/23/2004 11:19	none	none	
12/28/2004 3:18 PM	12/28/2004 3:08 PM	none	none	Reset RMU on 12/27/04
1/2/2005 7:06 PM	1/2/2005 6:56 PM	yes	none	
1/7/2005 10:54 PM	1/7/2005 10:44 PM	none	none	
1/13/2005 2:43 AM	1/13/2005 2:33 AM	yes	yes	
1/18/2005 6:31 AM	1/18/2005 6:21 AM	yes	yes	
1/23/2005 10:19 AM	1/23/2005 10:09 AM	none	none	
1/28/2005 2:07 PM	1/28/2005 1:57 PM	none	yes	
2/2/2005 5:56 PM	2/2/2005 5:46 PM	none	yes	
2/7/2005 9:44 PM	2/7/2005 9:34 PM	yes	yes	
2/13/2005 1:32 AM	2/13/2005 1:22 AM	yes	none	
2/18/2005 5:21 AM	2/18/2005 5:11 AM	yes	none	
2/23/2005 9:09 AM	2/23/2005 8:59 AM	none	none	
2/28/2005 12:57 PM	2/28/2005 12:47 PM	none	none	
3/5/2005 4:46 PM	3/5/2005 4:36 PM	none	yes	
3/10/2005 8:34 PM	3/10/2005 8:24 PM	none	none	
3/16/2005 12:22 AM	3/16/2005 12:12 AM	yes	none	3/11/05 Unit 2 batteries ap-
3/21/2005 4:10 AM	3/21/2005 4:00 AM	none	none	dead
3/26/2005 7:59 AM	3/29/2005 4:01 PM	none	yes	Unit 2 batteries were replaced
3/31/2005 11:47 AM	4/3/2005 7:49 PM	none	none	on 3/24/05
4/5/2005 3:35 PM	4/8/2005 11:38 PM	yes	yes	
4/10/2005 7:24 PM	4/14/2005 3:26 AM	none	none	
4/15/2005 11:12 PM	4/19/2005 7:14 AM	none	yes	
4/21/2005 3:00 AM	4/24/2005 11:03 AM	yes	none	
4/26/2005 6:49 AM	4/29/2005 2:51 PM	none	none	
5/1/2005 10:37 AM	5/4/2005 6:39 PM	none	none	
5/6/2005 2:25 PM	5/9/2005 10:28 PM	yes	yes	
5/11/2005 6:13 PM	5/15/2005 2:16 AM	yes	yes	
5/16/2005 10:02 PM	5/20/2005 6:04 AM	yes	none	
5/22/2005 1:50 AM	5/25/2005 9:52 AM	none	yes	
5/27/2005 5:38 AM	5/30/2005 1:41 PM	none	none	
6/1/2005 9:27 AM	6/4/2005 5:29 PM	none	yes	
6/6/2005 1:15 PM	6/9/2005 9:17 PM	yes	none	
6/11/2005 5:03 PM	6/15/2005 1:06 AM	none	none	
6/16/2005 8:52 PM	6/20/2005 4:54 AM	yes	none	

Appendix B

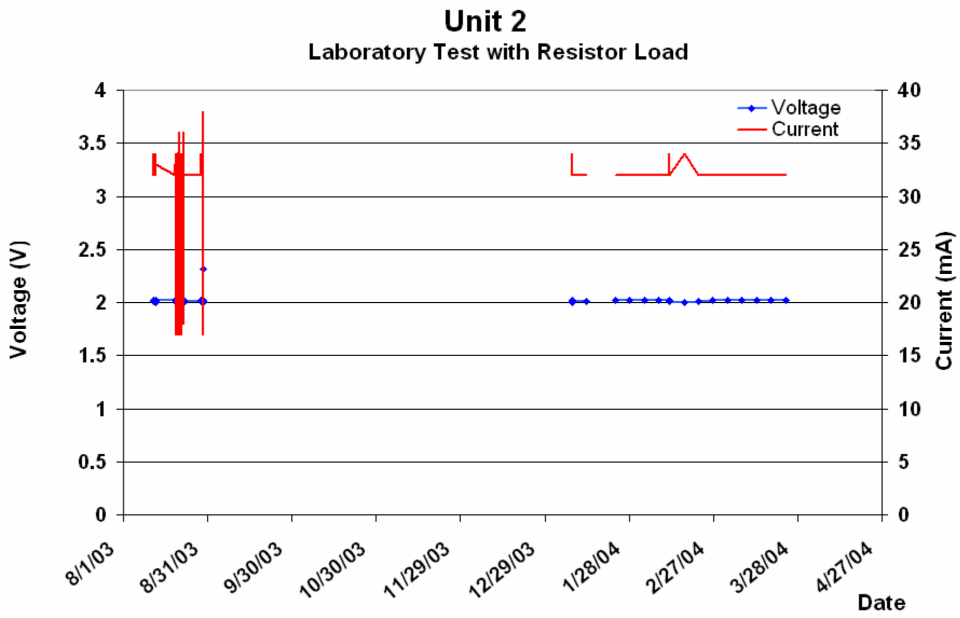

Figure B1: Voltage and current relation for Remote Unit 2 during several laboratory evaluation tests.

