ERDC/CERL TR-14-3

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DoD Corrosion Prevention and Control Program

Demonstration of Photovoltaic-Powered Cathodic Protection System with Remote Monitoring Capability

Final Report on Project F08-AR14

David M. Bailey, Charles P. Marsh, L.D. Stephenson,
John Taylor, Lawrence Clark, David Butler,
and Lindsay Millard

February 2014

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Final report

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Under Project F08-AR14, "Photovoltaic Cells for Cathodic Protection of Pipes and Tanks"

Abstract

This project demonstrated an application of photovoltaic (PV) technology to power cathodic protection (CP) systems for water tanks at Pohakuloa Training Area (PTA), HI. An impressed-current CP system was installed on each of three water tanks in isolated locations, where connecting with the local power grid would be expensive. The demonstrated system, powered only by PV arrays with a battery backup, uses ceramic anodes and includes a satellite-based remote-monitoring capability. This system provides uniform and reliable cathodic protection in the water tanks interior below the water line. Data collected by the remote monitoring system can be loaded into a spreadsheet, and performance can then be analyzed on a pass-fail basis.

The installed PV-powered CP systems operate as designed and conform to NACE SP 0169 criteria. It is expected that little maintenance will be needed to keep the system operating properly. Required maintenance will include periodic cleaning solar arrays and monthly recording of electrical output using a digital meter. Once every year, a qualified CP specialist should survey the system to ensure proper CP levels.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project F08-AR14, "Photovoltaic Cells for Cathodic Protection of Pipes and Tanks." The proponent was the US Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the US Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Bernie Rodriguez (IMPW-FM), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CF-M), US Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). The ERDC-CERL project manager was David M. Bailey. A portion of this work was performed by Mandaree Enterprise Corp. (MEC) and Leratek Incorporated, both of Warner Robins, GA. At the time this report was prepared, Vicki L. Van Blaricum was Chief, CEERD-CF-M; L. Michael Golish was Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CV-T, was the Acting Technical Director for Adaptive and Resilient Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Ilker Adiguzel.

The following individuals are gratefully acknowledged for their support and assistance in this project:

- Eugene Arter, Facility Manager Supervisor, Directorate of Public Works (DPW), Wheeler AAF, HI
- Thomas Carll, Director of Public Works, Pohakuloa Training Area, HI
- Patrick Patterson, Director of Public Works, Pohakuloa Training Area, HI
- Harold Hart, Pural Water Supervisor.

The Commander of ERDC was COL Jeffrey R. Eckstein, and the Director was Dr. Jeffery P. Holland.

Executive Summary

Impressed-current cathodic protection (ICCP) is an effective technology for preventing and controlling corrosion on steel Army infrastructure. These systems have historically been energized by direct current (DC) provided by rectifiers connected to the power grid. With the emergence of highly improved photovoltaic (PV) power systems with integrated battery backup, solar energy has become a viable alternative where grid power is not available. For example, electronics have recently been designed to allow a positive grounding system from the battery bank directly to the ground bed, which improves installation by preventing ground loops while providing better lightning protection. Typical situations where PV-powered ICCP is cost effective include remote locations without easy access to a power grid, or where grid power is either expensive or unreliable.

In this project, the application of PV technology to power an ICCP system with integrated remote-monitoring technology was demonstrated at Pohakuloa Training Area (PTA), HI, a severely corrosive location. The demonstration structures were three small water tanks for which a new impressed-current, ceramic/mixed metal oxide anode system was specified. This system included remote monitoring units (RMUs) to alert maintenance personnel if operating problems occur or if the level of corrosion protection falls below specifications.

It was demonstrated that an effective, reliable ICCP system can be powered solely by a PV source. It was also shown that an integrated RMU can provide reliable ICCP monitoring with little need for site visits. Remote monitoring greatly reduces inspection costs, but problems reported through the RMU must be addressed immediately. Initial maintenance needs for the PV power supply are expected to be low, but maintenance common to all PV systems should be expected over system service life. Examples include replacement of backup batteries or PV modules.

It is recommended that this technology be considered and economically compared to grid-connected ICCP. Where grid power is not available, economic analysis should include the cost of providing power to the target location. The use of this technology for other types of steel-based infrastructure should also be considered.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
Feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
Inches	0.0254	meters
Mils	0.0254	millimeters
square feet	0.09290304	square meters

1 Introduction

1.1 Problem statement

The Department of Defense (DoD) has many remote located facilities and training areas across the globe. These sites include critical infrastructure such as water storage tanks, pipelines, and other steel structures that utilize impressed-current cathodic protection (ICCP) for corrosion prevention and control. Cathodic protection (CP) is currently not used in many isolated sites due to the lack of electric power.

The cost of extending electric utility lines to remote sites has always been high and is steadily increasing. Furthermore, some remote sites cannot even be served by the grid, so steel structures located there are especially vulnerable to corrosion as their coatings degrade. In these situations, photovoltaic (PV) power becomes a logical and cost effective means for providing CP.

Major improvements have been made in PV technology over the past decade. Even with these advances, alternating current (AC) powered CP systems remain more cost effective for most applications. However, DoD's growing preference for renewable energy sources makes PV a potentially attractive option. Advances in the energy efficiency of the system controllers and monitors make more power available for protecting the steel, which is a central consideration for ICCP applications. PV may be the preferred solution in parts of the world where conventional electrical utility service is expensive or unreliable. The higher cost of installing PV-operated ICCP could be offset by the lower cost of power consumption over the long run.

With the use of reliable remote monitoring units (RMUs), problems with a CP system can be detected and corrected promptly before corrosion damage is significant. RMUs are used by the Army for a variety of infrastructure sustainment applications, providing prompt notification to maintenance personnel that a problem in the field needs to be remedied. In locations that are difficult to access and not served by the grid, reliable alternate power sources are critical both for continuous corrosion protection and monitoring of CP system operation.

Sustainable energy for powering CP systems is of high interest at Pohakuloa Training Area (PTA), HI, a remote installation located in a highly corrosive environment. This installation was selected for a demonstration of PV-powered CP and remote monitoring.

1.2 Objectives

The objectives of this demonstration were to install an integrated PV electric supply with advanced storage battery system to power an ICCP system and RMU; evaluate long-term system efficacy and costs; and document lessons learned for the benefit of prospective users.

1.3 Approach

The CP system design requirements were developed, and a variety of PV arrays, ICCP control components, and battery backup systems were evaluated to select the most suitable equipment for the purposes of the demonstration. A system was designed, installed, and commissioned as described in the main report.

All designs, installations, and testing were executed in compliance with established NACE International guidelines for achieving adequate CP in corrosive environments.

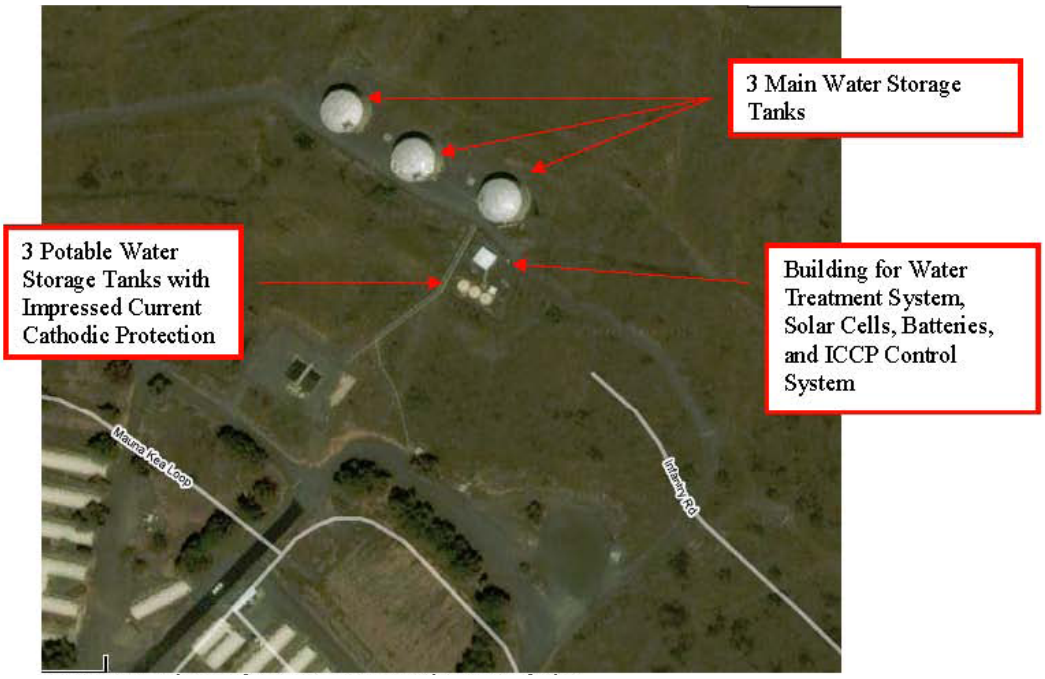
2 Technical Investigation

2.1 Overview

The structures chosen for this demonstration were three potable water tanks located at PTA (Figure 1). PTA is an Army training installation located on the big island of Hawaii – on the high plateau between the two volcanoes - Mauna Loa and Mauna Kea. The tanks are part of the site's water treatment facility (Figure 2) which is owned by the Army but managed and maintained by a support contractor. Water is trucked up to PTA and stored in three larger tanks prior to treatment. After treatment, the water is stored in the three project tanks prior to usage. The vessels measure 8 ft high and 15 ft in diameter, and have mostly bare steel interior surfaces and no protective coating.

Figure 1. Three demonstration tanks.

Figure 2. Aerial view of PTA water treatment facility.



2.2 Description of the technology

The key function of the ICCP system is to provide a constant supply of direct current (DC) to a system of anodes placed in the water tank to control corrosion of the steel wall surface inside the tanks. The design is intended to achieve adequate corrosion protection in excess of 20 years.

The current density needed for CP was determined to be 3 mA/sq ft, in accordance with Unified Facilities Guide Specification (UFGS) 26 42 15.00, "Cathodic Protection System (Steel Water Tanks)." Based on the surface area of the tank, 2.19 amps is required per tank. This determination is based on the assumption that the interior tank surface is bare. In all three tanks, however, some coating remains on a portion of the interior that provides some level of protection to the interior metal. Therefore, the 2.19 amps can be considered a conservative limit. Basic design calculations for the CP system are reproduced in Figure 3.

Figure 3. CP design calculations.

Hawaii Tanks

$L = 8\ [ft]$

$D = 15\ [ft]$

$x = 0.003\left[\frac{amps}{ft^2}\right]$

$$A = \pi\left(DL + \frac{D^2}{2}\right)x[amps]$$

$$A = 3.14\left(15(8) + \frac{15^2}{2}\right)0.003[amps]$$

$A = 2.19[amps]$

15,000 Ohm H_2O

$N = 18$

$L = 5\ [ft]$

$d = 0.01\ [ft]$

$S = 5\ [ft]$

$\rho = \Omega - cm = 15{,}000\ worst\ case$

$$R = \frac{0.00521\rho}{NL}\left(ln\left(\frac{8L}{d}\right) - 1 + \frac{2L}{S}ln(0.656N)\right)[ohms]$$

$$R = \frac{0.00521(15{,}000)}{18(5)}\left(ln\left(\frac{8(5)}{0.01}\right) - 1 + \frac{2(5)}{5}ln(0.656(18))\right)[ohms]$$

$R = 10.62\ [ohms]$

10,000 Ohm H_2O

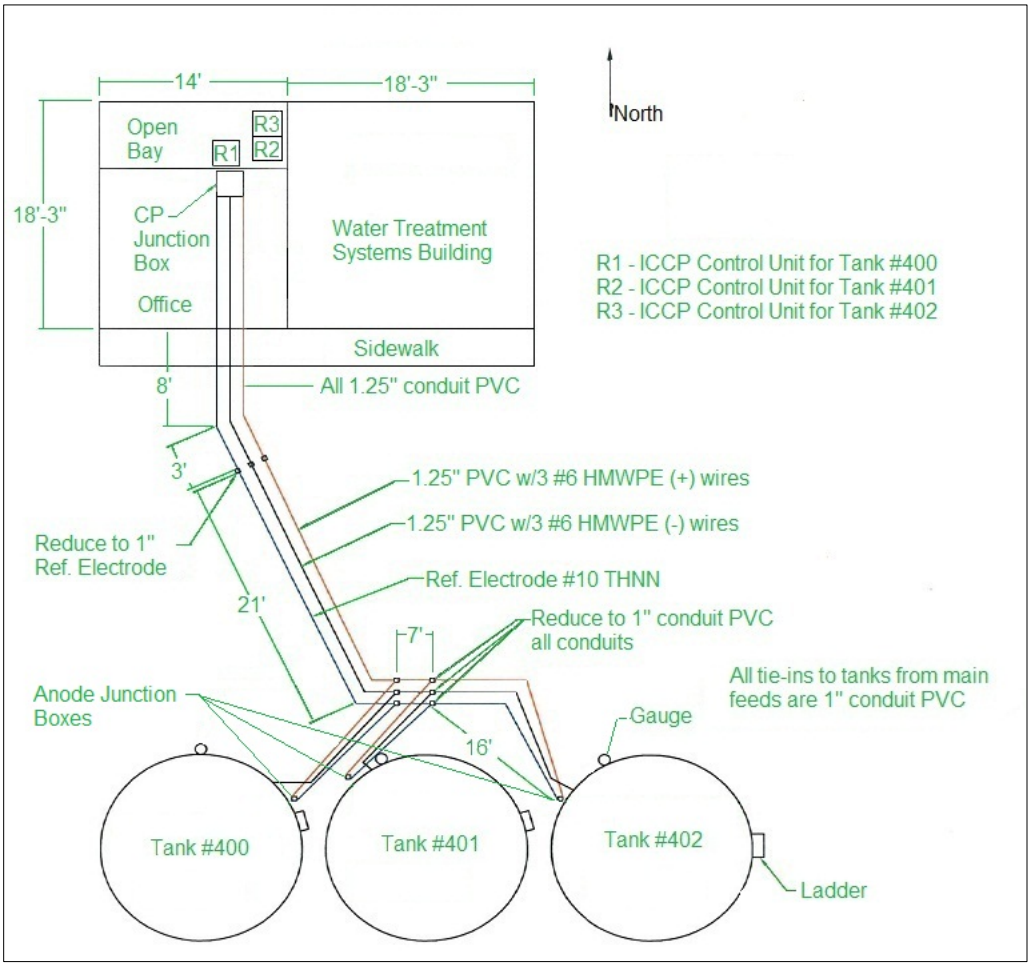
$\rho = \Omega - cm = 10{,}000\ worst\ case$

$$R = \frac{0.00521(10{,}000)}{18(5)}\left(ln\left(\frac{8(5)}{0.01}\right) - 1 + \frac{2(5)}{5}ln(0.656(18))\right)[ohms]$$

$R = 7.08\ [ohms]$

The particular system being demonstrated uses a PV power supply. It must provide current not only when the sun shines but also during periods of low insolation, such as night time and during overcast weather. In combination with solar panels, each water tank had a dedicated set of storage batteries and an ICCP control unit that afford this capability. A single remote monitoring system is used to provide access to ICCP system data from all three tanks via the web. These components are physically located at the small water treatment building located just north of the tanks. See Figure 4 for layout of ICCP system, which also shows the cable routing.

Figure 4. PV-powered CP system layout.



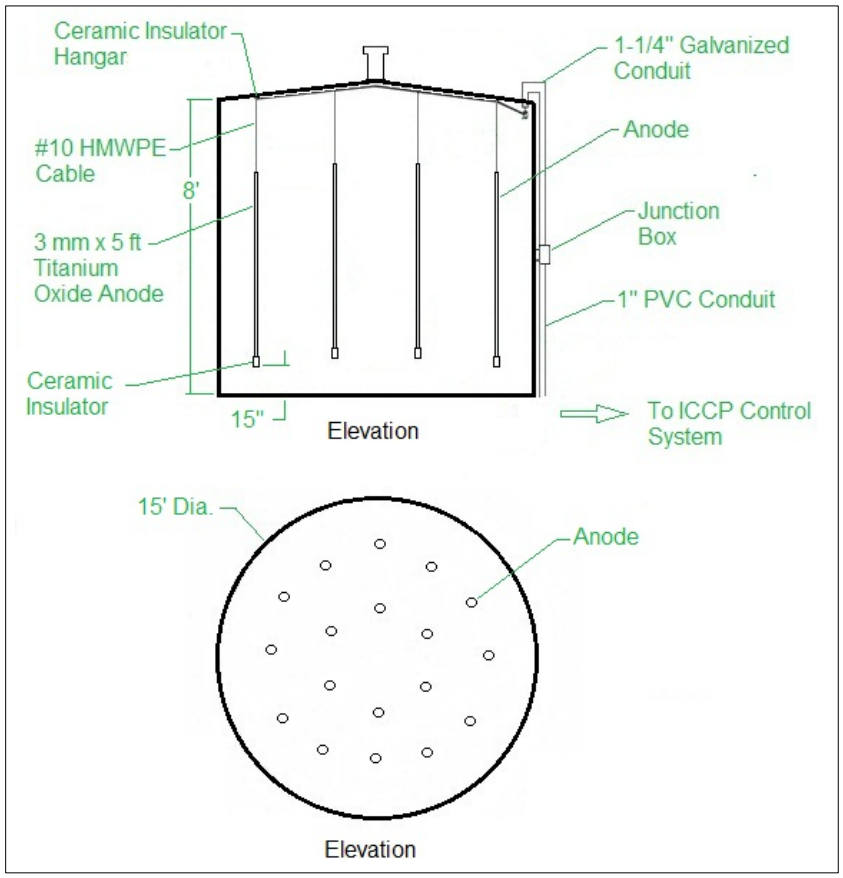
2.2.1 Anode system

Mixed metal oxide ceramic anodes were specified for this project. This material is not new, but has been improved continually over time. Ceramic anodes are smaller and lighter while providing current output and service life equivalent to more massive anodes of the past. The selected anodes were rods made of titanium oxides and are 5 mm in diameter and 5 ft long. The design is intended to achieve adequate corrosion protection in excess of 20 years (see Figure 3). Note that the calculations were computed with the assumption that the underside of the top surface of the tanks require protection. This is typically not the case in a standard design, so the approach results in additional design conservatism.

The design of the anode system for each tank consisted of 18 anodes suspended from the ceiling and distributed evenly about the tank (Figure 5). The Stelth 2 copper-copper sulfate permanent reference electrodes (Borin

Manufacturing, Culver City, CA) were used in each tank to measure the electrical potential between them and the tank structures.

Figure 5. Anode system design.