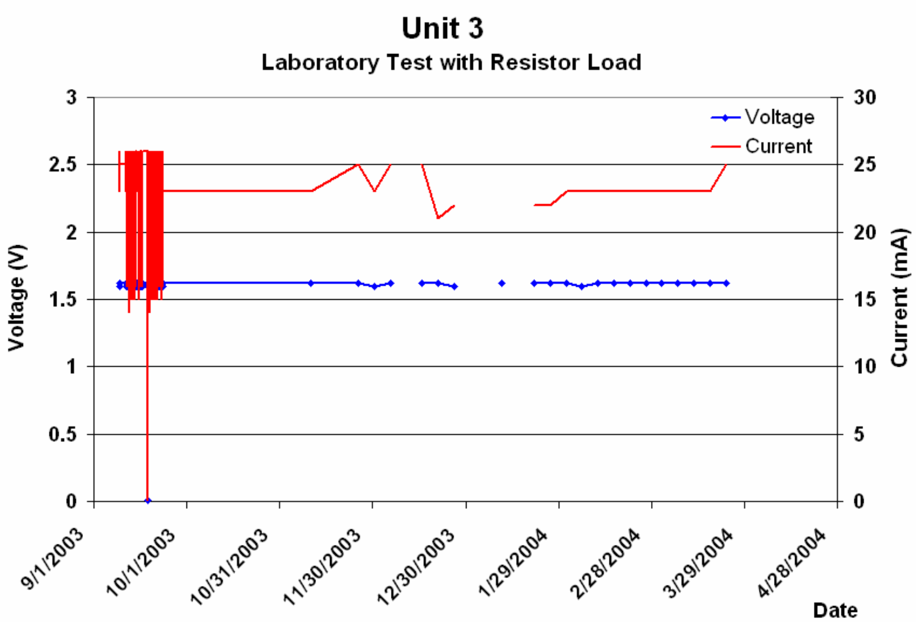

Figure B2: Voltage and current relation for Remote Unit 3 during several laboratory evaluation tests.

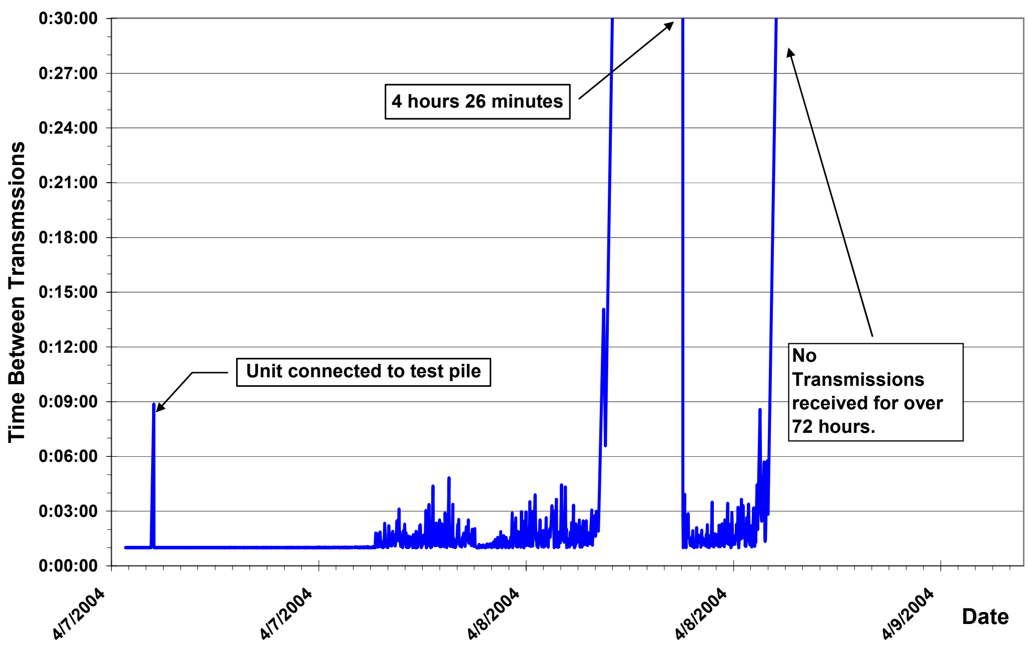

Figure B: Time between transmissions when MCPS Remote Unit 1, in test mode, was connected to a laboratory test pile prior to hardware reconfiguration by manufacturer

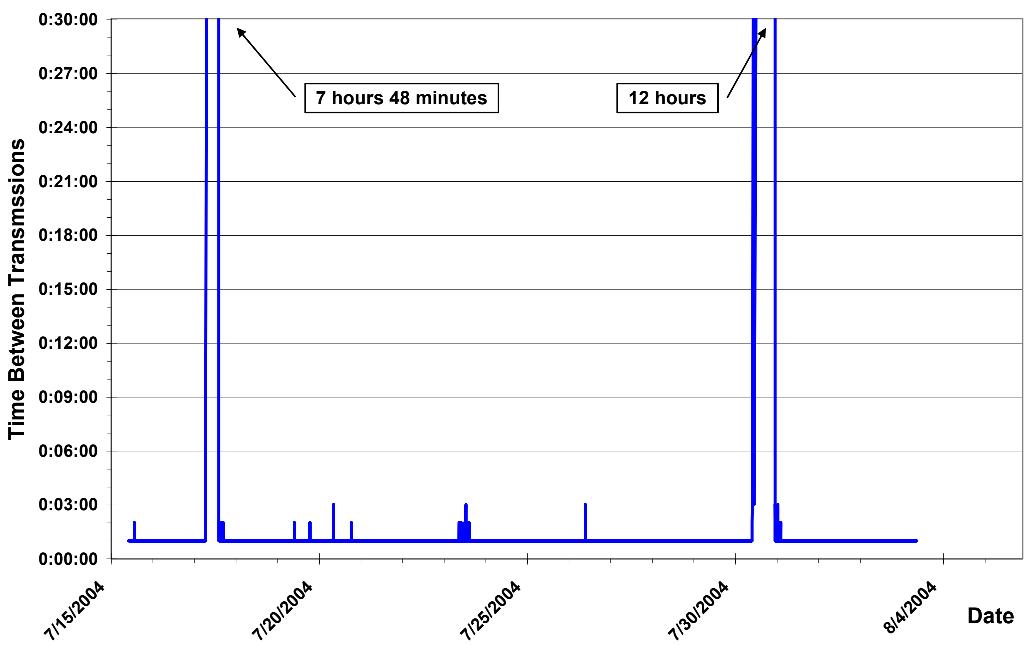

Figure B4: Time between transmissions when MCPS Remote Unit 2, in test mode, was connected to a laboratory test pile after hardware reconfiguration by manufacturer.

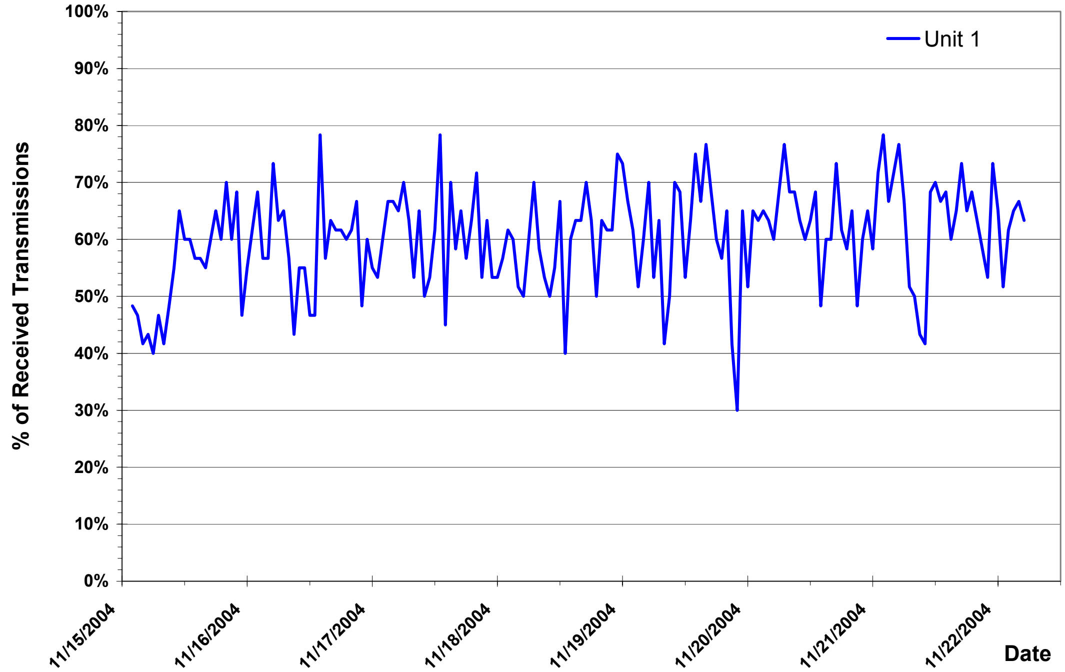

Figure B5: MCPS Remote Unit 1 in test mode connected to Dunn's Creek Bridge, plot showing the percentage of transmissions received during one hour intervals for a period of 7 days.

Appendix C

Presentation of the material in this appendix is for information only and does not constitute endorsement of any commercial product or service by the authors of the report or any of the supporting agencies or the University of South Florida. The following material is as provided by the manufacturer. No claim is made by the authors of the main technical report as to technical accuracy or completeness of the contents of this appendix.

INNOVATIVE BUSINESS SOLUTIONS INC.

Corrosion Division

Modular Cathodic Protection System Installation Guide

IBSI CORROSION DIVISION

Modular Cathodic Protection System Installation Guide

Version 1.1

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Table of Contents

Introduction

A typical Modular Cathodic Protection System consists of a Base Reporting Unit and one or more Remote Monitoring Units.

The MCPS provides cathodic protection (CP) and remote performance monitoring of reinforced concrete structures. It consists of two types of enclosures: a Remote Monitoring Unit (RMU) and a Base Reporting Unit (BRU). In a typical system, there is one BRU and one or more RMU's. The RMU operates on one (1.35V typical) or two (2.7 volts typical) batteries and applies cathodic protection to a reinforced concrete structure with negligible degradation to battery life. It also periodically reports its operating status using RF communications. The BRU receives status messages from each RMU and outputs it using an RS-232 port. The system architecture allows the operator to select the proper CP power setting and be assured that the system is functioning by monitoring status messages.