2.2.2 Solar array modules

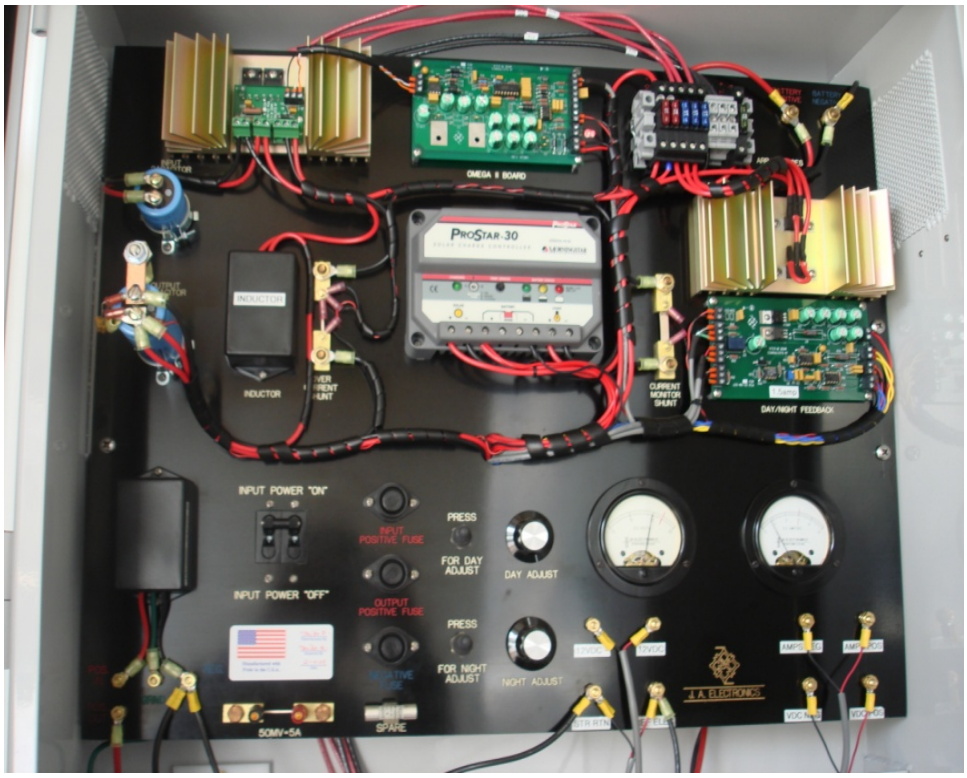
Kyocera KC130TM high-efficiency multi-crystal PV modules (Kyocera Corp, Kyoto, Japan) were selected for the project. They have a rated conversion efficiency of over 16%. Each module has slightly less than 1 m^2 of surface area and is rated at a maximum power output of 130 W (+10/-5%) under standard conditions and at a solar irradiance level of 1 kW/m^2.

Three PV solar array modules were wired in parallel to comprise a single solar panel. On average, each solar panel supplies power to one water tank CP system. The three panels were installed on the roof of the water treatment systems building.

2.2.3 PV-powered CP control units

The three tank PV-powered CP units (Figure 6) were assembled by JA Electronics Mfg. Co and include several components. The Omega II solar controller (JA Electronics) performs continual DC-to-DC voltage conversion to precisely regulate power to the CP anode bed in the water tank. It functions without the use of resistors or potentiometers, which typically dissipate excess power as heat. This elimination of energy dissipation provides improved overall solar power conversion efficiency. The controller board also includes output voltage and current meters for local viewing and adjustments.

Figure 6. PV-powered CP control unit.



The ProStar 30 solar charge controller (Morningstar Corporation, Newtown, PA) monitors the battery bank charge as well as the solar array output. During sunny days, the PV array both energizes the CP system and recharges the storage batteries. At nighttime and periods of insufficient insolation, the solar controller senses when power from the PV array falls below a set threshold, at which time the load is transferred to the batteries. It also constantly monitors CP system performance by collecting information from the permanent reference electrodes installed in the tank and automatically adjusts the voltage and power to the anode bed.

The control unit also has meters for viewing system parameters and control features for making manual adjustments and maintaining operation. Output voltage, output current, and reference electrode current data are collected by the data extraction modules which are located in the bottom of the unit. Lightning arrestors are provided on both the input and output voltage lines. The arrestors, also referred to as surge protectors, provide a short circuit path to ground in the event of a lightning strike, thereby preventing excessive current spikes that would damage circuitry.

2.2.4 Batteries

For any critical infrastructure application, storage battery life and maintenance requirements are primary considerations in the design of a PV-powered ICCP system. The batteries used in the system are maintenance-free Deka SOLAR model 8G4DLTP (East Penn Manufacturing Co., Lyon Station, PA), which have been designed specifically for renewable energy applications (Figure 7). They are 12 volt batteries rated at 210 amp-hours (ah) each and are valve-regulated with gelled electrolyte, giving them a greater cycle life. Three are connected in parallel for a total rating 630 ah to service each ICCP control system. These batteries provide backup power for times of insufficient isolation. With a full charge they can supply power for up to 10 days.

Figure 7. Deka SOLAR gel batteries.

2.2.5 Remote monitoring system

Another component used in this demonstration was an RMU with continual data collection and secure communications technology. The NTG Watchdog (Elecsys Corporation, Olathe, KS) monitoring system records and sends the CP anode voltage, current, and electrical potential to soil (difference between ground bed and reference electrode) readings to the user via satellite uplink to a secure web page hosted by the manufacturer. In addition to the data collected periodically at each ICCP control unit several times a day, the web page allows the authorized user to poll the CP system for instantaneous readings. The monitoring system also notifies the user of any CP interruptions or errors. Figure 8 shows the RMU.

Figure 8. NTG Watchdog RMU.

2.3 Installing the technology

Equipment installation was a fairly routine operation with few exceptions. Placement of the anodes in the water tanks required measures for ensuring electrical isolation from the interior wall metal being protected. The cabling, which had 10 gage wiring was insulated with high-molecular weight polyethylene (HMWPE) jacketing. Ceramic insulators were attached to the tank support structures at the ceiling to suspend the cabling and rods, as shown in Figure 9. Ceramic insulators were also used as mechanical ballast (i.e., weights) to help stabilize the anodes in the water once the tanks were filled. For each anode, an insulator was suspended approximately 15 in. from the tank floor using a 3/8 in. diameter nylon rope (Figure 10). The rope was then secured to the anode and cable using

plastic ties to further limit movement. Additional insulator weights were added for anodes suspended in the region around the water inflow pipes to minimize their movement during periods of turbulent flow.

Figure 9. Ceramic insulator used to suspend anode cable from tank structure.

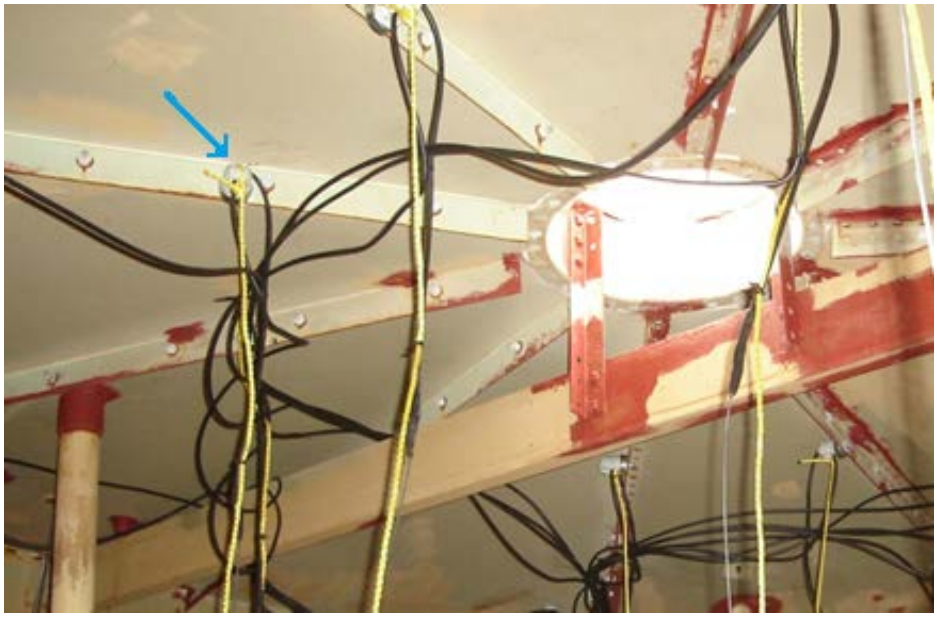


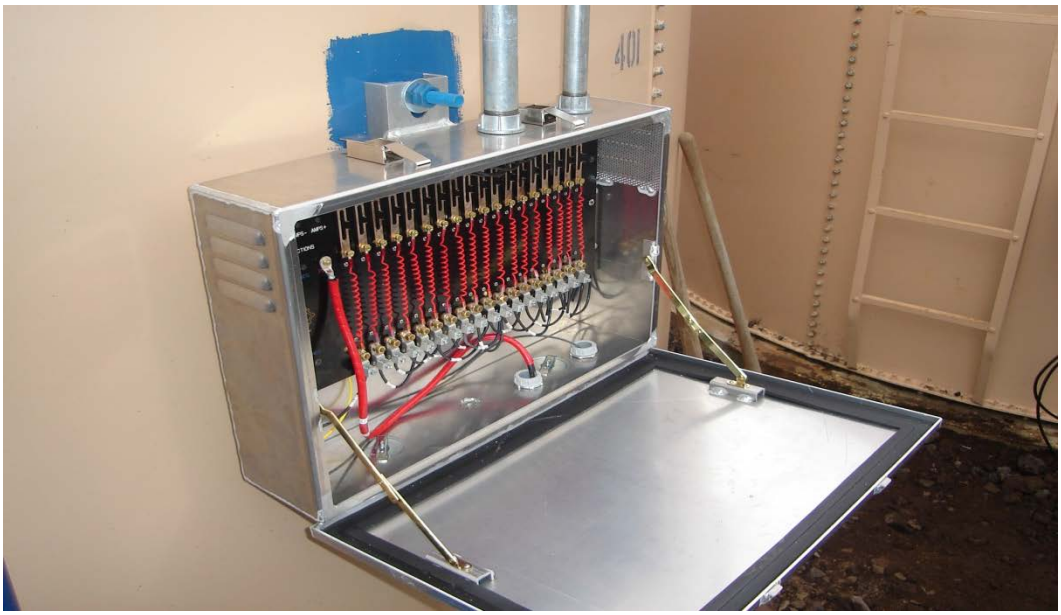
Figure 10. Anodes suspended and stabilized with ceramic insulators and nylon rope.

The permanent reference electrodes were suspended in a similar manner using the nylon rope; however the weight of the electrodes eliminated the need for ceramic insulators as ballast. For each tank, the permanent reference electrodes were placed 1 ft above the tank floor and at a height halfway up the wall and 1 ft away from the wall surface (Figure 11).

Figure 11. Reference electrodes suspended with nylon rope.

For each tank, the cabling for the anodes and reference electrodes pass through an opening in the ceiling located along the perimeter. The cabling was placed in galvanized metal conduit and run down the outside wall to an anode junction box that serves as a collection point for the leads and an access point for testing (Figure 12). Each box had 18 circuits, with 10 gage wire and THNN jacketing. From the anode junction boxes, a positive and negative cable for each water tank was run underground and laterally over to a CP junction box located in the water treatment building (see Figure 4). The 6 gage HMWPE-insulated cables, rated for direct burial, were placed in polyvinyl chloride (PVC) conduit to provide protection from the sharp edged volcanic rock.

Figure 12. Anode junction box mounted on outside wall of tank.



The three CP control units were encased in waterproof enclosures and mounted on the outside wall of the open-bay section of the water treatment systems building. A rack was built below each of the units for holding its set of three dedicated batteries (Figure 13). The RMU was also housed in a weatherproof enclosure and placed in the open bay section. The transmitter was attached to the west wall, providing the most direct line of sight to the communications satellite.

Figure 13. Three CP control units and sets of batteries.

Due to space constraints at the site, the three solar panels were installed on the roof of the building. Ideally, for maximum exposure to the sun, they would be installed at a 19.5 degree angle facing due south. However, they were positioned horizontally to minimize the risk of damage from high winds passing through the valley between the two volcanoes (Figure 14).

Figure 14. Three solar arrays mounted on roof of water treatment building.

2.4 Technology operation and monitoring

The CP system was energized and adjusted to normal operating levels on 19 March 2009. An initial commissioning was performed 3 weeks after system startup, on 9 April 2009, after allowing time for adequate system polarization to be achieved and current outputs to stabilize. The commissioning report is included as Appendix A.

Initial startup indicated that current outputs of 1.02 – 1.21 A were sufficient to achieve adequate CP levels for the water tank interiors. Care was given to not exceed –1.20 V instant-off in order to prevent debonding of paint from the coated portions of the tank interiors. Any loss of coating over time would require an increase in CP current levels to maintain adequate protection. Polarization occurred quite rapidly, indicating good dielectric performance of the remaining interior coating. As a more steady-

state mode of operation was achieved, CP current levels decreased to 0.56 – 0.68 A by May 2009 and then stabilized. Fluctuations that have occurred can be attributed to the continual changing of the tank water levels over time.

A project subcontractor assessed solar controller efficiency at 95% and the total PV system efficiency at 79% (see Appendix A), which far exceeds PV systems previously available for CP applications.

This project required the contractor to perform bi-weekly inspections and reporting for the first 6 months and then monthly for another 18 months. The contractor visually inspected the batteries, rectifiers, and arrays. A digital multimeter was used to take outputs that were recorded to provide information about the status of PV cells, batteries, cathodic outputs, and electric potentials.

In additional to the physical collection of data, the RMU was programmed to record system readings at four specific times each day (0000, 0600, 1200, and 1800 hours) to monitor both day and night operating modes. Specific data collected included structure-to-electrolyte potentials, system voltage, and system current. The data were uploaded via the RMU's satellite uplink. A monthly report was generated and transmitted through a secure web connection for access by the contractor, to be checked for anomalies. Data were collected in this manner for 2 years. All collected RMU data are tabulated in Appendix B.

3 Discussion

3.1 Metrics

NACE Standard Practice SP 0169 (2007) was the standard for determining whether adequate CP of the tanks was achieved and maintained.

For a bare steel structure to be adequately protected, the CP system design must meet at least one of criteria listed below:

1. A negative (cathodic) potential of at least 850 mV with the CP applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.
2. A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode.
3. A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization can be measured to satisfy this criterion.

The system was analyzed in two phases with respect to the third criterion to determine whether adequate CP was achieved. The initial polarization was measured during system initialization and recorded. At 6 and 12 months the system was de-energized and the rate of depolarization noted and recorded to establish if this criterion was achieved.

3.2 Results

The CP system was operating at optimum levels during the period of performance evaluation. The data indicate potentials greater than -850 mV in relation to a saturated copper-copper sulfate reference electrode. The reference cells were placed near the inflow pipe and tank gauge in order to measure worst-case scenario potentials (NACE 2012). With water turbulence it is possible to temporarily disrupt the passivation layer, thus affecting the degree of polarization. Voltage (IR) drop measurements should be minimal across the water/steel interface. All measured potentials have been in the range adequate for CP, thereby complying with criterion 1.

With respect to the second criterion, the requirement for 850 mV polarized potential was determined by turning on the CP system and allowing it to polarize for several days. The instant-off potential was recorded with current interrupted for 1 second to ascertain whether proper potentials were obtained by eliminating IR drop from the rectified output of current. All potentials have been in the –850 to –1,100 mV range. This range is important in that it should avoid debonding any remaining interior paint, which can result from over-voltage (i.e., starting at a value of –1,200 mV or greater absolute magnitude where the evolution of hydrogen gas can occur).

Compliance with the third criterion was evaluated by determining if 100 mV polarization was being achieved. This was done by subtracting the baseline potentials, which were taken before system activation, from the instant-off potentials recorded when the current was briefly interrupted. If the values are greater (more negative) than 100 mV in the instant-off state, adequate polarization formation has occurred. These values are indicated in the Delta V column on the data sheets in Appendix B. All values are greater than the 100 mV formation threshold.

A depolarized survey was conducted at 7 months and 12 months after the CP system was first energized to determine if decay polarization could be observed. Generally, slow polarization decays associated with a good bonded coating occur over days or weeks. A poorly coated, or completely bare structure, will exhibit a rapid polarization decay.

During the surveys, the system rectifiers were turned off for 72 hours and potentials were obtained. All measured values indicated that polarization decay had occurred. Values ranged from 0.002 mV to 0.189 mV (see Appendix B). The 0.002 mV measurement indicates a poorly coated or bare part of the tank depolarizing rapidly. The higher values, up to 0.189 mV, are indicative 0f tank sections that have some degree of coating protection because depolarization is occurring at a slower rate. Intact areas of coating are advantageous in that they reduce the demand for system current. These measurements are both consistent and indicative of the relative internal coating conditions observed in each of the tanks.

By meeting all three NACE criteria for effective CP, the system installed is working properly within design parameters. If the system is maintained as is, then the 20-year design life should be achieved or surpassed.

3.3 Lessons learned

Within 2 days after initial startup, the rectifier output meter displays began to blink. Investigations found that the system structure-to-reference electrode potentials were normal and that polarization of the tank interiors was being achieved. After observing the CP system for several days, several patterns were observed. If a unit was momentarily shut down by means of the internal output disconnect, the output meters stabilized for several hours. During a cloudy or rainy day, the meters remained stable. When the system completed the transition from day mode to night mode, the meter displays operated as expected until around 1100 hours the next day. At that time, the displays would start to blink, indicating that the rectifier was operating outside its normal range. The condition would persist until the sun lowered in the late-afternoon sky. This observation suggested that the blinking may be related to the intensity of sunlight reaching the PV collectors.

The rectifier manufacturer proposed several ideas to determine the cause of the blinking. The first was that the differences in outputs from day to night mode were too close. To test this, the contractor's CP technician adjusted the outputs so that the day mode was slightly greater than the night mode, but the result was negative. Another suggestion was that that the remote monitoring system was sending a signal back to the rectifiers that caused them to blink. To test this, the RMU system was disconnected, but the blinking persisted. A third suggestion was that the three rectifier systems might be interacting due to slight variations in output voltage, given that they are connected. The CP technician believed this scenario to be implausible for two reasons: (1) each tank had a CP system that was largely isolated to its own similar but unique object (e.g., variations in coating condition, water level, dissolved oxygen, temperature, etc.), and (2) because the idea could not account for the blinking at about the same time each day. If one system was fighting another, the problem should not be time-related. To eliminate this possibility, the first two rectifiers were turned off, and the third was observed. The meter on the energized rectifier continued to blink. The experiment was repeated with a different rectifier, keeping it energized while the other two were turned off. The result was the same. After this testing, a hypothesis that correlated the blinking of the meters to the position of the sun appeared to be the most likely explanation.