Figure 1. The MCPS enclosures are shown. The large enclosure is a Remote Monitoring Unit containing two batteries, CP application and monitoring electronics module mounted above them and an RF antenna attached to the top. The smaller enclosure is a Base Reporting Unit containing the same electronics module and an RF antenna attached to the top.

MCPS Components

The MCPS consists of two different enclosures. The RMU enclosure houses the cathodic protection application and monitoring, battery monitoring and RF communications electronics, along with one or two extremely long-life, low voltage Enser batteries. The MCPS is briefly described in the subsections that follow. For more information on the MCPS functions and operation, see the MCPS Product Summary available from IBSi.

Remote Monitoring Unit

The RMU consists of four major functional hardware components: Battery Voltage Regulator, Microcontroller, RF Module and Cathodic Protection (CP) Power Regulator and Monitor. These components are shown in Figure 2.

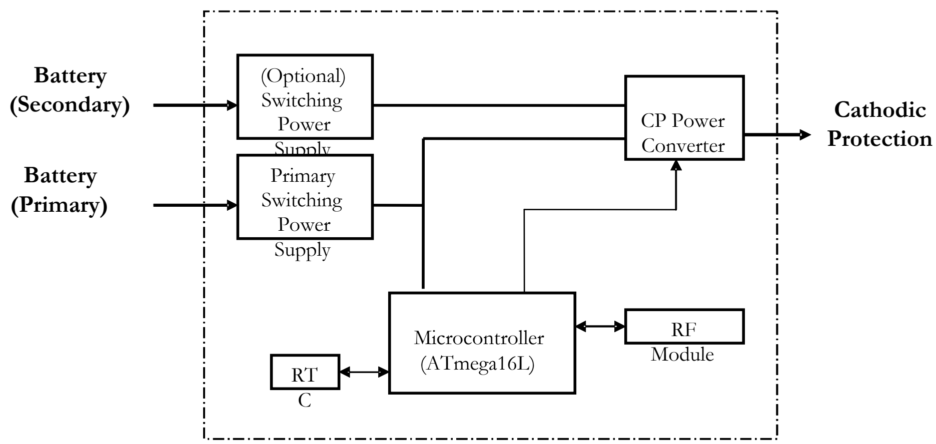

Figure 2. The MCPS function units include two battery voltage regulators, a microcontroller, an RF module and the cathodic protection power regulator and monitor.

The Battery Voltage Regulator operates from a voltage source of between 1 to 4 volts and produces a regulated output of 5 volts. The microcontroller regulates the CP voltage applied to the reinforced concrete structure according to a setting selected by the user, communicates CP performance information to the BRU and manages the operating mode of its components for the highest efficiency possible. The RF Module transmits CP performance and battery condition to the BRU and is capable of communicating reliably up to 4000 feet line-of-sight path using small 1/2 wavelength antennae. The CP Power Regulator may be configured to maintain a voltage between 1.0 and 2.5 Volts applied to the reinforced concrete structure to within 0.1 Volts.

Base Reporting Unit

The BRU receives RF data from one or more RMUs in the form of digital communications packets consisting of header, payload and a trailer sequences. The header consists of the transmitting unit network and address identities. The payload also contains an RMU identity along with CP voltage and current readings. The trailer consists of error check information to ensure data integrity. The header and trailer are stripped off by the RF Module and the payload is output on an RS-232 cable. The BRU is powered from an external power source using 1 to 4 volts.

Configuration and Cabling

Each RMU or BRU is configured by the user. The same electronics module is used for either a RMU or a BRU. The user selects the desired MCPS function (RMU or BRU), a unit identity, the cathodic protection output voltage and the operating mode (normal or test) using DIP switches. The red DIP switch of the MCPS electronics is shown in Figure 3. The definition of the switch settings is provided in Chapter 1.

MCPS Configuration involves setting switches.

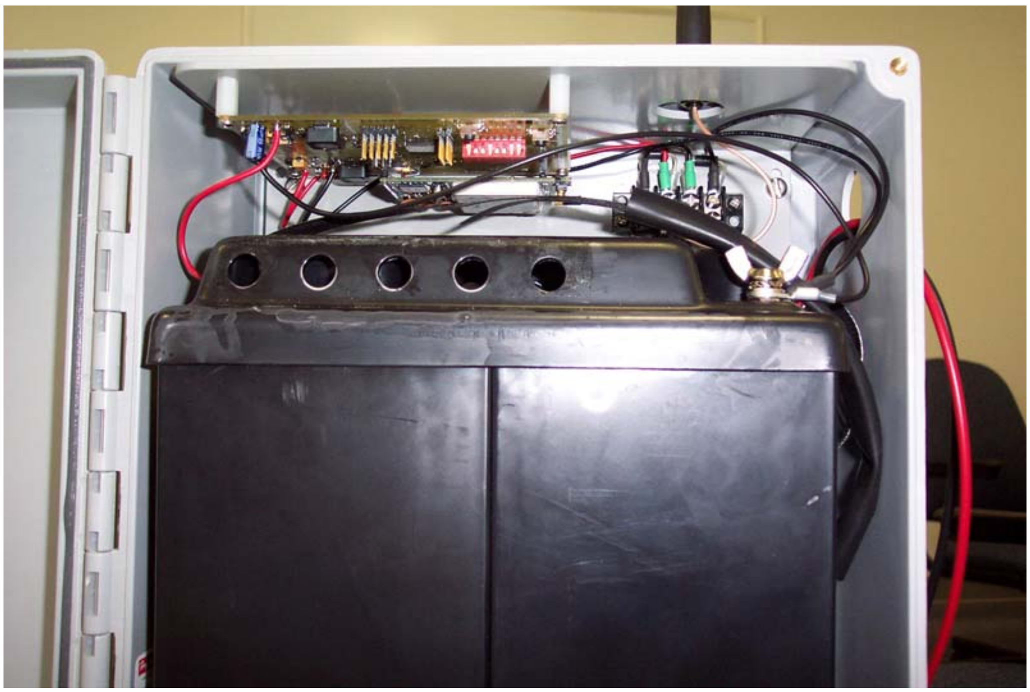

Figure 3. The RMU electronics is shown, along with the Enser batteries and the terminal block used to connect the cathodic protection application cabling.

The cathodic protection application cabling enters the RMU and connects to a terminal block. The opening on the right side of the RMU allows for attaching a water tight electrical conduit. The cabling for an RMU or BRU is described in Chapter 1.

Chapter

1

Preparation for Installation

Installation and use of the MCPS requires similar steps for the RMU and the BRU. The steps involved in preparing an RMU or BRU are provided below.

Steps for preparing the RMU and the BRU

An MCPS electronics module may be configured as an RMU or a BRU.

Remote Monitoring Unit

1. Configure the operating mode and parameters of the MCPS electronics module.
2. Validate RF transmission to the BRU at the target location of the RMU.
3. Attach the RMU Box to a supporting structure.
4. Attach cabling to apply the cathodic protection power to a concrete structure.
5. Attach power cabling between the MCPS electronics module and the battery inside the RMU Box.

Base Reporting Unit

Installing a BRU requires a series of similar steps as listed below.

1. Configure the operating mode of the circuit board.
2. Attach the BRU Box to a support structure.
3. Connect cabling to accept RS-232 signal levels and an external power source.
4. Attach external power source to the MCPS electronics.

Storing the System

The MCPS has been designed for operation in harsh climactic conditions. The electronic components have been conformal coated and the batteries contain a gelled electrolyte. The batteries will not leak if inverted. The batteries and the containment vessel have water proof membranes to mitigate any water ingress.

Even though the MCPS is extremely durable, IBSi recommends storing the unit upright, in a dry location and between -20° C (-4° F) to +50° C (+122° F) for maximum life. The batteries have a guaranteed shelf life of 2 years.

Configuration Switches

The MCPS electronic module is configured using a DIP switch. The definition of the switch functions is provided below. For more information on the MCPS functions and operation, see the MCPS Product Summary available from IBSi.

Table I. MCPS Electronics Configuration Switch Definitions

Switch	Description	RMU	BRU
8 – 5	Cathodic Protection Voltage Selection. These switch settings are polled periodically. 0000 1.0 Volts 0001 1.1 0010 1.2 0011 1.3 0100 1.4 0101 1.5 0110 1.6 0111 1.7 100 0 1.8 1001 1.9 1010 2.0 1011 2.1 1100 2.2 1101 2.3 1110 2.4 1111 2.5 Volts	User	N/A
4	MCPS Electronics Operation. This switch setting is detected at power-up. 0 BRU 1 RMU	1 (OFF)	0 (ON)
3 – 2	Unit Identity used by RMUs. These switch settings are detected at power-up. 00 Unit 0 01 Unit 1 10 Unit 2 11 Unit 3	User	N/A
1	Operating Mode used by RMU. This switch setting is polled periodically. 0 Test Mode	User	N/A

	1	Normal Mode		

Configuring an RMU

An RMU is configured using the DIP switches on the MCPS electronics. In order for the MCPS electronics to operate as an RMU, Switch 4 must be OFF. This switch setting is read at power-up and determines which operations the microcontroller performs. The Unit Identity is also detected at power-up and this value is part of the Health Status Message sent to the BRU. If more Unit Identity values are required, contact IBSi for alternatives.

DIP Switch Summary

SW 8-5:	CP Voltage
SW 4:	RMU/BRU
SW 3-2:	Unit ID
SW 1:	Normal/Test

The mode of operation is selected using switch 1. In Test Mode, an RMU samples the cathodic protection power and transmits a Health Status Message every second. In the normal mode, an RMU samples the cathodic protection voltage and current every minute and outputs a Health Status Message every 5 days. The Test Mode should be reserved for testing during an RMU installation since the power required to operate in this mode far exceeds that of the normal mode. The cathodic protection voltage is selected using switches 8 to 5. This value may be changed at any time. The setting is sampled each time the cathodic voltage and current is sampled so it may be up to one minute before a new setting is reflected in a Health Status Message.

Example RMU Configuration

Figure 4 shows the MCPS electronic module and the switches used to configure it. Switch 8 is on the left. A switch is in the ON position when it is closest to the MCPS electronic module (the UP position as shown). The switches in Figure 4 are configured as follows:

Table II. Configuration Switch Settings shown in Figure 4.