At this point, the rectifier manufacturer considered the site location and determined that none of their systems had ever been installed so far south in latitude or high in elevation. Given the combination of these characteristics, the solar arrays were producing more electricity at PTA than they would be expected to produce in the southwestern United States, where the company had installed numerous units. The circuit card that controlled power from the solar array to the rectifier was set at 1.5 A. This is the normal setting for this type of rectifier. However, the arrays were producing approximately 1.7 A and exceeding the threshold of the card. There is a switch on the card to reduce input power. After adjusting it to 1 A, the blinking stopped. The rectifier outputs remained stable for over a month after the adjustment and no longer appear to be an issue. As needed in the future if the PV module's current output degrades, the switch can be reset to increase power to the card. This course of action should extend the effective service life of the PV system and improve life-cycle cost performance.

4 Economic Summary

The projected return on investment (ROI) is based on the costs and assumption outlined below. It is calculated using the methodology specified in Office of Management and Budget (OMB) Circular No. A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs."

4.1 Costs and assumptions

Conventional Baseline Case. The cost of installing a conventional ICCP system for the three water tanks will serve as the baseline case for the ROI assessment. The total cost of corrosion protection using conventional impressed current CP for all three tanks (i.e., not including PV power, remote monitoring, or data uplink) is estimated to be $100,238. This baseline case includes standard electric utility service. A cost breakdown extracted from the contract costs for the PTA demonstration is as follows:

- Impressed current CP systems for three tanks (including anodes, cables, and all other components) — $47,474
- Shipping — $1,500
- Equipment rental — $1,740
- Labor and travel (includes profit and overhead) — $49,524
- Total — $100,238.

Also, an extension of electric utility lines for 1 mile was assumed, using January 2010 HELCO rates ($9,000 per 300 ft section), at a cost of $158,400. This increases the initial baseline cost to $258,638. Also, ongoing maintenance and repair costs for the tanks, power lines, and power line right-of-way were assumed to be $7,500 annually. This cost includes routine site inspections. See Appendix C for all cost breakdowns.

PV-Powered ICCP System. The total cost of protection using PV-powered ICCP with remote monitoring for the three tanks at PTA was $163,553. A breakdown extracted from the contract is as follows:

- ICCP systems with PV panels and batteries for three tanks (including anodes, cables, and all other components) — $82,766
- Shipping—$1,500
- Equipment rental—$1,740

- Labor and travel (includes profit and overhead)—$77,547
- Total—$163,553.

In addition to the initial $163,553 cost for the PV-powered CP system, an annual $1,000 expense for system inspection and validation was programmed. Finally, $10,000 for maintenance and repair was assumed at five-year intervals.

4.2 Projected return on investment (ROI)

To calculate the potential ROI for this demonstration, it was assumed that 50 remotely located DoD facilities could benefit from using the demonstrated technology. Using the total cost of the demonstration project ($660K), and extrapolating the costs and benefits for 50 additional implementations provides an ROI of 11.50 (Table 1). The net present value savings over 30 years based on this analysis is $7.6M.

Table 1. Return on investment calculation.

Return on Investment Calculation

Investment Required			660,000
Return on Investment Ratio	11.50	Percent	1150%
Net Present Value of Costs and Benefits/Savings	9,125,778	16,716,101	7,590,323

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	12,931,900		8,111,607	3,400	7,581,108	12,089,331	4,508,223
2	375,000		50,000	3,910	43,670	330,940	287,270
3	375,000		50,000	4,497	40,815	309,783	268,968
4	375,000		50,000	5,171	38,145	290,032	251,887
5	375,000		500,000	5,947	356,500	271,615	-84,885
6	375,000		50,000	6,839	33,315	254,419	221,104
7	375,000		50,000	7,864	31,135	238,410	207,275
8	375,000		50,000	9,044	29,100	223,514	194,414
9	375,000		50,000	10,401	27,195	209,619	182,424
10	375,000		500,000	11,961	254,150	196,692	-57,458
11	375,000		50,000	13,755	23,755	184,697	160,942
12	375,000		50,000	15,818	22,200	173,523	151,323
13	375,000		50,000	18,191	20,750	163,174	142,424
14	375,000		50,000	20,919	19,390	153,538	134,148
15	375,000		500,000	24,057	181,200	144,618	-36,582
16	375,000		50,000	27,666	16,935	136,383	119,448
17	375,000		50,000	31,816	15,830	128,798	112,968
18	375,000		50,000	36,588	14,795	121,789	106,994
19	375,000		50,000	42,077	13,825	115,322	101,497
20	375,000		500,000	48,388	129,200	109,403	-19,797
21	375,000		50,000	55,646	12,075	104,001	91,926
22	375,000		50,000	63,993	11,285	99,081	87,796
23	375,000		50,000	73,592	10,545	94,608	84,063
24	375,000		50,000	84,631	9,855	90,593	80,738
25	375,000		500,000	97,326	92,100	87,002	-5,098
26	375,000		50,000	111,924	8,610	83,848	75,238
27	375,000		50,000	128,713	8,045	81,047	73,002
28	375,000		50,000	148,020	7,520	78,662	71,142
29	375,000		50,000	170,223	7,030	76,658	69,628
30	375,000		500,000	195,757	65,700	74,997	9,297

Economic analysis indicates that CP systems in remote locations can reliably and cost-effectively be powered by PV panels and storage batteries.

5 Conclusions and Recommendations

5.1 Conclusions

The solar powered CP system is operating as designed. Very little maintenance should be necessary to keep the system operating properly. Some minimal maintenance, like cleaning solar arrays and measuring monthly outputs with a digital meter, should be all that is necessary to keep the system operating well. Once every calendar year, a qualified CP specialist should survey the system to ensure proper CP levels.

The project demonstrated that a PV powered ICCP system can be remotely monitored and the system kept fully operational at all times, eliminating the cost and inconvenience of visiting remote sites to make routine inspections. Another advantage of this system is that it is not vulnerable to interruptions of CP related to power failures on the grid. The third advantage is that once the system is in place, there is no continuing cost for ongoing power consumption. An ancillary benefit is that this system does not compete for power with other applications on the grid in areas where power production capacity is limited.

This CP system is a highly reliable and efficient technology now available for implementation to protect strategic and high-value facilities required to be self-sustaining.

5.2 Recommendations

5.2.1 Applicability

Solar powered CP systems are inherently less reliable than conventional electrical powered systems. However, the applicability of solar-powered CP depends both on geographic location and the cost of serving a remote site with grid power. PTA is located at 9.5 degrees latitude, where sunshine is very direct and usually not obscured by clouds. At higher latitudes or where cloud cover prevails, reliable solar design would be much more difficult and expensive to achieve. PTA is well suited for this kind of solar application because of its abundant solar energy, its remote location, and an expensive power infrastructure that is nearing its production capacity. Systems like this will increasingly become the most affordable and sustainable option for critical military applications in isolated areas.

Based on the results reported here, the demonstrated technology is also applicable at other remote locations. A PV-powered CP system can be used in remote areas for many applications, such as pipe lines, underground storage tanks, and other steel infrastructure. This technology could also be used to meet the ever-increasing CP monitoring requirements for steel in reinforced concrete pier pilings, seawalls, harbors, and wharves.

5.2.2 Implementation

This technology should be considered and economically compared to grid-tied ICCP when designing cathodic protection for ferrous infrastructure. A favorable life-cycle cost basis is probable for remote facilities, where connection to the grid is expensive or the power supply is not reliable. However, the economic comparison will also be affected by the suitability and difficulty of implementing PV at a specific location.

Adoption of the demonstrated application could be implemented into policy with revisions to the Unified Facilities Guide Specifications (UFGS), section 26 42 22.00 20, “Cathodic Protection System (Steel Water Tanks” (February 2013); and more widely by revisions to UFGS section 26 42 17.00 10, “Cathodic Protection System (Impressed Current)” (November 2008).

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Appendix A: Subcontractor Assessment of the Demonstration System

LERATEK
INCORPORATED

Assessment
of the
Photovoltaic Powered
Impressed Current Cathodic Protection
at
Pohakuloa Training Area, Hawaii

Order Number W9132T-LER-001

Prepared for:
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1.0 INTRODUCTION

This report documents the technical performance assessment conducted by Leratek, Inc. (hereinafter Leratek) on a state of the art solar powered Impressed Current Cathodic Protection (ICCP) system installed at Pohakuloa Training Area (PTA), Hawaii. The ICCP system was installed to provide long term corrosion protection for three small steel water tanks that supply PTA with its potable water. Mandaree Enterprise Corporation (MEC) installed the ICCP system at PTA under contract to the US Army Construction Engineering Research Laboratory (CERL), and tasked Leratek to perform a detailed inspection and technical assessment to determine if the installed ICCP system met its objectives. The assessment was performed from April to June, 2009.

2.0 BACKGROUND

Mission and/or business requirements often necessitate locating permanent facilities in otherwise remote locations. Many of these facilities, such as pipelines, steel tanks, well casings, and even highway bridges are made from steel or other metals that require corrosion protection to protect the investment and minimize maintenance costs over the long term. Corrosion protection can be characterized as passive (paints, coatings, passivation schemes, galvanizing, or sacrificial anodes) or active (electrically powered Cathodic Protection (CP) systems). While the passive protection provided by coatings is relatively inexpensive, coatings don't last forever and must be re-applied periodically. In many cases, it is difficult if not impossible to re-coat structures once they are constructed. In such cases, active protection (CP) is sought to provide long term corrosion protection. CP systems provide enhanced long term corrosion protection for permanent metal structure facilities worldwide. In remote locations, getting electrical power to the CP system can be expensive. When the cost of extending power lines is too great, photovoltaic (solar) cells can provide the needed electricity. Of course, solar cells only work when there is sufficient insolation, so any system being powered by solar cells requires batteries and a control system to provide power during nighttime and other periods of low insolation. CP systems in common use today have several design deficiencies that make them less than optimal for use in conjunction with solar power. Seeking more efficient CP systems better suited to solar power, CERL contracted with MEC to design and install a state of the art, highly efficient solar powered ICCP system for a water storage tank facility at a remote Army training site.

2.1 The Facility

Pohakuloa Training Area (PTA) is a remote US Army training site in the interior of the island of Hawaii (the big island). Untreated water is trucked in and stored in three large storage tanks on the hillside above PTA. A water treatment facility treats the water and sends it to three smaller potable water storage tanks, which in turn supply PTA below with potable water. Figure 1 shows the layout of the water supply facility. The solar panels, battery racks, and ICCP control system electronics are installed at the water treatment building while the ICCP distribution boxes and anode system are installed on the three smaller, potable water tanks.

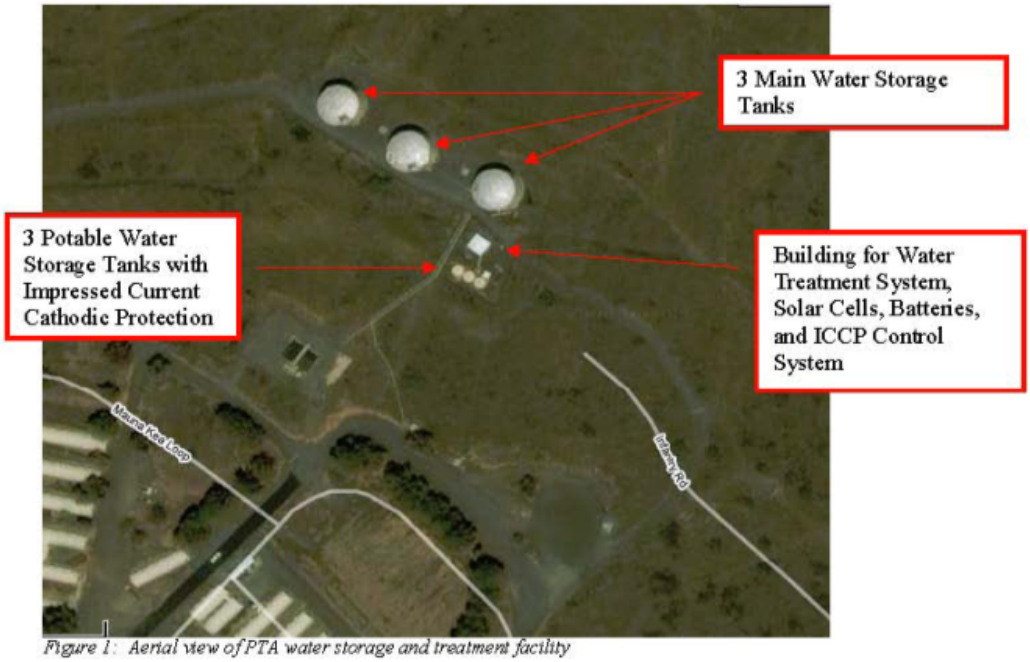


Figure 1: Aerial view of PTA water storage and treatment facility

2.2 The ICCP System

The ICCP system installed at PTA is comprised of several major components: Solar panels and battery racks which provide power, a solar powered cathodic protection unit which houses all controls for the ICCP system, a distribution box on the outside of each water tank, reference electrodes, and anodes installed inside each tank. From solar panel to anodes, an independent ICCP system was installed for each of the three water tanks, whereas a single monitoring system was used to uplink data to a satellite to facilitate monitoring of all three ICCP systems via the web.

2.2.1 Solar Panels

Kyocera KC130TM high efficiency multicrystal photovoltaic modules are used to build up the solar panels. 3 modules (wired in parallel) are used for each solar panel, and with one solar panel for each water tank ICCP system, the total installation utilizes 9 KC130TM modules. The solar panels are installed on the roof of the water treatment building. The KC130TM is affordable, commercially available, and has a rated conversion efficiency of over 16%. Each module is slightly less than 1 square meter of surface area, and is rated at a maximum power output of 130 watts (+10/-5%) under standard conditions and at a solar irradiance level of 1000 watts/m^2. The solar panels power the ICCP system during the day

while also recharging the batteries that power the system at night. Complete properties of the modules are listed in Appendix 1. The three installed solar panels are shown in Figure 2.

Figure 2: Solar panels (3) installed on the roof of the water treatment facility at PTA. Note junction boxes on roof connecting 3 Kyocera KC130TM modules in parallel for each solar panel.

2.2.2 Batteries

Deka SOLAR Photovoltaic Batteries are used in the ICCP system for power during periods of low solar insolation. One battery rack is used for each of the three systems installed, for a total of 9 batteries on site. A battery rack consists of 3 Deka SOLAR 8G4DLTP sealed, valve-regulated, gelled-electrolyte batteries specifically designed for renewable energy applications. These batteries carry a rating of 210 amp-hours, and are wired in parallel to form each rack. With a proper voltage regulated charge controller, gelled-electrolyte batteries are maintenance free and have a greater cycle life than absorbed glass mat (AGM) and a far greater cycle life than conventional flooded lead-acid batteries [1]. In fact, when installed in a system with sufficient battery capacity designed to avoid deep discharging below 10% of the depth of charge, these batteries can last an impressive 5700 cycles [2]. The battery racks are installed under a sheltered porch, open to the atmosphere, on the back of the water treatment building. An installed battery rack is shown in Figure 3.

Figure 3: A battery rack consists of three (3) Deka SOLAR gel batteries, rated at 210 amp-hours each, wired in parallel for a rack capacity of 630 amp-hours.

2.2.3 Solar Powered Cathodic Protection Control Unit

Each of three solar powered cathodic protection units are installed on the wall of the back porch of the water treatment facility immediately above their respective battery racks. Protected inside a gray utility box, the JA Electronics cathodic protection unit performs several important functions, including control and monitoring of the battery bank charge, controlling the day to night transition from solar panel to battery and vice versa, continually performing DC to DC voltage conversion to precisely power the ICCP anode bed in the water tanks, and data extraction to provide monitoring information to the satellite uplink system. The cathodic protection unit also has control/setup features to monitor and maintain the overall system. The JA Electronics solar powered cathodic protection unit is shown in Figure 4. The data extraction modules are located in the bottom of the unit and shown in Figure 5.

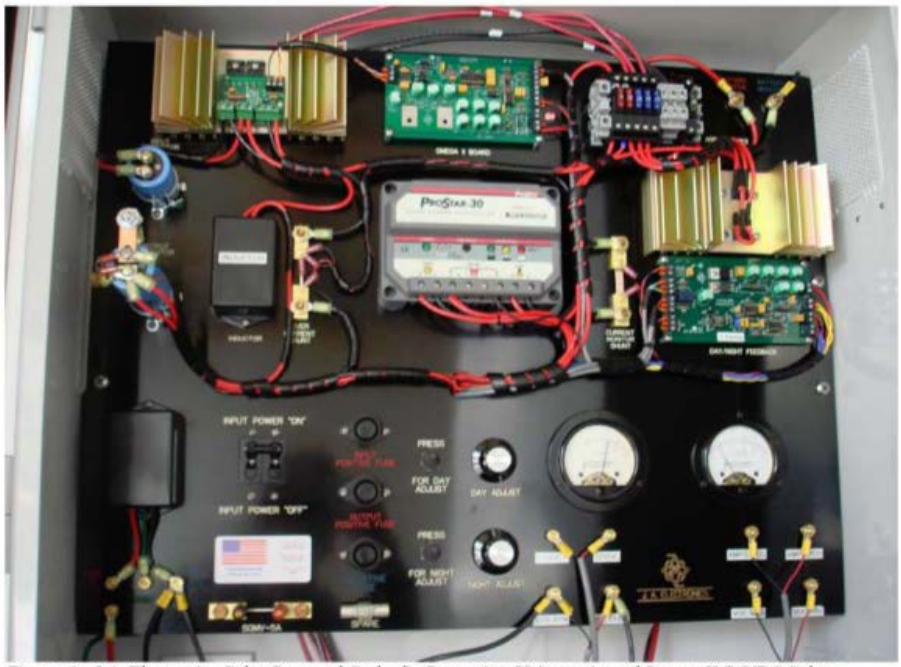


Figure 4: J.A. Electronics Solar Powered Cathodic Protection Unit consists of Omega II DC/DC Solar Converter, PROSTAR 30 Regulator Solar Controller, Solar MOSFET Assembly, and Day/Night Controller Solar Motherboard.

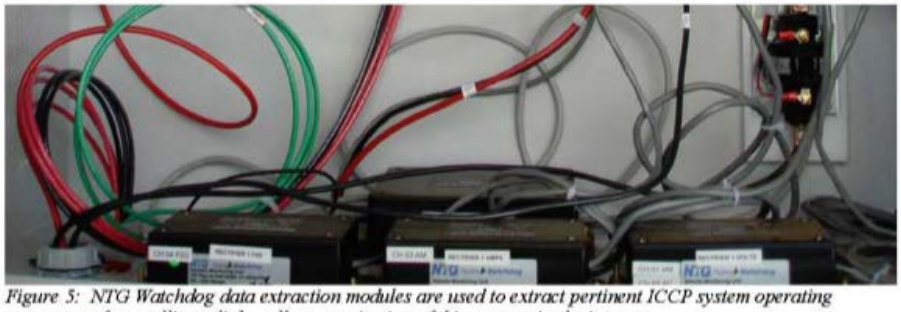


Figure 5: NTG Watchdog data extraction modules are used to extract pertinent ICCP system operating parameters for satellite uplink – allows monitoring of this system via the internet.