SW 8	SW 7	SW 6	SW 5	SW 4	SW 3	SW 2	SW 1
ON	OFF	OFF	ON	OFF	OFF	ON	ON

The configuration of the RMU shown in Figure 4 sets the cathodic protection voltage at 1.6 volts, the Unit Identity of 1 and test mode operation.

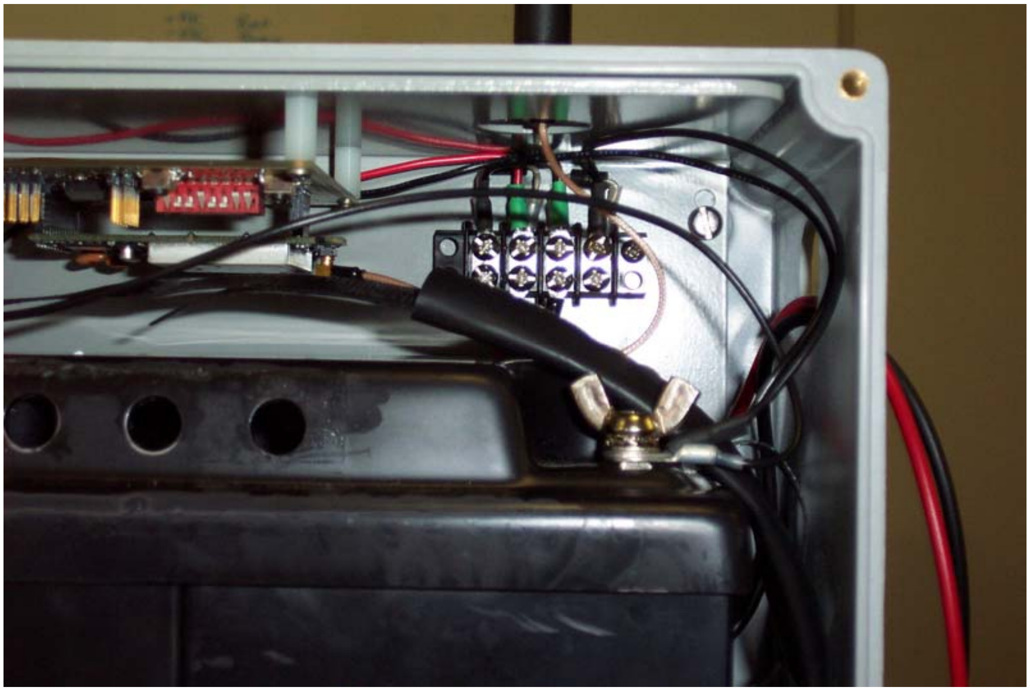

Figure 4 The configuration switches and cabling terminal block of an RMU are shown. The switches are used as an example configuration setting discussed in this section.

Preparing the RMU Cabling

Attach the cabling from the structure to the terminal block within the containment vessel. Be sure to match the positive wire of the structure to the positive terminal of the terminal block. The cable color coding follows the de-facto standard of red for positive (+) and black for negative (-). For the most weather tight configuration, run cabling in an approved electrical conduit.

Configuring a BRU

A BRU is configured using the DIP switches on the MCPS electronics module. In order for the MCPS electronics to operate properly, Switch 4 must be in the ON position. This switch setting is read at power-up. The Unit Identity and CP Voltage switches are not applicable on the BRU.

Example BRU Configuration

Figure 4 shows the MCPS electronics and the switches used to configure it. Switch 8 is on the left. A switch is in the ON position when it is closest to the MCPS electronic module (the UP position as shown in the figure). The switch settings for a BRU are shown in Table III.

Table III. Configuration Switch Settings shown in Figure 4.

SW 8	SW 7	SW 6	SW 5	SW 4	SW 3	SW 2	SW 1
N/A	N/A	N/A	N/A	**ON**	N/A	N/A	**OFF**

Chapter

2

Attaching and Cabling

Attaching the RMU and BRU to a concrete structure will vary with each application.

THe MCPS consists of two types of enclosures: a Remote Monitoring Unit (RMU) and a Base Reporting Unit (BRU). In a typical system, there is one BRU and one or more RMU's. An RMU is typically attached to a bridge piling or bent. To achieve the optimum RF communications, the unit should be located with the most direct line of sight with the BRU. The BRU receives Health Status Messages from each RMU and outputs them using an RS-232 serial port (TX, RX, GND). This interface is compatible with data acquisition units, data loggers and other data storage and transmission devices. The BRU is typically located near the terminus of the bridge structure.

Figure 5. The MCPS enclosures are shown. The large enclosure is a Remote Monitoring Unit. It should be located on the structure that will receive the cathodic protection application. The smaller enclosure is a Base Reporting Unit. It should be located as near as possible to a data acquisition unit, data logger or other data storage or long-distance transmission device.

Attaching the RMU to a Structure

The RMU provides cathodic protection to any steel reinforced concrete structure, but will typically be attached to a bridge piling or bent. To achieve the optimum RF communications, the unit should be located so as to provide the best direct line of sight with the BRU. Attach the RMU with stainless steel hardware and concrete anchors (not included) to ensure a quality installation.