2.2.4 ICCP Anode System Junction Box

Each potable water tank has an anode system junction box permanently mounted to the exterior of the tank. The junction box covers 18 anodes installed in each tank as well as the reference electrode for that tank. Figures 6 and 7 illustrate the junction box.

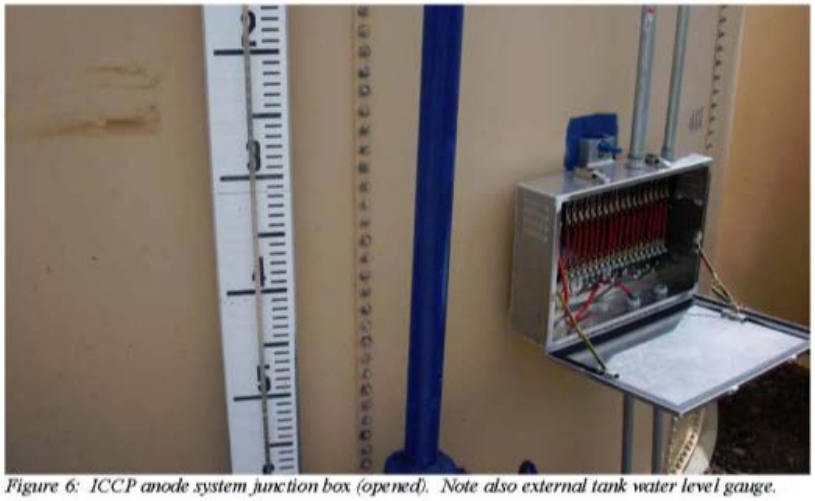


Figure 6: ICCP anode system junction box (opened). Note also external tank water level gauge.

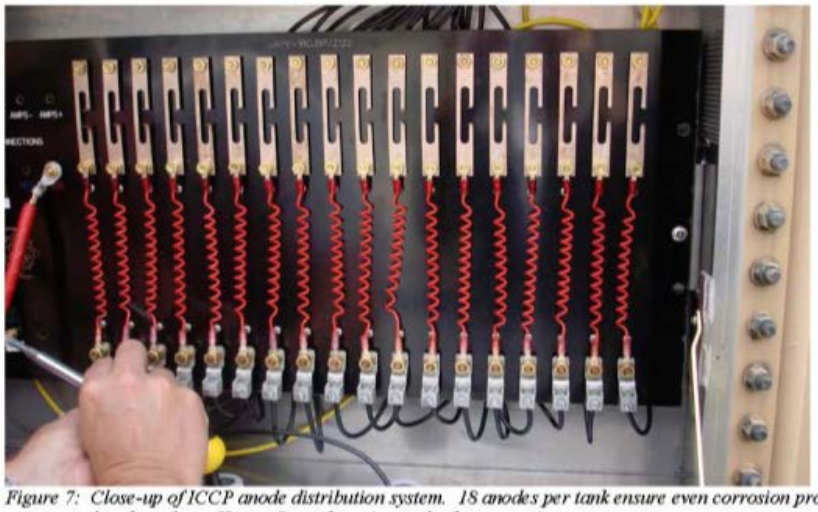


Figure 7: Close-up of ICCP anode distribution system. 18 anodes per tank ensure even corrosion protection across steel tank surface. Here a Leratek engineer checks connections.

2.2.5 Anode System (ground bed)

The ICCP anode system, or ground bed, consists of 18 ceramic anodes spaced evenly in the interior of each round steel potable water tanks. Since the system was already installed when Leratek arrived for system assessment, photos could not be taken of the installed system inside the water tanks. The ceramic anodes are a fairly recent innovation, and are made from Titanium mixed metal oxide. The anodes are 3mm x 5 ft long, and hang from the tank roof via dielectric hangers. The anodes are crimped, sealed, and ballasted at their bottom. Sometimes referred to as intermetallic, they have properties of both metals and ceramics. For this application, the relevant properties are that they conduct electricity to impress current on the steel tank for corrosion protection, but as the ceramic anode, they resist sacrificial corrosion and have a life expectancy in the multiple decade range. A diagram illustrating the installation scheme is included in Figure 8.

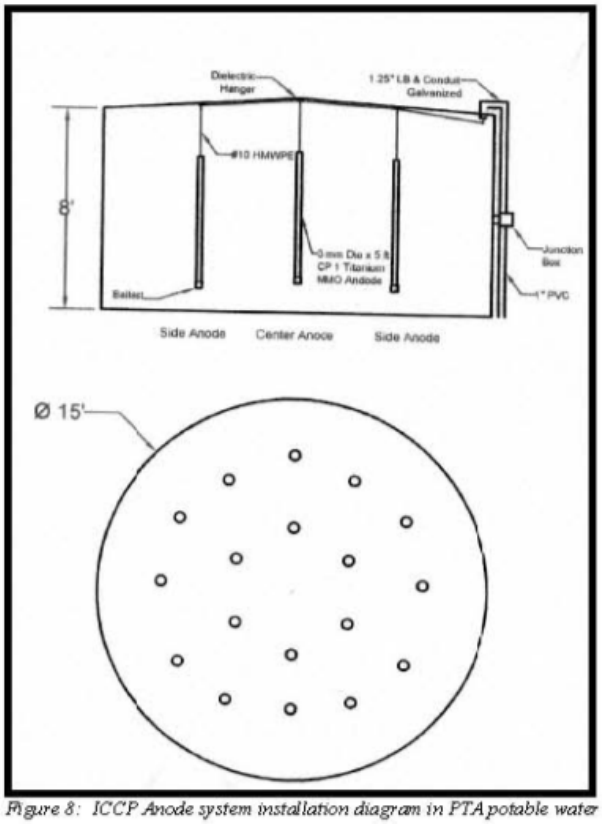


Figure 8: ICCP Anode system installation diagram in PTA potable water tanks.

2.2.6 NTG Watchdog Monitoring System

The NTG Watchdog monitoring system accurately records and sends the ICCP anode voltage (ground bed), current, and potential to soil (difference between ground bed and reference electrode) readings to the user via a satellite uplink located on the roof of the water treatment building. The information is then available via the internet on the NTG Watchdog website featuring password enabled limited access. The website is user-friendly and in addition to the already set schedule of reporting each cathodic protection unit's readings several times a day, the website allows the user to poll the site for instantaneous readings. Furthermore, the Watchdog system will notify the user of any discontinuance or errors at the site. Leratek has found NTG, the company that maintains the Watchdog system, to provide ideal customer-oriented technical assistance 24/7. Figure 9 depicts the NTG Watchdog Monitoring system uplink box.

Figure 9: NTG Watchdog monitoring system uplink box.

2.3 Theory of Operation

The purpose of the ICCP system in this assessment is to prevent, over a long term, corrosion of steel water tanks. Steel is an alloy of primarily of iron (Fe) and carbon (C). Corrosion in steel is the oxidation of the iron in the alloy. Corrosion occurs in steel because carbon and iron have different electro potential. In terms of the galvanic series, carbon is "noble" to iron, meaning when both are present in a corrosion cell, the carbon is unchanged and the iron combines with oxygen. For corrosion to occur, four elements must be present:

1) An anode
2) A cathode
3) An electrical connection between the anode and cathode, and
4) An electrolyte present between the anode and cathode

For the steel water tank, the iron portion of steel is the anode, the carbon portion of steel is the cathode, the steel itself is electrically conductive, and the water in the tank is the electrolyte. As confirmed by common experience, put water on steel and it will rust. In the corrosion process the anode gives up its electrons, making the molecule free to bond with oxygen. The cathode has excess electrons and is protected. There are various means of preventing the corrosion of steel, coatings usually being the easiest and cheapest by preventing contact with an electrolyte. However, as stated in the introduction, coatings must be maintained and that is often difficult.

For a water storage tank, an ICCP system is the state of the art method to protect the tank long term. As the name implies, the technique works by connecting (impressing) a negative direct current (cathode) and its excess electrons onto the whole of the steel structure; this makes the entire steel surface cathodic and protected. The positive lead from the power source is directed to a set of titanium mixed metal oxide rods suspended in the water, forming the anode surface, referred to as the ground bed. The titanium mixed metal oxide rods are extremely resistant to corrosion even with a positive current impressed on them, and last for over 20 years in practice. Thus the steel continually has excess electrons and does not react with oxygen to form rust.

The voltage supplied by the cathodic protection control circuit is determined by a reference electrode. The reference electrode is a copper/copper sulfate electrode suspended in the tank water. The potential between the reference electrode and the tank structure is measured, and the system is calibrated such that the steel tank structure is maintained at a negative voltage (always at least -0.85 to -1.1 volts DC) greater than the potential between the reference electrode and the tank structure. As long as this difference is maintained, the tank is protected from corrosion.

Now that the theory of cathodic protection is explained, we turn to the installed ICCP system to illustrate how it uses solar power, batteries, and control circuitry to efficiently provide power to the ICCP system on an automated basis year round. Figure 10 depicts the relationship of the major components. Figure 11 illustrates the solar powered cathodic protection unit design.

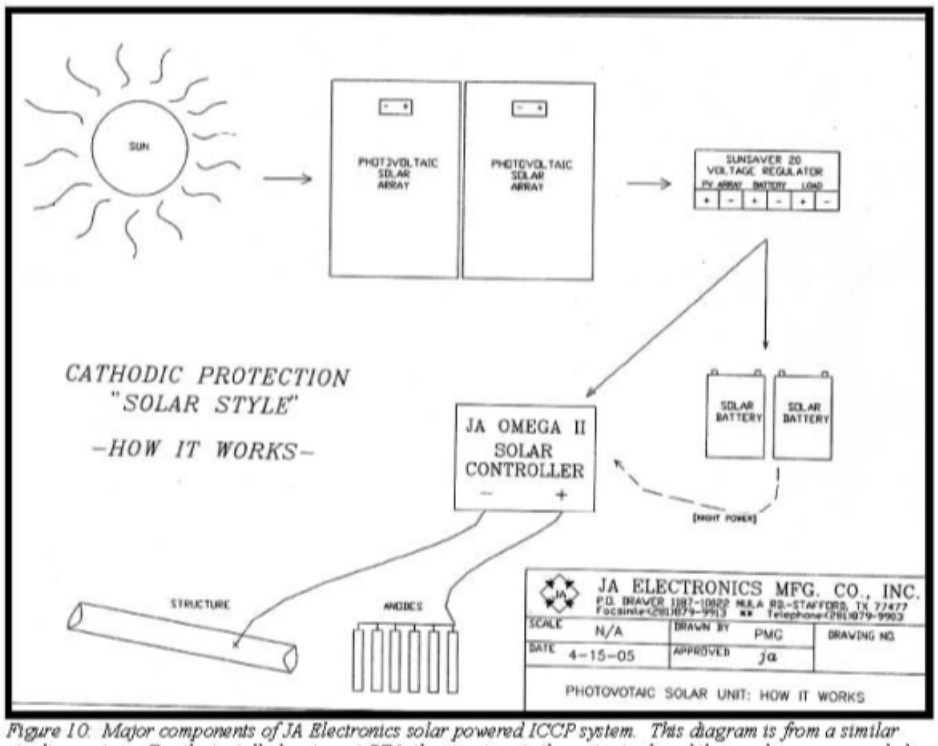


Figure 10. Major components of JA Electronics solar powered ICCP system. This diagram is from a similar pipeline system. For the installed system at PTA, the structure is the water tank and the anodes are suspended inside the water tank. Also, the Sunsaver 20 was replaced with a PROSTAR 30 Regulator Solar Controller.

As seen in Figure 10, the solar panels provide all the power the system will ever need. There is no hookup to any utility power. During the day, the solar panels power the ICCP system as well as charge the battery racks. During inclement weather and nighttime, the batteries will power the system. The PROSTAR 30 voltage regulator monitors the battery bank charge and solar array output, and regulates the charging voltage to the batteries to ensure they are not overcharged as might happen with older, constant current battery chargers. The solar controller monitors solar panel output voltage and current, and switches the system seamlessly for day/night transitions based on values selected during system setup. The solar controller also monitors the cathodic protection system, constantly taking feedback from the reference electrode and adjusting the voltage and power to the anode ground bed and structure accordingly.

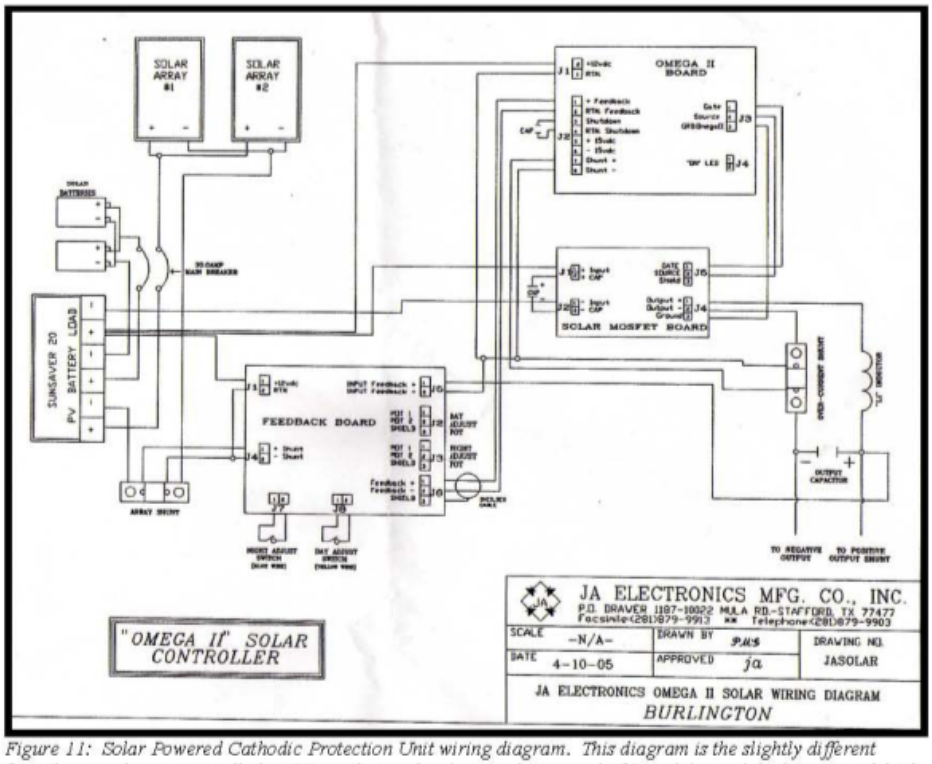


Figure 11: Solar Powered Cathodic Protection Unit wiring diagram. This diagram is the slightly different from the actual system installed at PTA in that each solar panel consisted of 3 modules and the battery rack had 3 batteries, and the Sunsaver 20 was upgraded to a PROSTAR 30.

The Omega II Solar Controller is illustrated in Figure 11. Advanced elements of this ICCP system are seen in the Solar MOSFET board, part of a highly efficient DC-DC voltage converter that does not utilize resistors or potentiometers to regulate voltage by dissipating excess power as heat. Thus more of the solar power is available to charge the batteries while simultaneously powering the ICCP ground bed. The actual efficiencies of the system are discussed later in this report. The system has installed meters for output voltage and current on the circuit board for local viewing and adjusting of system parameters. Although not shown in Figure 11, the NTG Watchdog monitoring system extracts the output voltage, output current, and reference electrode current data, and uplinks the data to the Watchdog website via satellite on a regular schedule. The system can also poll the same data at any time.

3.0 ASSESSMENT OF THE ICCP SYSTEM

Leratek Inc. performed an assessment of the installed ICCP system at PTA, Hawaii in April, 2009 after the system had been installed and operating for approximately one month. The assessment was performed according to three major task areas in the MEC to Leratek contract Statement of Work. A fourth task directed the actual writing and delivery of this report.

3.1 Positive Ground System

"Leratek shall evaluate the system to determine if the electronics have been designed to allow a positive ground system from the battery bank directly to the ground bed, improving installation by preventing "ground loops", while providing better lightning protection. Determine if this feature is applicable to the system design installed by MEC and/or if the installed system provides for this capability."

The installed system has a positive ground system from the battery bank to the ground bed (anodes). This was verified through visual inspection of the system setup and review of the cathodic protection unit wiring and layout drawings as shown in Figure 10.

For a positive ground system, it is not recommended that the PV wires and battery bank be grounded through a separate ground line. Upon inspection of the installed system, they are not. It is necessary though that the PV frames, with associated racks, are grounded through connection to the building structure, which is grounded to earth via copper pipe as shown in Figure 12.

Figure 12: Building ground to earth; PV frames are attached to building; PV lines are not (located with gray tubing, isolated from structure ground)

In addition, the installed system provides lightning protection both on the input and output voltage lines by way of lightning arrestors, one being located jointly with the Watchdog monitoring components on the output as shown in Figure 13. Lightning arrestors (also called surge protectors) create a short circuit to the ground that is interrupted by a non-conductor. Lightning arrestors prevent over voltage from damaging the circuitry being protected.

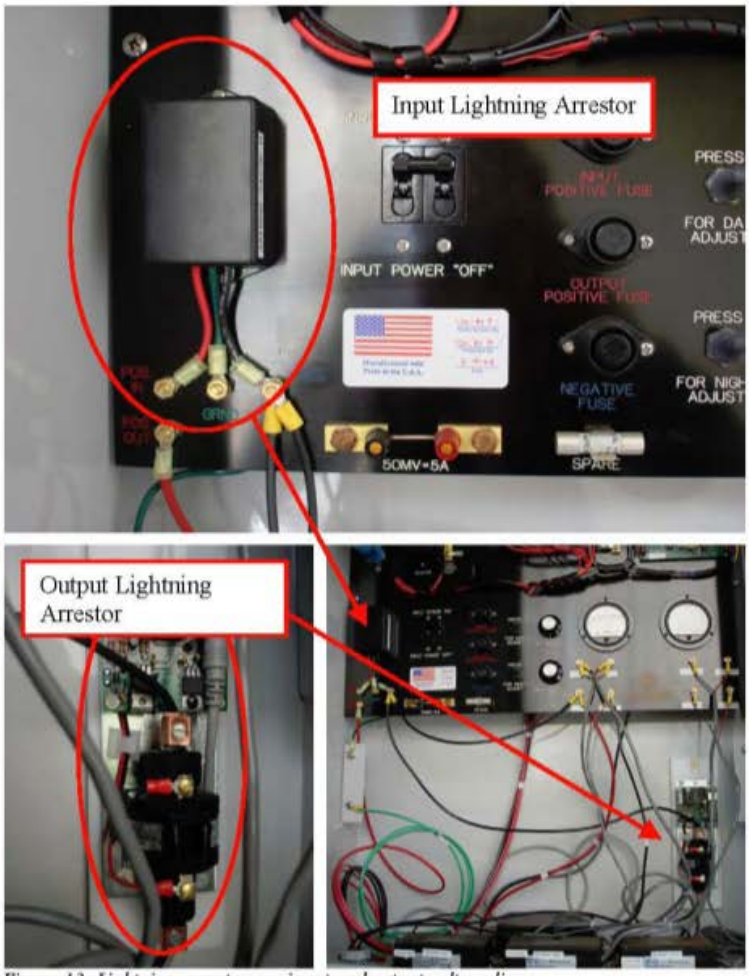


Figure 13: Lightning arrestors on input and output voltage lines.

The installed positive ground approach eliminates sensitive electronics in the ground path, which will reduce the chance of system failure due to lightning.

3.2 Photovoltaic Powered System Efficiency

"Many solar cell powered systems have not been properly designed, as they did not encompass a complete understanding of the differences between PV power and conventional AC powered rectifier systems. Also, conventional solar electric systems have tended to be expensive, which leads to various methods of cutting costs, almost all of which reduced system reliability. For example, previously 400 Watt arrays were employed where less than 20% of the power produced was actually available to the ground bed with 80% wasted in system inefficiencies, and even the best designed systems using the conventional controls have overall losses of 40-60%. Assess and quantify the performance of the MEC installed system to determine its capabilities as they relate to the parameters identified above."

Solar cells, due to the physics of their construction and mode of operation, behave as a power source differently than batteries or utility power. Briefly, solar cells are constructed by fusing two oppositely charged semi-conductor layers to each other. These layers are silicone crystals doped such that one layer has excess electrons (n or negative semi-conductor) and the other layer has a deficit of electrons (p or positive semi-conductor). When the two layers are stacked in contact, the electrons from the "n" layer attempt to migrate to the "p" layer. As the first electrons crowd at the n-p layer interface, they repel electrons behind them, forming a barrier. Equilibrium is reached resulting in a measurable electrical field on the solar cell. A solar cell must have this field in order to function; this field acts similar to a diode allowing electron flow in only one direction. The equilibrium reached during construction can be disrupted when photons of light strike the cell. The photons are absorbed, freeing one electron per photon to move according to the electric field. If the two layers are connected by a separate wire path, the excess electrons on the "n" layer will flow through the wire to the "p" layer and will do useful work (power) while they flow. As long as photons of light are being absorbed by the solar cell, electrical current can flow in the prescribed direction. The electrical field at the boundary layer between the "n" and "p" layers is affected by the total current flowing (load) in the external circuit the solar cell is powering. Since the internal field varies, the output voltage varies (quite a bit compared to battery fluctuations). Further, as one might suspect, solar cell output varies as a function of the solar irradiance striking the cell and the temperature of the cell. Hence, solar cell manufacturers publish technical data curves of voltage (V) as a function of current (I), for various temperatures and solar irradiance levels.

The current vs. voltage characteristics of the photovoltaic modules installed on site (Kyocera KC130TM 130W) are depicted in Figure 14. (current-voltage curve obtained from panel datasheet – Appendix A). The black curves in Figure 14 are replicated from the Kyocera data sheets. The power output of a photovoltaic module is inversely proportional to the temperature of the module, and proportional to the solar irradiance striking the module. At mid day, the photovoltaic module is heated above ambient temperature by the solar irradiance. To better assess midday performance, and to be conservative, a V vs. I plot was interpolated from the manufacturer's data sheets for a photovoltaic module temperature of 1.5 times the average ambient air temperature from the dates of the survey, or 110F. These curves are shown in red in Figure 14. Figure 15 shows current vs. voltage for at differing irradiance levels for 77F.

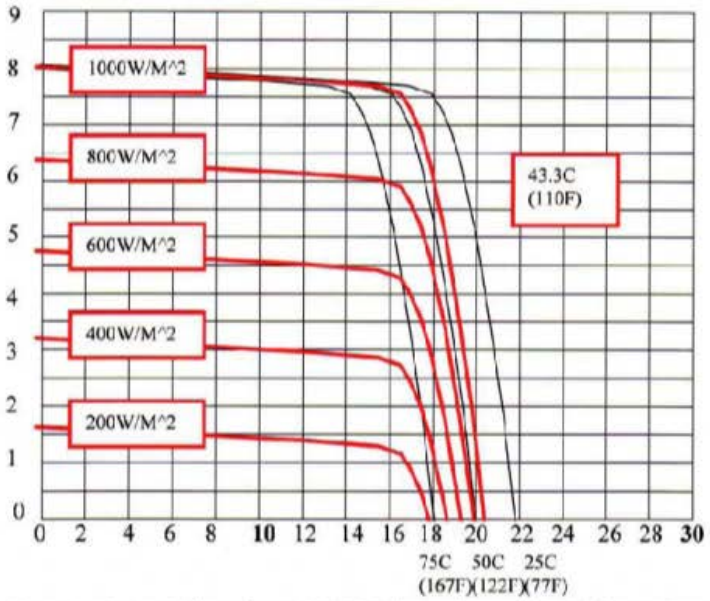


Figure 14: Current-Voltage for one KC130TM photovoltaic module, 110 degrees F in red.

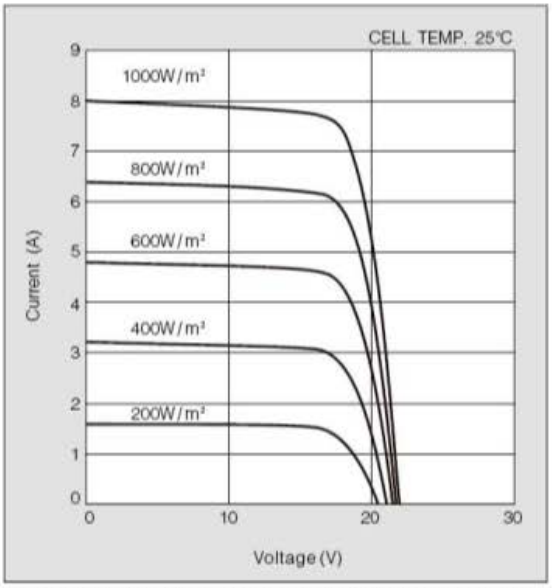


Figure 15: Current vs. Voltage for Kyocera KC130TM photovoltaic module as a function of irradiance [3].

Solar irradiance is a measure of the radiant flux density on the panel given in watts/square meter. Over a day, the average solar irradiance for the Pohakuloa site is around 250 W/m^2. (refer to Appendix F for solar map of location [4]). During the day, however, the irradiance level starts off low and reaches as high as 1100 W/m^2 at solar noon. Solar noon was around 1230 hrs during this task. Afternoon clouds from the east or clouds of sulfur dioxide gas from nearby volcanoes periodically reduced the irradiation level somewhat. A study by the University of Hawaii – Hilo agricultural department characterized the level of change in solar irradiation over a day [5]. The results are shown in Figure 16.

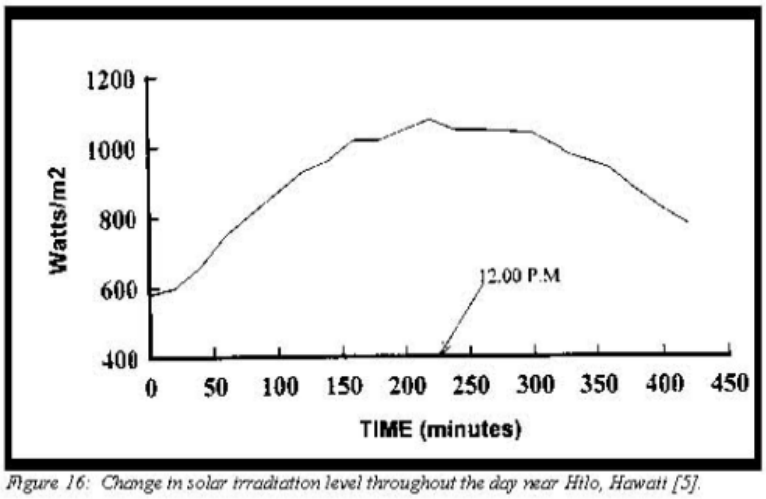


Figure 16: Change in solar irradiation level throughout the day near Hilo, Hawaii [5].

Examination of figures 14, 15, and 16 conveys the manner in which power from solar cells is so different than power from utilities or batteries. Utilities will deliver as much power as you can pay for at a regulated voltage. Batteries deliver a nominal voltage and amp-hours until discharged. Solar cells deliver anywhere from 0 to approximately 22 volts depending on the load (current draw) connected to the cell, with the maximum current the solar cell can deliver being a function of the intensity of the solar irradiance at a given point in time. Besides the current-voltage charts shown in figures 14 and 15, Kyocera publishes the following standard test condition (STC; 25C and 1000W/m^2) performance data for the KC130TM photovoltaic modules:

Maximum Power:	130W (+10%/-5%)
Maximum Power Voltage:	17.6V
Maximum Power Current:	7.39A
Open Circuit Voltage:	21.9V
Short Circuit Current:	8.02A

The maximum power (Watts = Volts x Amps) occurs at the knee of the current-voltage curve. What is not intuitive is if the load applied to a solar panel is reduced to near zero

amps, the voltage rises towards the open circuit voltage limit. This is because the total current draw affects the internal electrical field of the solar cell. This is why solar powered systems require special solar controllers to regulate voltage supplied to most electronic systems. For the ICCP system at PTA, the gel batteries require very specific charging voltages or they can become permanently damaged, and the ICCP system requires specific voltages to forestall the corrosion reaction.

Since voltage from a solar cell rises as the load decreases, the best way to assess the ICCP system in operation was to take voltage readings at various times to see how heavy or light a load was on the solar panels. Leratek spent several days at the PTA site examining the system and taking measurements without disrupting system performance. Measurements were taken of the battery voltage, the solar panel voltage, and the output voltage to the anode ground bed of the ICCP system. The battery voltage was as connected into the charging system – these batteries are considered fully charged at 12.85V as measured after being disconnected for a 24 hour period. When connected to a load/charging circuit, they are considered fully charged at 14.1V. Since Leratek could not shut down the system for this assessment, the measurements were taken in the connected system. A typical day's observations are shown in Figure 17.

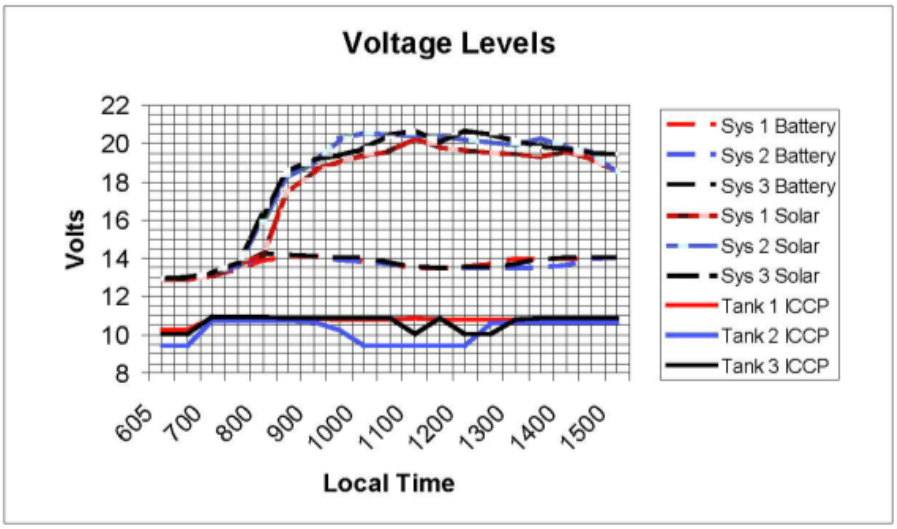


Figure 17: Measured voltage levels for batteries, solar panels, and ICCP systems at PTA during typical day. Sunrise was 0617 local time for this day.

Figure 17 shows that on this day, the battery banks were fully recharged (from nighttime drawdown) at 14.1 volts by 0800. The draw from the ICCP system is low – just under 1 amp per system during the survey – so once the batteries are charged from the night drawdown, the solar panels have little work to do. The steep rise in solar panel voltage after 0800 is evidence of both a very small electrical load on the panels as well as the increasing solar irradiance on the panel. This is certain evidence that the ICCP electronics (controllers, DC-

DC voltage converters, etc.) are highly efficient in that they do not, in and of themselves, load the panels enough to drop the voltage far from the open circuit voltage rating of 21.9V. Later in the afternoon, as the panel temperature increases due to solar heating, the voltage tapers off somewhat IAW Figure 14. The fact that the batteries were fully charged by 0800 during this assessment might lead to the mistaken conclusion that the solar array is oversized and needlessly expensive. As will be shown in later sections, the sizing of the solar array was driven by two design parameters; first to be able to charge the large battery arrays in a single day after up to 10 days of no solar power, second to prevent the large battery system from ever being deeply discharged. Preventing deep discharge dramatically increases battery life and hence reduces maintenance on this remote system.

To further assess the power efficiency of this system, consider the system state at 1100 hours. The solar panel voltage data from Figure 17 at 1100 hours gives an average voltage of the three panels as 20.4 V. From Figure 16, the solar irradiance at 1100 hours is approximately 1000 watts/m^2, which is the most that is counted upon during the day by the manufacturer of the panel. From Figure 14 at 1000 watts/m2, the open circuit voltage of this panel is 21.9V at 77F and 20V at 122F. At 1100 on the day the data was taken, the ambient temperature was 75F and the skies were clear; the sun is nearly overhead and the solar panels are almost certainly at a higher temperature than ambient temperature. Splitting the difference between the 122F curve and 77F curve, we will assume the panel temperature was at 100F. From Figure 14, at 20.4V, the curve gives a current of 1.5A splitting between the 77F and 122F curves. This is per photovoltaic module, and each solar panel has three modules for an output of 4.5A per solar panel. From Figure 14, from the knee of a 100F curve, the maximum power available from a photovoltaic module is approximately 7.5A @ 17V. For a panel, the maximum power available is 22.5A @ 17V. At 1100 hrs on the day this data was taken, the ICCP system was drawing exactly 1A at 10.81V. Power efficiency can now be calculated (converting all units to watts).

(4.5A)(20.4V) – (1A)(10.81V) (ICCP system) = 91.8W – 10.8W = 81W waste

The waste is attributed to losses in the Solar Power Cathodic Protection Unit regulating circuitry, small but uncertain amperage associated with float charging of the battery bank, and operation of the Watchdog monitoring/uplink system. The solar panels are capable of (22.5A)(17V) = 383W power output. 81W waste is 21% of the available power the panels can produce, **therefore this system was operating at 79% power efficiency with respect to the manufacturer's rated output of these photovoltaic modules.**

A final way to assess the efficiency is to multiply the efficiency ratings of the major components inside the Solar Power Cathodic Protection Units:

Prostar 30 controller: 95%
Omega II converter and circuits: 95%
Batteries (Deka 8G4DLTP): 85 – 95%

.95 x .95 x .85 to .95 = 76.7% - 85.7% efficient which checks well with observation.

Overall, the power efficiency of the Solar Powered ICCP system is excellent, with a demonstrated efficiency of 79% versus a calculated efficiency range of 76.7 % to 85.7%. This is power far in excess of that required to be available to the groundbed, but it allows large battery racks which ensure working of the ICCP system despite 10 days of negligible sunlight and allow long battery life.

3.3 CP System Requirements

Leratek shall evaluate the MEC installed system to determine and quantify how effectively and efficiently it meets the new PV powered CP systems requirements of 1) fewer PV modules, 2) high efficiency controllers, 3) powered systems which provide 5 to 10 days of autonomy (sunless days). In these systems, the batteries should be protected by a low voltage cutoff, which shuts down the controller before damage to the batteries occurs.

3.3.1 Fewer Photovoltaic (PV) modules

The number of solar panels required for the MEC installed system is determined by the maximum power requirement. The solar panel size and quantity will need to accommodate the maximum load. The most power that will be required of the solar panels is after 10 days of autonomy (sunless days) when the drawn down batteries must be re-charged.

The installed system utilizes three 130 Watt PV modules per cathodic protection unit. The modules are connected to each other in parallel forming a panel, thus a panel provides up to 390 Watts of power per cathodic protection unit. There are three units on site, therefore there are a total of nine 130 Watt PV modules (3 solar panels) on the roof as shown in Figure 18.

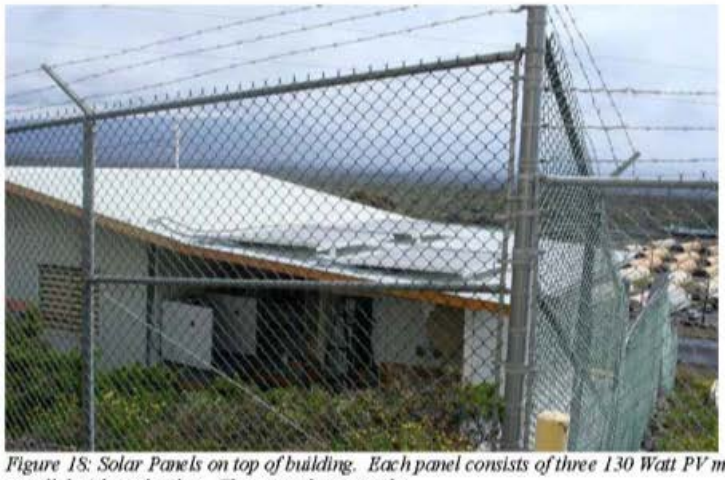


Figure 18: Solar Panels on top of building. Each panel consists of three 130 Watt PV modules connected in parallel with each other. There are three panels.

One 130 watt PV module is efficient for day-to-day operations if the sky is clear, however if there are 10 days without sun, a single 130 watt PV module won't be able to recharge the entire battery bank quickly or efficiently as shown below.

The charge needed for the batteries after 10 days of autonomy is 248.4 amps. This amount was calculated from measured data of 0.9 amps ICCP draw x 24 hours/ day x 10 days = 216 amps required by the ICCP system over 10 days. Per the battery datasheet (Appendix A), 105% to 115% of the total amps drawn is required to recharge the battery. Assuming the worst case of 115% recharge inefficiency, then 115% of 216 amps drawn = 248.4 amps required for recharge.