Attaching the RMU CP Power Cabling

Attach the negative wire from the rebar contained within the structure to the negative (black) terminal block of the RMU (CP-). Run the cable in an approved conduit and attach the conduit securely to ensure a water-tight connection. All user connections are made to the lower row of the terminal block. Note that the two outer terminal block connections of the lower row are not used.

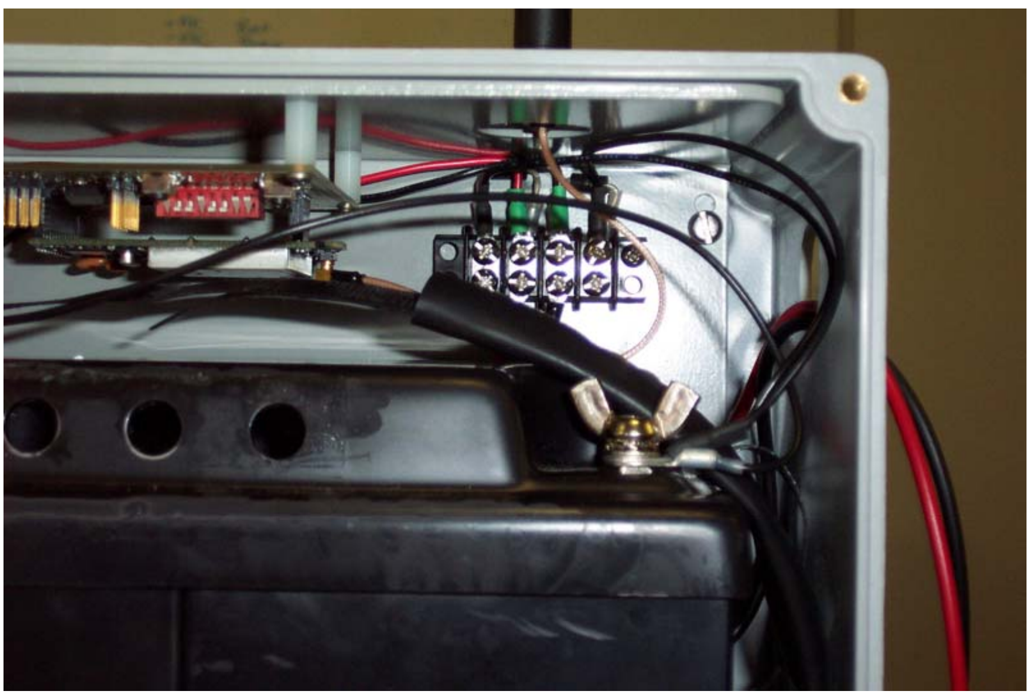

Figure 6. Be sure to match the positive wire of the structure to the positive terminal of the terminal block. Color coding is standard red (+) and black (-). For the most weather tight configuration run cabling in an approved electrical conduit.

Attach the red wire from the anode to the terminal block connection that positive (red) terminal block of the RMU (CP+) as shown in Figure 6 and detailed in Figure 7.

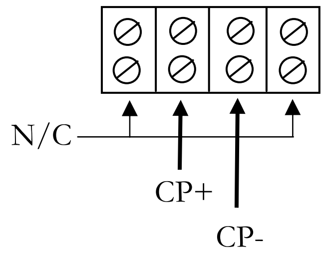

Figure 7 The terminal block connections used to attach the Cathodic Protection cabling to the RMU are shown.

The cabling within the RMU enclosure includes lightning protection for the CP voltage cables.

RF Communications Performance Testing

The RF communications performance varies greatly, particularly in environments with large concrete structures. The RF electronics of the MCPS provides reliable communications at distances beyond 1500 meters with a direct line-of-sight between an RMU and a BMU. The RF performance will be reduced significantly when a direct line-of-sight link is not available or when the antennae in the system are located too close to the ground or water. The RF link performance testing should be part of determining the best available site for an RMU. This can be done by configuring the RMU to be in test mode.

Attaching the BRU

The BRU is a weather-proof self contained unit. The cabling includes wiring for power and communications.

Connecting the BRU Cabling

The BRU provides four bare wires to conform to the users preferences. The user may utilize a common RS-232 connector for supplying power and to support communications. The cable color coding is described below.

Red……….PWR (2.0 – 4.0 volts, 5.0 volt option with factory modification)
Black……...GND (PWR RTN)
White……..RS – 232 TX (output)
Blue………RS – 232 TX-RTN

Chapter

3

Powering the System

Powering the MCPS is accomplished by connecting the battery leads to the battery terminals.

The MCPS does not contain a power switch. When the battery terminals are connected to the battery, the unit will begin to operate. Connect the black wire that leads from the MCPS terminal block to the negative battery post and tighten the wing nut securely. Connect the red wire from the MCPS to the positive battery terminal.

Power-Up Operation

The MCPS performs the following operations at power-up.

1. System initialization,
2. Blink debug LED (if present),
3. Output Health Status Message (packet type=Start-up Packet), and
4. Begin operation per mode setting.

Powering an RMU On and Off

Ensure that the DIP switches are configured to the desired settings and connect the battery terminals. The BRU is powered up utilizing the Red (+) and Black (-) wires that lead from the enclosure. Depending on which configuration the user is utilizing, the BRU can be powered directly from a DC source or through a RS 232 connector.