Three 130 watt PV modules are necessary. For example, the max current available from one PV module is 7.2 amps per hour, thus 7.2 x 12 hours/day of solar activity = 86.4 amps available from sunrise to sunset. However, the number of amps available needs to be at least 248.4 amps to fully charge the battery bank.

When PV modules are wired together in parallel to form a solar panel, their output current is tripled. Therefore, if one PV module has an output of 86.4 amps, then three paralleled together = 259.2 amps. This is enough to fully charge the battery bank back up after 10 days of autonomy. Granted, there is not 7.2 amps per hour for the entire 12 hour sunny day, but then there is no such thing as a day of zero solar power even in the worst weather condition. The analysis is sufficient to show that the correct number of 130 watt PV modules is 3, rather than 2 or 4.

The installed 390 watt solar panel consisting of 3 parallel 130 watt PV modules efficiently and effectively power the cathodic protection system and are sized to ensure the battery bank is charged after 10 days of autonomy. Any solar panel size higher or lower than 390 watts would be inefficient.

3.3.2 High Efficiency Controllers

A solar charge controller regulates the amount of power flowing from a solar panel to a rechargeable battery. It ensures the batteries are not overcharged nor deeply discharged. The controller installed in the system is a Prostar 30 by Morningstar shown in Figure 19.

Figure 19: PROSTAR-30 Solar Charge Controller.

The Prostar-30 controller is very efficient – rated at 95% efficiency due to its utilization of PWM (pulse width modulation) charging method. Some additional attributes that make this controller efficient is that it incorporates MOSFETs and self-regulates for temperature differences and voltage drops.

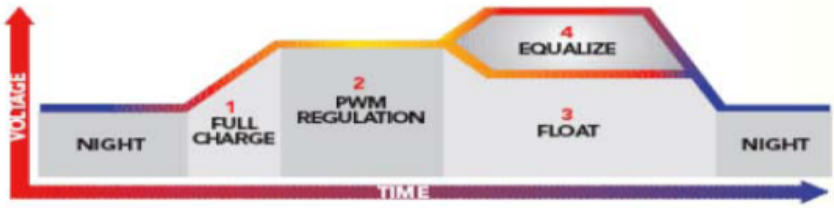
The controller manages four stages of charging during a day as shown in Figure 20. They are:

1) Full Charge: Recharging with 100% of available solar energy

2) PWM constant-voltage regulation to prevent heating and battery gassing

3) Float charging (also known as trickle charge)

4) Equalize – not used for gel batteries (Not Applicable)



Photovoltaic Charging Parameters		
Bulk Charge	Max Current (amps)	30% of 20 Hr Rate
Absorption (Regulation) Charge	Constant Voltage	2.35 - 2.40 vpc
Float Charge	Constant Voltage	2.25 - 2.30 vpc
Equalize Charge	Constant Voltage	2.40 - 2.45 vpc
Temperature Coefficient	0.005 mv / °C	

Figure 20: Prostar 30 charging stages and Deka battery charging parameters. There are 6 cells per battery; the rate in the third column (vpc) is volts per cell.

A load that exceeds available solar output will return the controller to the PWM mode. A controller that utilizes PWM battery charging is up to 30% more efficient than basic 'on-off' regulators as they reduce the charging current from the solar panels instead of stopping the charge altogether. This reduced charging current is slow enough to prevent the battery from overheating or gassing. The efficiency of PWM controllers is between 85 - 95%.

When in PWM mode, the current from the solar panels adjusts according to the batteries' condition and recharging requirement. During the site survey, an audible clicking was heard throughout the day. This clicking was the PWM function checking the battery status.

Although PWM charging is much more efficient than on-off regulation charging, there is one other type of controller that is even more efficient. This type of controller utilizes Maximum Power Point Tracking (MPPT). It sees efficiencies in 94% - 98% range. The cost is higher (almost double) for an MPPT controller. For this application however, the cost isn't worth the additional percentage as the Prostar 30 will sufficiently control the battery charge from the solar panels.

Overall, the installed controller, Prostar 30, is an efficient controller. The high efficiency comes in large part from its use of PWM charging, which has proven up to 97% efficient in other applications [6]. Lastly, this controller has a very low self consumption rate of 1 mA of current.

3.3.3 Batteries to provide 5 to 10 days of autonomy

The batteries used in the system are Deka solar gel batteries, 8G4DLTP model shown in Figure 21. They are 12V batteries rated at 210 ah (amp hours) each, and three are connected in parallel per cathodic protection unit for a total 630 ah. There are nine batteries on site (3 x 3 cathodic protection units).

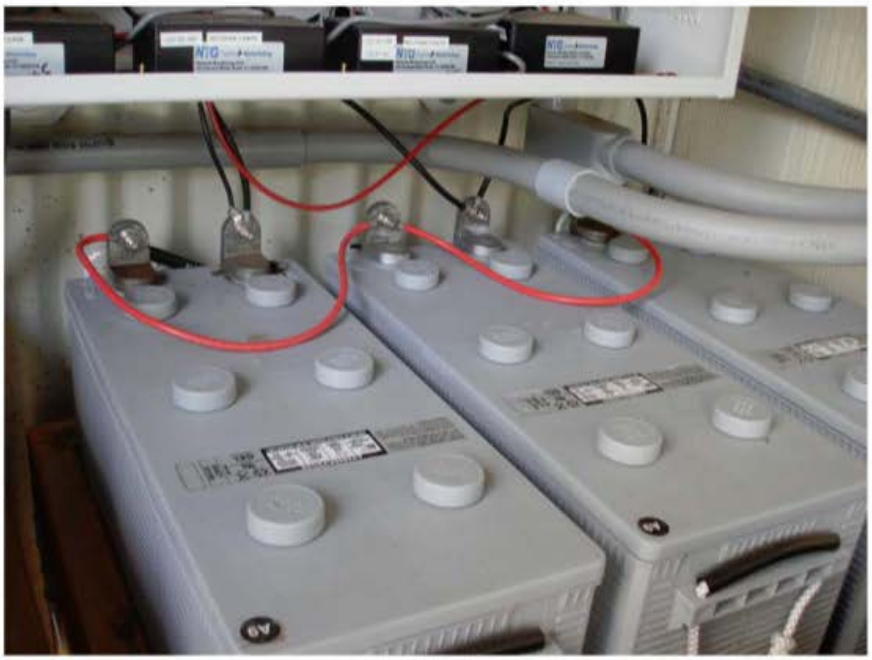


Figure 21: Deka Solar Batteries 8G4D. Each rectifier utilizes 3 batteries connected in parallel.

For 10 days of autonomy, the batteries are estimated to draw .9 amps per hour. From the battery datasheet (Appendix A), if the system was requiring 2.19 amps per hour, it would take 100 hours to fully discharge the battery. Since there are three batteries per cathodic protection unit, not one, and since they are connected in parallel, the total time to discharge triples to 300 hours.

Ten days is only 240 hours, so this means that even at a load requirement of 2.19 amps, which is almost double what is needed for the installed system, the batteries are well within the 10 days of autonomy requirement. The batteries are likely able to go for 15 days autonomously, however the solar panel requirement would increase to allow full charge following 15 days of darkness.

One note is that even in the dimmest daylight, the solar panels are producing power; they will always produce some power during a day, let alone 5 – 10 days. For remote locations that experience long periods of true darkness during the day, such as Alaska in the winter months, this requirement would be more valid. For Hawaii however, it is not realistic. Nevertheless, the installed batteries will be able to run the cathodic protection for 5 – 10 days without sun.

3.3.4 Low Voltage Cutoff

The installed system is protected by a low voltage cutoff within the controller. The Prostar 30 will disconnect the load off the batteries if they are going to be drawn past their minimum operating voltage. The voltage parameters for the controller are shown in Figure 22 and include the low voltage cutoff amount:

Battery Voltage Setpoints*

	Gel	Sealed	Flooded
Regulation Voltage	14.0	14.15	14.4
Float	13.7	13.7	13.7
Equalization	n/a	14.35	14.9/15.1
Load Disconnect	11.4	11.4	11.4
Load Reconnect	12.6	12.6	12.6

Note: values are for 12V. Use 2X for 24V and 4X for 48V.

Figure 22: Battery Voltage Setpoints for Deka Solar Batteries (Gel) [7]

Per the controller datasheet (Appendix A) and Figure 22, the load will be disconnected at 11.4 Volts and reconnected once the batteries have been charged back up to at least 12.6 Volts.

The low voltage disconnect for the system is current compensated to prevent false disconnect when the battery is heavily loaded.

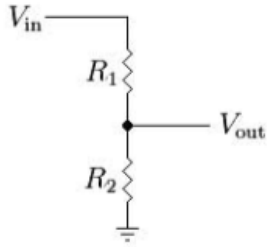
3.4 DC to DC Power

"Leratek shall evaluate the MEC installed system to quantify its performance and design as related to the efficient use of DC to DC converter components that gives conversion efficiencies in the area of 95%. No rheostats or dropping resistors would be used to lower the output voltage, thus saving the power dissipated in the traditional "rectifier" systems."

The installed system utilizes a DC to DC solar converter and feedback controller (patented Omega II design by JA Electronics) and associated MOSFET (metal-oxide semiconductor field-effect transistor) switching circuitry to step down the input voltage. A more common term for this type of circuit is a Buck Converter, which will be described in more detail.

A DC to DC converter essentially transforms DC voltage from one level to another. In the case of the installed system, the input voltage needs to be reduced from the relatively high voltage output of the solar panels and battery system (which can reach as high as 21.9 volts DC) down to the lower voltage required by the ICCP system (~10.5 volts DC).

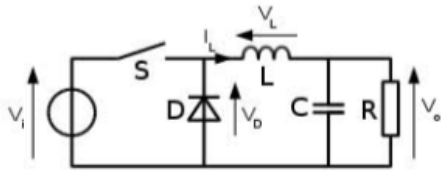
In the past, a traditional rectifier system would utilize a "voltage divider circuit" to reduce the input voltage as shown in Figure 23. A voltage divider circuit incorporates dropping resistors to reduce the current, thus reducing the voltage (per Ohm's law, V (volts) = I (current) x R (resistance)).



The voltage divider circuit equation is Vout = Vin x (R2 / (R2 + R1). Each of the resistors will have an associated power dissipated because of the current that is running through them. This power dissipated comes out in the form of heat, which is wasted energy.

Figure 23: Traditional Voltage Divider Circuit.

A better method to improve power efficiencies when dropping a voltage is using a buck converter circuit as shown in Figure 24. A buck converter circuit uses inductors and capacitors, in addition to a switch system (MOSFETs), to ensure there is no excess power wasted. Buck converters are a commercialized technology proven in industry to have conversion efficiencies of up to 95%.



In a buck converter, when the switch is closed, the inductor is getting fully charged as the difference between the input voltage and output voltage creates a current to flow and build up (V inductor = Vi – Vo).

Figure 24: Buck Converter Circuit. [8]

The diode in the circuit is reverse biased by the voltage source, so current is not allowed to flow through it. When the switch opens, the diode goes back to forward bias and the voltage across the inductor equals the negative output voltage (V inductor = 0 (for no Vi because of the diode) – Vo). Since the voltage drops, the current across the inductor discharges and reduces as well as shown in Figure 25.

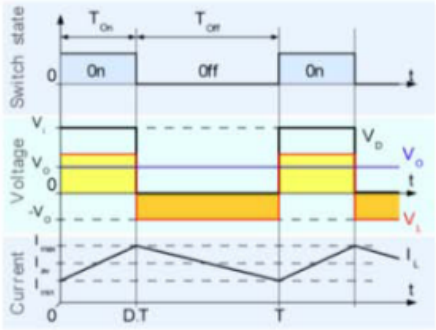


Figure 25: Switch state of Buck Converter. [8]

The switch is a MOSFET, which is a type of transistor as shown in Figure 26. A transistor is a solid piece of semiconductor material with three terminals for connecting to a circuit. A voltage or current applied to two of the three terminals affects the current flowing through the other pair. Transistors are used to either amplify signals or work as switches, turning current off and on. The MOSFET is a transistor used to switch and is very common in modern electronics because of its "gate" ability and use in electrical logic design (off and on states). A transistor schematic is below. For a MOSFET, the "Base" is called "Gate," the "Collector" is called the "Source," and the "Emitter" is called the "Drain." A voltage at the gate can control the current between the source and the drain.

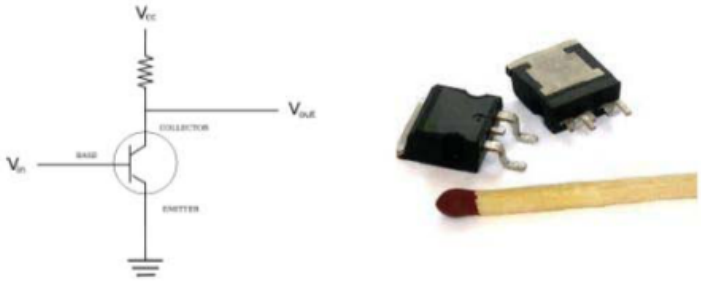


Figure 26: Transistor Junction with Terminology and two surface-mount MOSFETs. [9]

Feedback from the ICCP system reference electrode determines when a voltage is placed on the MOSFET gate, which will open or close the converter, which ultimately steps down the voltage – this is the DC/DC conversion.

As an example of the efficiency of DC to DC converter components, consider the MOSFET switch compared to dropping resistors in a voltage divider circuit. MOSFETs have very low internal resistance values (on the order of .015 Ohms). Thus, for a 1 Ohm resistor with a 12 V voltage drop, that dissipates 12 Watts of power (Watts = V x I). The same circuit with a MOSFET would dissipate 0.18 Watts of power.

For the installed system, the feedback comes back from the ICCP system reference electrode, through a feedback board, and into the converter circuitry. An input capacitor reduces voltage ripple to ensure a smooth signal. The signal goes through the MOSFET switch, which ultimately produces a current that will in-turn step the voltage down for use by the tanks.

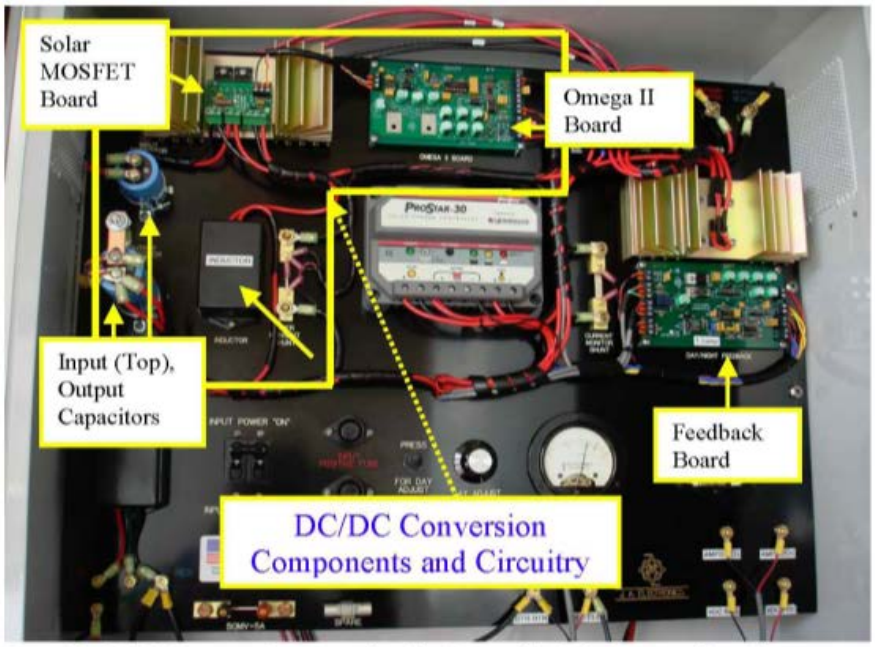


Figure 27: DC/DC Conversion Circuitry within Solar Powered Cathodic Protection Unit. The components that make up the converter include the OMEGA II controller board that receives info from the feedback board, an input and output capacitor, an inductor, and the MOSFET "switch" board.

Figure 28 is a close-up of the Omega II Board and Figure 29 is a close-up of the Solar MOSFET Board. The Omega II Board red indication light (LED) comes on when the MOSFET switch is on (indicating the inductor is building up voltage and current).

Figure 28: Close-up of Omega II Board. This board provides the controls on the feedback for the switching done on the MOSFET board (Figure 32).

Figure 29: Close-up of Solar MOSFET Board. Provides the converter switching.

3.5 Low Insolation

"Leratek shall evaluate the MEC installed system and design to determine how the requirement for the system to revert to battery storage or DC power such that no significant depolarization takes place during the period of low insolation is being met, or if it is applicable to the design requirements for this system."

Depolarization is observed when the current is no longer flowing through to provide cathodic protection to the system. In other words, depolarization occurs when the solar powered cathodic protection unit is turned off. The intent of this task is to show if there is a moment of system shut-off during low insolation, at which depolarization would occur. The answer is no.

Low insolation occurs during the night, so we took measurements on the system after a full evening of darkness and prior to sunrise. It was observed that during the period when the solar panels began to pick up the load, there was a seamless transition with no drop in power being supplied as shown in Figure 30. With no observed significant decrease in current, there would have been no depolarization.

In addition, slight low insolation occurred in the afternoon around 1:30pm. Again, a seamless transition from solar panels to batteries was observed, with no drop in current or volts.

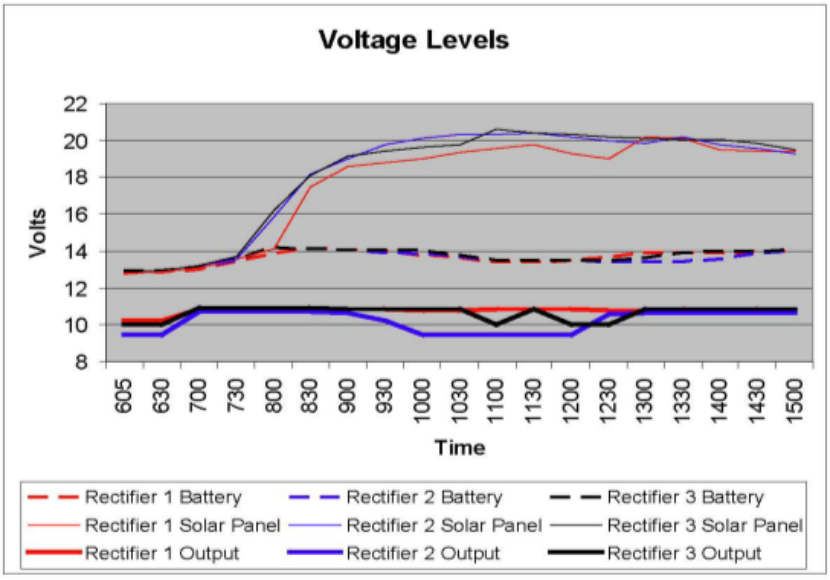


Figure 30: Voltage levels for Solar Panels, Batteries and Rectifier Output.

3.6 Remote Monitoring Unit

"Leratek shall evaluate the MEC installed system with controller and remote monitoring to determine its compliance with the following parameters being collected and used by the controller for operation of the system: 1) current output in impressed current mode, 2) corrosion potential of steel wall, 3) ICCP system operating voltage. In addition, the monitoring system should allow viewing of voltage and current being provided by the PV system and the status of the batteries and solar cells."

Remote monitoring units provide cathodic protection measurements, which are indicative of the effectiveness of the cathodic protection setup. The system installed at the site is an NTG, Inc. "Pipeline Watchdog Remote Monitoring Unit (RMU)." The system measures potential to soil, the supplied voltage, and the supplied current to the protected structure (tanks). In addition, the unit controls the times at which the system is measured, and furthermore can be set to poll on command online from the user – anytime, anywhere.

This system is well-designed for true remote monitoring and data collection of installed cathodic protection units in the most severe environments. In case of equipment malfunction, the unit sends an alarm by email and/or text message to the user and will automatically return to normal operation reporting, if able.

The Watchdog RMU works by receiving measurements directly off of small, self contained modules installed inside the solar powered cathodic protection unit on desired measurement points as shown in Figure 31.

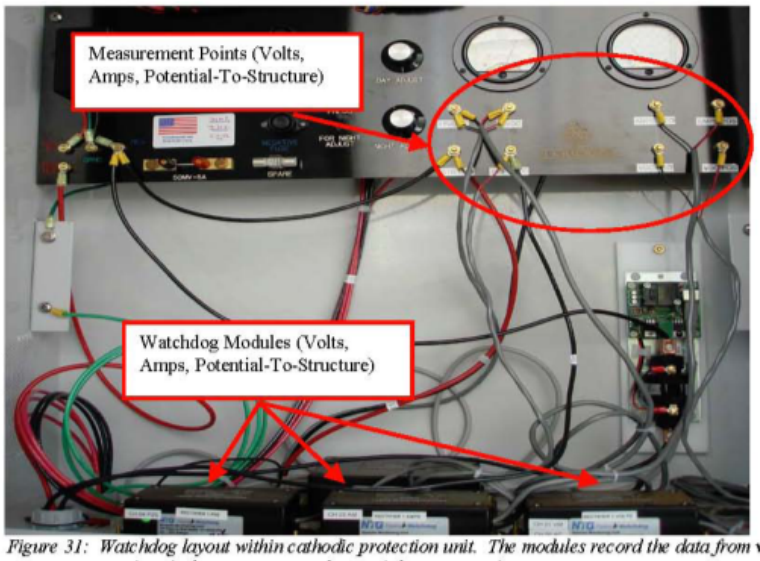


Figure 31: Watchdog layout within cathodic protection unit. The modules record the data from various measurement points (voltage, current and potential to structure).

These modules wirelessly transmit readings to the RMU base station, located within 100ft of the cathodic protection unit as shown in Figure 32. Since the base station is isolated from the units and modules, it is essentially immune to lightning strike damages and surges.

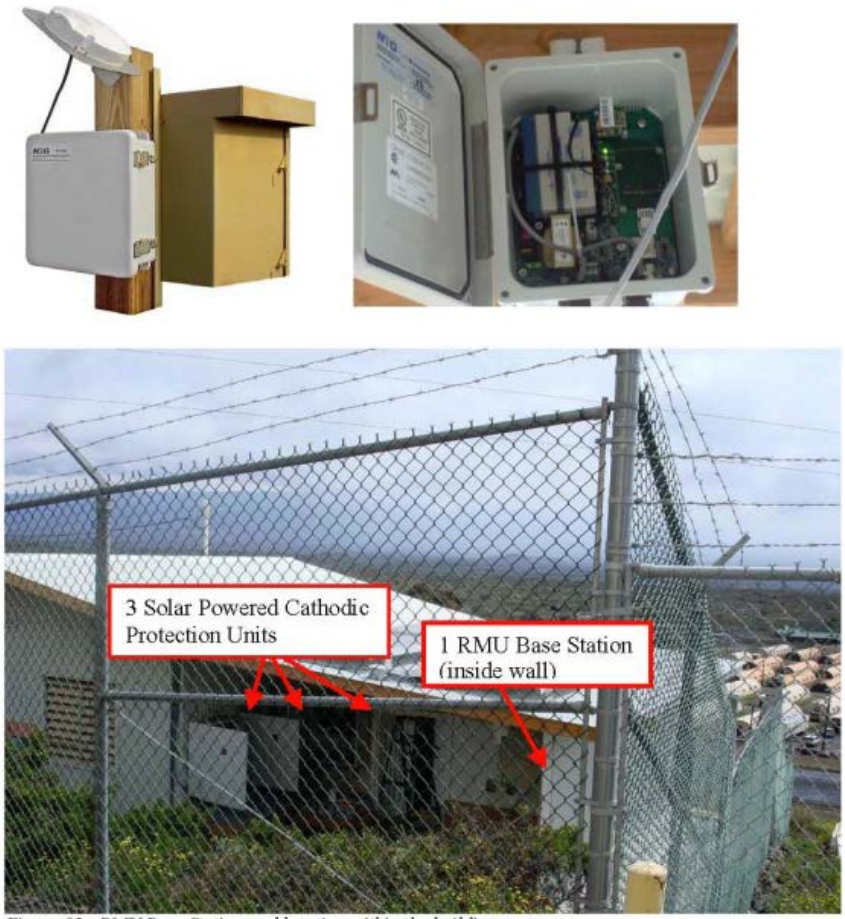


Figure 32: RMU Base Station and location within the building.

From the base station, data is transmitted and received via Skywave Inmarsat D+ satellite networks to NTG's secure Pipeline Watchdog monitor web server, where it is then available for user access.

To access the site online, each user must first enter their email address and password as shown in Figure 33.

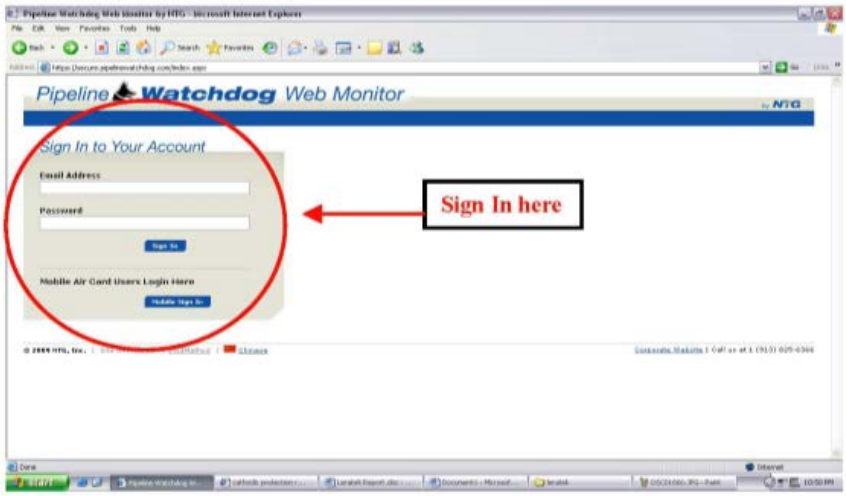


Figure 33: Watchdog Online Sign-In Screen.

Next, the user will be able to view a summary of all systems installed, with last measured data. In this case, there are three cathodic protection units (one for each tank). To monitor one, simply click its name as shown in Figure 34.

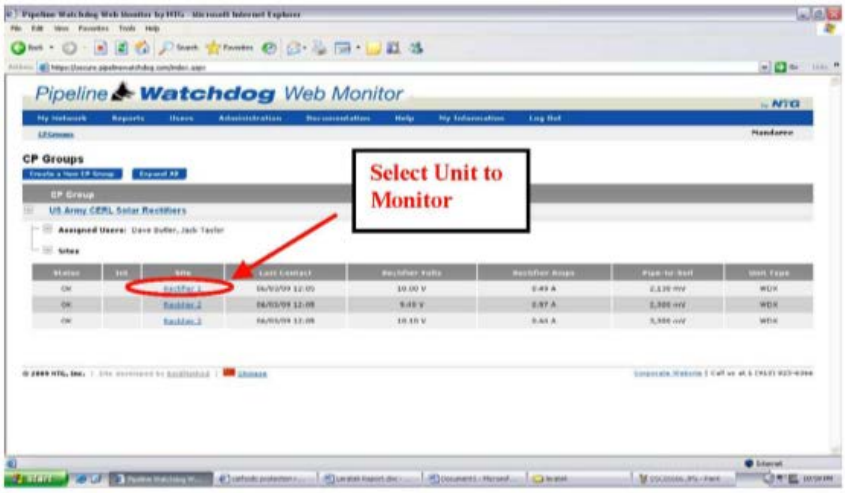


Figure 34: Watchdog Online Overview of Installed Sites and Equipment

Once selected, the unit's data will be displayed. From here, the user can poll the system for instant readings, view the latest site measurements, communication history, and information about the site (to include a satellite image of the location). As an example, and to verify this monitoring unit reports the data required for the installed system, the user would click on "View History" under "Latest Site Measurements" as shown in Figure 35.

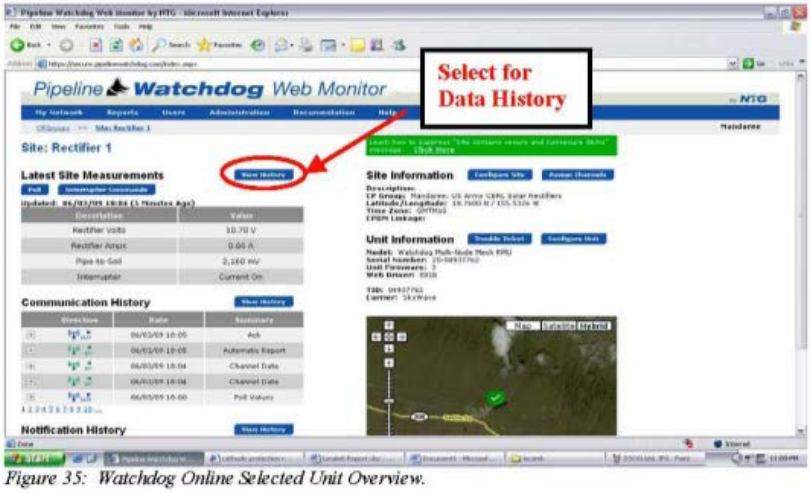


Figure 35: Watchdog Online Selected Unit Overview.

The next screen will come up, providing a complete history of data collected at scheduled intervals (set by the user) as shown in Figure 36.

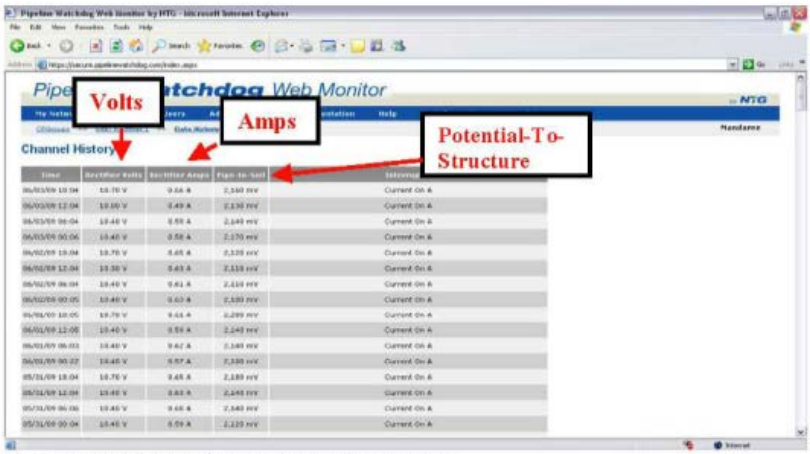


Figure 36: Watchdog Online Measurement Data History.

Current output in impressed current mode (impressed current cathodic protection (ICCP) is the type of cathodic protection used at this site), corrosion potential of the steel wall (the tanks), and ICCP system operating voltage were each verified at site with multimeters and consequently re-verified via the monitoring system on the web to ensure the readings were accurate. The Watchdog monitoring system accurately records and reports all of these parameters.

The status of the batteries and solar cells are not quickly or directly available (no Watchdog modules are directly connected to their measurement points). Because of the cathodic protection controller circuitry, if the batteries or the solar cells went lifeless, the circuitry would see this as low or no insolation for the case of the solar panels and remedy off of battery power, and vice versa with the batteries going dead. If the batteries went offline, the user should receive an error during "no sun" period because the solar panels will eventually fail to produce power as well. When no data is reported to the Watchdog recorders, an error will be issued to the user via email and displayed on the website.

Overall, the NTG Watchdog RMU offers reliable wireless communications for easy-to-use Internet access for monitoring and collecting data remotely. All settings can be changed online, to include alarm set points, reporting frequency, receipt and quantity of cathodic protection unit data reports. The data reports are format-selectable for easy import (i.e., .XLS, .XML, .CSV).

3.7 Battery Efficiency

"Leratek shall evaluate the MEC installed system to determine if or how much the battery bank is mitigating power loss."

Rechargeable batteries are not 100% efficient – some energy is lost as heat and chemical reactions when charging and discharging. If you use 1000 watts from a battery, it might take 1050 or 1250 watts or more to fully recharge it. [10]

The installed Deka batteries are true, deep cycle gel batteries. Gel batteries in general approach upwards of 98% efficiency [11]. Deep cycle batteries are required for this application as they are designed to be discharged over and over again, over many cycles before they are unusable. Gel batteries are maintenance free and can be mounted in any attitude since it's impossible to spill acid from them.

These batteries have solid lead plates and very low internal resistance. According to their technical specifications, if you used x amount of watts from the battery, it would require 105% to 115% to be put back in. In other words, if you used 100 watts from the battery, it would take 105 to 115 watts to fully recharge it. This equals a battery efficiency of 85% to 95%.

Compared to other types of batteries, such as NiCad which experience 65% efficiency [12], the Deka batteries installed are very efficient and in conjunction with the Prostar 30 controller, will minimize the amount of power lost.

3.8 Comparison to other systems

"Leratek shall research and identify other PV powered CP systems and provide technical information on these systems. Identify PV systems capable of use with the CP systems and provide technical information on them. Identify current battery technology that is best for use with PV powered cathodic protection systems and provide technical information. Assess the PV and battery power employed on the MEC installed system."

This task required Leratek to compare the solar panels, batteries, solar charge controller, and a DC-DC converter to competing CP systems.

The DC-DC converter within the installed system is part of a patented design called the Omega II. The converter utilizes buck converter technology, which has a standard efficiency of 95%. There were no readily available competitors against which to effectively compare the Omega II design as it is patented, however, the buck converter is a basic electrical circuit that is not difficult to manufacture.

Solar panels and batteries will be compared later in this section, so the focus on comparing cathodic protection systems will be centered on solar charge controllers.

Cathodic Protection System Controllers (Appendix C):

Brand	Model	Output V	Output A	Efficiency	Cost	Type
XC3	XC1230-LVD-M	0-24V	0-30A	93%	$199	PWM
Solar Converter Inc.	12/24-30	0-50V	0-30A	96%	$389	MPPT
Steca	PR 3030	6.9-17.2	0-30A	95%	$217	PWM
Morningstar	**Prostar 30**	**2-24V**	**0-30A**	**95%**	**$189**	**PWM**

Table 1: Comparison of Solar Charge Controllers.

The MPPT controller (section 3.3.2) is slightly more efficient; however the higher cost outweighs the 1% additional efficiency in terms of applying it to the system. PWM charging will be sufficient for the system. Overall, the installed Prostar 30 is the best value for its efficiency and price.

Some companies will build (package) the cathodic protection system for the user, based on load inputs and voltage/current requirements. The installed system at Pohakuloa, from JA Electronics, is one of these types of pre-packaged systems. The solar panels, batteries, controller, and converter were all selected by JA Electronics based on the requirement of preventing corrosion on the tanks. The dimension, calculated resistance, and other technical parameters were provided to JA Electronics to put together a cathodic protection system. Other companies that design cathodic protection units include SunWize, ETA Engineering, Inc., and SolarCraft, Inc. (Refer to Appendix B for more information on these alternative sources). The installed system by JA Electronics provides the same capability as these other sources; the other sources did not provide a feature that was significantly greater than what is

currently installed except perhaps a better housing for the battery banks. However, JA Electronics would be able to add that as an option if requested.

The next area of comparison is the solar panels. The table below compares four panels and shows their associated specifications.

Solar Panels (Appendix D):

Name	Max Power A	Max Power V	Max Wattage	Price	Solar Efficiency
Sun Electronics, SUN-HS-130	6.55	19.8	130	$657	19.7%
Sharp, ND130-UJF	7.5	17.4	130	$695	13.1%
Talco STP-130-12	7.55	17.2	130	$998	13.6%
Kyocera, KC130TM	**7.4**	**17.9**	**130**	**$517**	**16.1%**

Table 2: Comparison of Solar Panels.

The installed Kyocera, KC130TM panels are the best value; although they do not have the highest solar efficiency, they will produce more current at the maximum power point than the SUN-HS-130.

Last, the table below compares several battery types:

Batteries (Deep Cycle) (Appendix E):

Description	Voltage	AH at c/20	Type	Retail Price
BCI DC200-12	12	200	AGM	$499
MK Battery 8G8D	12	225	Gel	$675.00
Trojan J185AC	12	225	Flooded	$330
Deka 8G4D	**12**	**210**	**Gel**	**$575.00**

Table 3: Comparison of Deep Cycle Batteries.

The Deka battery is chosen the best because it is non-liquid, which is ideal for a remote site where a maintenance free battery is desirable. In addition, 210 amp hours is plenty for 10 days of autonomy, so even though the MK Battery offers 225 amp hours, the system doesn't need it.

As identified above in the bold print for each section, the installed system components are the best choice for providing corrosion protection on site when compared to similar products on the market.

4.0 CONCLUSION AND RECOMMENDATIONS

The MEC ICCP system installed at PTA is sufficiently providing cathodic protection to the potable water tanks, and should continue to protect for 20+ years with minimal maintenance. The system achieves all of its design goals:

- The solar powered cathodic protection units incorporate a positive ground system preventing ground loops and protecting electronics from lightning.
- The solar powered cathodic protection units efficiently utilize the available power from the solar panels, with a design efficiency range of 76-85% and a measured efficiency of 79%.
    - This is largely the result of using a high efficiency DC-DC converter.
- The system can easily function for over 10 days with zero sunlight on batteries alone, and the solar array is correctly sized to completely recharge the battery racks in a single day of good solar irradiance following the 10 days of zero sunlight.
- The batteries are gel cell batteries sized to prevent deep discharge and hence last for 3 times the life of conventional flooded lead acid batteries.
- Titanium mixed metal oxide ceramic anodes protect the water tank and will not require servicing for the lifetime of the system.
- The Watchdog monitoring system accurately records and sends the voltage, current, and Potential to Structure readings to the user using a satellite uplink to a website. The website is user-friendly and in addition to the already set schedule of reporting each cathodic protection unit's readings several times a day, the website allows the user to poll the site for on-the-spot readings. Furthermore, the Watchdog system will notify the user of any discontinuance or errors at the site with the setup.