Changing Configuration

The MCPS is configured using an 8-pin dual in-line package (DIP) switch as described in Chapter 2. The parameters provided by this switch are described in **Table I.** The configuration may be changed to provide a new configuration.

It is recommended that power be removed by disconnecting the red (+) cable from the battery terminal. Use a non-metallic object of sufficient length and strength to flip the pin to the on or off position. Replace the red (+) cable to power up the system.

Resetting the MCPS Electronics

Press the reset button located on the electronics board. While this will work for some reset situations, other situations require the power to be removed and applied again. The location of the reset buttons are provided in Figure .

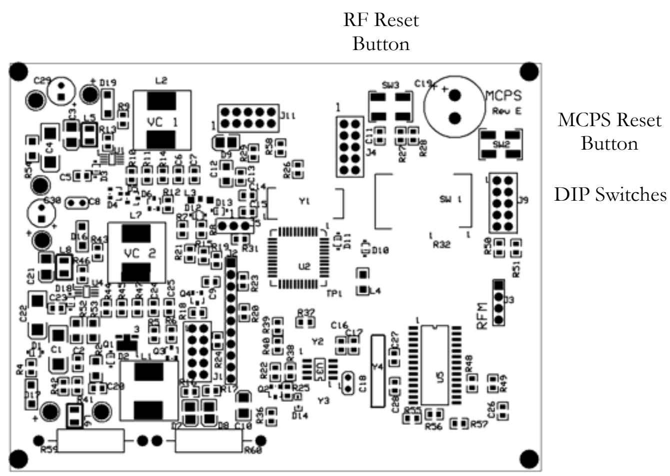

Figure 8. The terminal block connections used to attach the Cathodic Protection cabling to the RMU are shown.

Chapter

4

Understanding Status Reports

Initialization and Health Status Reports are sent from each RMU to a BRU that identify the sending unit and provide information about the cathodic protection voltage and current being applied to the structure.

The MCPS provides an Initialization Report and periodic Health Status Reports to the Base Reporting Unit using the RF communications. Each report consists of a sequence of ASCII characters. The Initialization Report is sent immediately after power-up in all operating modes. The frequency of the Health Status Reports is determined by the value of DIP Switch pin 1 at power-up. In Test Mode, these messages are sent every one minute. In Normal Mode, messages are sent every five days.

Initialization Report Format and Contents

The Initialization Report is sent after power and is a sequence of ASCII characters. An example is provided below.

IBSi MCPS version 00.00.07<LF><CR>

Health Status Report Format and Contents

A Health Status Report provides information about the RMU. At a minimum, reports may be used to ensure that each RMU is functional. The lack of a report may indicate that the battery is no longer functioning properly or that the unit has incurred some damage. Additional information is available about the CP operating voltage and current levels. These may be used to ensure that the CP application cabling is in place and the RMU is functioning properly. The format of a packet is provided below.

Packet Type Header

T-> Test Mode Message
N-> Normal Mode Message
E-> Error Message

Module Identity (decimal value; DIP SW 3-2 value; actual values: 1, 2, 3 or 4)
CP Voltage Measured (decimal value; resolution = 2.56 mV/bit)
CP Current Measured (decimal value; resolution = 1.205 mA/bit)

Example:

T-> id:1 V:647 I:33 <CR><LF>

NOTE: With no load on the CP terminal block connections, the RMU reports only an Initialization Message and will not transmit a Health Status Message.

Health Status Reports are output as a sequence of ASCII characters at the BMU. The RMU and BMU RF electronics support a RF communications protocol wrapper that ensures reliable data delivery.

RF Transmissions – Normal Mode

In the normal mode, Health Status Reports are sent from an RMU approximately every five days. The RMU also sends an Initialization Report to indicate that is has been powered up and is operating.

RF Transmissions – Test Mode

In the test mode, Health Status Reports are sent from an RMU every one minute. The RMU sends an Initialization Report to indicate that is has been powered up and is operating. This mode should be used to validate the location of an RMU. Once the site of the RMU has been selected, the RMU configuration should be changed to Normal Mode (DIP switch 1) to conserve battery power.

RF Communications Performance Testing

The RF communications performance varies greatly, particularly in environments with large concrete structures. The RF electronics of the MCPS provides reliable communications at distances beyond 1500 meters with a direct line-of-sight between an RMU and a BMU. The RF performance will be reduced significantly when a direct line-of-sight link is not available or when the antennas in the system are located too close to the ground or water.

To ensure optimum RF performance for a given systems, the following rules should be applied.

1. Antennas should be oriented vertically. The RMU and BRU are designed to provide this orientation under typical installation.

2. The BRU antenna should be as high off of the surrounding ground or water level as possible. The RMU antenna height is also important to an individual link.

3. The BRU should not be attached at a location that precludes a direct line-of-sight link with the RMUs. RF communications reliability may be severely reduced or eliminated with link obstructions such as concrete.

4. If possible, the RMU should be located in such a way that a direct line-of-sight to the BRU is provided. Of course, this configuration may not be possible. RF communications is possible without a direct line-of-sight between the RMU and BMU. However, RF testing should be performed as part of the procedure for selecting an RMU attachment location to ensure that Health Status Reports will be received by the BRU. Configuring the RMU for Test Mode and monitoring the reports received at the BMU is a part of the recommended RMU installation procedure.