Some recommendations:

1) Because the level of water in the tanks directly affects the ICCP system power being drawn, recommend installing an electronic reader/meter that records the water levels in the tanks, then connect this information into the Watchdog setup if feasible. Without this additional information, it may be difficult to conclude why the current level may suddenly drop without being on site. One can speculate, but water level readings would assist in effectively managing the operation of the cathodic protection system from a distance.

2) Seal/coat all electrical connections with exposed bare wire (to include the battery leads off the bank) with corrosion prevention compound (CPC) electrical paste and/or heatshrink wraps to ensure protection against environmental factors such as rain, salt in the air, etc.

3) If possible, reassess the performance of the installed system on an annual basis to ensure the setup is still operating as advertised and to check for corrosion on the electronic components and open metal (if not implementing recommendation 2).

4) Provide a technical manual for maintenance and servicing of the system to the operators of the water treatment facility, allowing them to perform the minimal maintenance required.

5.0 REFERENCES

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Glossary [14]

Ampere (amp) — A unit of electrical current or rate of flow of electrons. One volt across one ohm of resistance causes a current flow of one ampere.

Ampere-Hour (Ah/AH) — A measure of the flow of current (in amperes) over one hour; used to measure battery capacity.

Anode — The positive electrode in an electrochemical cell (battery). Also, the earth or ground in a cathodic protection system. Also, the positive terminal of a diode.

Battery — Two or more electrochemical cells enclosed in a container and electrically interconnected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels. Under common usage, the term battery also applies to a single cell if it constitutes the entire electrochemical storage system.

Battery Capacity — The maximum total electrical charge, expressed in ampere-hours, which a battery can deliver to a load under a specific set of conditions.

Battery Cell — The simplest operating unit in a storage battery. It consists of one or more positive electrodes or plates, an electrolyte that permits ionic conduction, one or more negative electrodes or plates, separators between plates of opposite polarity, and a container for all the above.

Cathode — The negative pole or electrode of an electrolytic cell, vacuum tube, etc., where electrons enter (current leaves) the system; the opposite of an anode.

Cathodic Protection — A method of preventing oxidation of the exposed metal in structures by imposing a small electrical voltage between the structure and the ground.

Cell Junction — The area of immediate contact between two layers (positive and negative) of a photovoltaic cell. The junction lies at the center of the cell barrier or depletion zone.

Charge — The process of adding electrical energy to a battery.

Charge Controller — A component of a photovoltaic system that controls the flow of current to and from the battery to protect it from over-charge and over-discharge. The charge controller may also indicate the system operational status.

Charge Rate — The current applied to a cell or battery to restore its available capacity. This rate is commonly normalized by a charge control device with respect to the rated capacity of the cell or battery.

Conversion Efficiency — See photovoltaic (conversion) efficiency.

Converter — A unit that converts a direct current (dc) voltage to another dc voltage.

Current at Maximum Power (Imp) — The current at which maximum power is available from a module.

Cutoff Voltage — The voltage levels (activation) at which the charge controller disconnects the photovoltaic array from the battery or the load from the battery.

Cycle — The discharge and subsequent charge of a battery.

DC-to-DC Converter — Electronic circuit to convert direct current voltages (e.g., photovoltaic module voltage) into other levels (e.g., load voltage). Can be part of a maximum power point tracker.

Deep-Cycle Battery — A battery with large plates that can withstand many discharges to a low state-of-charge.

Direct Current (DC) — A type of electricity transmission and distribution by which electricity flows in one direction through the conductor, usually relatively low voltage and high current. To be used for typical 120 volt or 220 volt household appliances, DC must be converted to alternating current, its opposite.

Discharge — The withdrawal of electrical energy from a battery.

Electric Circuit — The path followed by electrons from a power source (generator or battery), through an electrical system, and returning to the source.

Electric Current — The flow of electrical energy (electricity) in a conductor, measured in amperes.

Electrochemical Cell — A device containing two conducting electrodes, one positive and the other negative, made of dissimilar materials (usually metals) that are immersed in a chemical solution (electrolyte) that transmits positive ions from the negative to the positive electrode and thus forms an electrical charge. One or more cells constitute a battery.

Electrode — A conductor that is brought in conducting contact with a ground.

Electrolyte — A nonmetallic (liquid or solid) conductor that carries current by the movement of ions (instead of electrons) with the liberation of matter at the electrodes of an electrochemical cell.

Electron — An elementary particle of an atom with a negative electrical charge and a mass of 1/1837 of a proton; electrons surround the positively charged nucleus of an atom and determine the chemical properties of an atom. The movement of electrons in an electrical conductor constitutes an electric current.

Float Charge — The voltage required to counteract the self-discharge of the battery at a certain temperature.

Full Sun — The amount of power density in sunlight received at the earth's surface at noon on a clear day (about 1,000 Watts/square meter).

Gassing — The evolution of gas from one or more of the electrodes in the cells of a battery. Gassing commonly results from local action self-discharge or from the electrolysis of water in the electrolyte during charging.

Gel-Type Battery — Lead-acid battery in which the electrolyte is composed of a silica gel matrix.

Insolation — The solar power density incident on a surface of stated area and orientation, usually expressed as Watts per square meter or Btu per square foot per hour. See diffuse insolation and direct insolation.

Irradiance — The direct, diffuse, and reflected solar radiation that strikes a surface. Usually expressed in kilowatts per square meter. Irradiance multiplied by time equals insolation.

I-V Curve — A graphical presentation of the current versus the voltage from a photovoltaic device as the load is increased from the short circuit (no load) condition to the open circuit (maximum voltage) condition. The shape of the curve characterizes cell performance.

Load — The demand on an energy producing system; the energy consumption or requirement of a piece or group of equipment. Usually expressed in terms of amperes or watts in reference to electricity.

Low Voltage Disconnect — The voltage at which a charge controller will disconnect the load from the batteries to prevent over-discharging.

Maintenance-Free Battery — A sealed battery to which water cannot be added to maintain electrolyte level.

Maximum Power Point (MPP) — The point on the current-voltage (I-V) curve of a module under illumination, where the product of current and voltage is maximum. For a typical silicon cell, this is at about 0.45 volts.

Maximum Power Point Tracker (MPPT) — Means of a power conditioning unit that automatically operates the photovoltaic generator at its maximum power point under all conditions.

Open-Circuit Voltage (Voc) — The maximum possible voltage across a photovoltaic cell; the voltage across the cell in sunlight when no current is flowing.

Overcharge — Forcing current into a fully charged battery. The battery will be damaged if overcharged for a long period.

Parallel Connection — A way of joining solar cells or photovoltaic modules by connecting positive leads together and negative leads together; such a configuration increases the current, but not the voltage.

Photovoltaic(s) (PV) — Pertaining to the direct conversion of light into electricity.

Regulator — Prevents overcharging of batteries by controlling charge cycle-usually adjustable to conform to specific battery needs.

Resistance (R) — The property of a conductor, which opposes the flow of an electri current resulting in the generation of heat in the conducting material. The measure of the resistance of a given conductor is the electromotive force needed for a unit current flow. The unit of resistance is ohms.

Short-Circuit Current (Isc) — The current flowing freely through an external circuit that has no load or resistance; the maximum current possible.

Trickle Charge — A charge at a low rate, balancing through self-discharge losses, to maintain a cell or battery in a fully charged condition.

Volt (V) — A unit of electrical force equal to that amount of electromotive force that will cause a steady current of one ampere to flow through a resistance of one ohm.

Watt — The rate of energy transfer equivalent to one ampere under an electrical pressure of one volt. One watt equals 1/746 horsepower, or one joule per second. It is the product of voltage and current (amperage).

Appendix B: RMU Data

RECTIFIER # 1

TANK # 400

MANUFACTURER - J.A.Electronics

MODEL # PVCONBOX (SOLAR)

SERIAL # 2080915

DC RATING - 12 volt, 3 amp

LOCATION - office bldg.

Shunt 50 mV= 5 amp

DATE:	AS FOUND	AS LEFT	COMMENTS	SURVEYOR
3/19/2009	0 volts/ 0 amps	10.85 volts/ 1.06 amps	initial start-up	JT
3/20/2009	10.9 volts/ .96 amps	10.9 volts/ .96 amps	24 hour polarization check	JT
3/23/2009	10.9 volts/ .9 amps	10.9 volts/ .9 amps	72 hour polarization check	DB
4/9/2009	10.9 volts/ .55 amps	10.9 volts/ .55 amps	efficiency testing	LM
5/12/2009	10.3 volts/ .66 amps	10.3 volts/ .66 amps	periodic check	JT
6/29/2009	10.6 volts/ .69 amps	10.6 volts/ .69 amps	periodic check	JT
10/5/2009	10.5 volts/ .59 amps	0 volts/ 0 amps	de-polarization survey	JT
10/8/2009	0 volts/ 0 amps	10.6 volts/ .58 amps	end de-polarization survey	JT
12/4/2009	10.6 volts/ .79 amps	10.6 volts/ .79 amps	periodic check	JT
3/14/2010	10.5 volts/ .1.0 amps	0 volts/ 0 amps	de-polarization survey	JT
3/18/2010	0 volts/ 0 amps	10.5 volts/ .83 amps	end de-polarization survey	JT

TANK # 400	DATE	BASE	"ON"	"INSTANT OFF"	DELTA V	COMMENTS	SURVEYOR
Reference Electrode 1	3/19/09	-0.551	-2.160			initial start-up	JT
Reference Electrode 2	3/19/09	-0.560	-4.200			initial start-up	JT
Reference Electrode 1	3/20/09		-2.160	-1.020	0.469	24 hour polarization	JT
Reference Electrode 2	3/20/09		-3.960	-1.060	0.500	24 hour polarization	JT
Reference Electrode 1	3/23/09		-2.180	-1.030	0.479	72 hour polarization	DB
Reference Electrode 2	3/23/09		-3.980	-1.080	0.520	72 hour polarization	DB
Reference Electrode 1	4/9/09		-2.254	-1.060	0.509	efficiency testing	LM
Reference Electrode 2	4/9/09		-4.010	-1.090	0.530	efficiency testing	LM
Reference Electrode 1	5/12/09		-2.170	-.998	0.447	periodic check	JT
Reference Electrode 2	5/12/09		-3.970	-1.040	0.480	periodic check	JT
Reference Electrode 1	6/29/09		-2.220	-.950	0.399	periodic check	JT
Reference Electrode 2	6/29/09		-3.920	-.990	0.430	periodic check	JT
Reference Electrode 1	10/5/09		-2.160	-.980	0.429	de-polarization survey start	JT
Reference Electrode 2	10/5/09		-3.800	-1.020	0.460	de-polarization survey start	JT
Reference Electrode 1	10/8/09		-2.370	-.740	0.189	red- de-polarized potential	JT
Reference Electrode 2	10/8/09		3.990	-.730	0.170	red- de-polarized potential	JT
Reference Electrode 1	12/4/09		-2.220	-1.050	0.499	periodic check	JT
Reference Electrode 2	12/4/09		-3.730	-1.040	0.480	periodic check	JT
Reference Electrode 1	3/14/10		-2.280	-1.030	0.479	de-polarization survey start	JT
Reference Electrode 2	3/14/10		-3.880	-1.020	0.46	de-polarization survey start	JT
Reference Electrode 1	3/18/10		-2.370	-.817	0.266	red- de-polarized potential	JT
Reference Electrode 2	3/18/10		-3.920	-.816	0.256	red- de-polarized potential	JT

TANK # 400

Current (amp)	Anode 1	Anode 2	Anode 3	Anode 4	Anode 5	Anode 6	Anode 7	Anode 8	Anode 9	Anode 10	Anode 11	Anode 12	Anode 13	Anode 14	Anode 15	Anode 16	Anode 17	Anode 18	Survey or
3/19/2009	0.08	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.06	0.05	0.04	0.04	0.04	0.04	0.04	0.05	JT
TOTAL	1.04																		
5/12/2009	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	JT
TOTAL	0.66																		
6/29/2009	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	JT
TOTAL	0.69																		
10/5/2009	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	JT
TOTAL	0.54																		
12/4/2009	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	JT
TOTAL	0.73																		
3/14/2010	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	JT
TOTAL	0.87																		

RECTIFIER # 2

TANK # 401

MANUFACTURER - J.A.Electronics

MODEL # PVCONBOX (SOLAR)

SERIAL # 2080916

DC RATING - 12 volt, 3 amp

LOCATION - office bldg.

Shunt 50 mV= 5 amp

DATE:	AS FOUND	AS LEFT	COMMENTS	SURVEYOR
3/19/2009	0 volts/ 0 amps	10.78 volts/ 1.02 amps	initial start-up	JT
3/20/2009	10.7 volts/ .92 amps	10.7 volts/ .92 amps	24 hour polarization check	JT
3/23/2009	10.7 volts/ .9 amps	10.7 volts/ .9 amps	72 hour polarization check	DB
4/9/2009	10.6 volts/ .87 amps	10.6 volts/ .87 amps	efficiency testing	LM
5/12/2009	9.5 volts/ .56 amps	9.5 volts/ .56 amps	periodic check	JT
6/29/2009	10.7 volts/ .83 amps	10.7 volts/ .83 amps	periodic check	JT
10/5/2009	10.2 volts/ .64 amps	0 volts/ 0 amps	de-polarization survey	JT
10/8/2009	0 volts/ 0 amps	10.4 volts/ .69 amps	end de-polarization survey	JT
12/4/2009	10.4 volts/ .77 amps	10.4 volts/ .77 amps	periodic check	JT
3/14/2010	10.4 volts/ 1.02 amps	0 volts/ 0 amps	de-polarization survey	JT
3/18/2010	0 volts/ 0 amps	10.4 volts/ .8 amps	end de-polarization survey	JT

TANK # 401	DATE	BASE	"ON"	"INSTANT OFF"	DELTA V	COMMENTS	SURVEYOR
Reference Electrode 1	3/19/09	-.688	-2.580			initial start-up	JT
Reference Electrode 2	3/19/09	-.660	-3.860			initial start-up	JT
Reference Electrode 1	3/20/09		-2.370	-1.100	0.412	24 hour polarization	JT
Reference Electrode 2	3/20/09		-3.430	-1.070	0.410	24 hour polarization	JT
Reference Electrode 1	3/23/09		-2.580	-1.080	0.392	72 hour polarization	DB
Reference Electrode 2	3/23/09		-3.850	-1.050	0.390	72 hour polarization	DB
Reference Electrode 1	4/9/09		-2.595	-1.052	0.364	efficiency testing	LM
Reference Electrode 2	4/9/09		-3.810	-1.020	0.360	efficiency testing	LM
Reference Electrode 1	5/12/09		-2.500	-1.010	0.322	periodic check	JT
Reference Electrode 2	5/12/09		-3.880	-1.015	0.355	periodic check	JT
Reference Electrode 1	6/29/09		-2.470	-1.010	0.322	periodic check	JT
Reference Electrode 2	6/29/09		3.680	.960	0.300	periodic check	JT
Reference Electrode 1	10/5/09		-2.470	-.990	0.302	de-polarization survey	JT
Reference Electrode 2	10/5/09		-3.720	-1.000	0.340	de-polarization survey	JT
Reference Electrode 1	10/8/09		-2.660	-.690	0.002	red- depolarized potential	JT
Reference Electrode 2	10/8/09		-3.910	-.710	0.050	red- depolarized potential	JT
Reference Electrode 1	12/4/09		-2.510	-1.040	0.352	periodic check	JT
Reference Electrode 2	12/4/09		-3.710	-1.010	0.350	periodic check	JT
Reference Electrode 1	3/14/10		-2.450	-1.040	0.352	de-polarization survey	JT
Reference Electrode 2	3/14/10		-3.630	-.990	0.330	de-polarization survey	JT
Reference Electrode 1	3/18/10		-2.430	-.760	0.072	red- depolarized potential	JT
Reference Electrode 2	3/18/10		-3.730	-.777	0.117	red- depolarized potential	JT

TANK # 401

Current (amp)	Anode 1	Anode 2	Anode 3	Anode 4	Anode 5	Anode 6	Anode 7	Anode 8	Anode 9	Anode 10	Anode 11	Anode 12	Anode 13	Anode 14	Anode 15	Anode 16	Anode 17	Anode 18	Surveyed by
3/19/2009	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	JT
TOTAL	0.72																		
5/12/2009	0.05	0.05	0.04	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	JT
TOTAL	0.56																		
6/29/2009	0.07	0.06	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.03	0.03	0.04	0.04	0.04	0.04	JT
TOTAL	0.83																		
10/5/2009	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	JT
TOTAL	0.61																		
12/4/2009	0.05	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	JT
TOTAL	0.71																		
3/14/2010	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.04	0.04	0.04	0.04	0.04	0.04	JT
TOTAL	0.90																		

RECTIFIER # 3

TANK # 402

MANUFACTURER - J.A.Electronics

MODEL # PVCONBOX (SOLAR)

SERIAL # 2080917

DC RATING - 12 volt, 3 amp

LOCATION - office bldg.

Shunt 50 mV= 5 amps

DATE:	AS FOUND	AS LEFT	COMMENTS	SURVEYOR
3/19/2009	0 volts/ 0 amps	10.8 volts/ 1.21 amps	initial start-up	JT
3/20/2009	10.9 volts/ 1.01 amps	10.9 volts/ 1.01 amps	24 hour polarization check	JT
3/23/2009	10.8 volts/ .95 amps	10.8 volts/ .95 amps	72 hour polarization check	DB
4/9/2009	10.1 volts/ .72 amps	10.1 volts/ .72 amps	efficiency testing	LM
5/12/2009	10.1 volts/ .68 amps	10.1 volts/ .68 amps	periodic check	JT
6/29/2009	10.9 volts/ .95 amps	10.9 volts/ .95 amps	periodic check	JT
10/5/2009	10.5 volts/ .7 amps	0 volts/ 0 amps	de-polarization survey	JT
10/8/2009	0 volts/ 0 amps	10.6 volts/ .73 amps	end de-poarization survey	JT
12/4/2009	10.6 volts/ .85 amps	10.6 volts/ .85 amps	periodic check	JT
3/14/2010	10.5 volts/ 1.06 amps	0 volts/ 0 amps	de-polarization survey	JT
3/18/2010	0 volts/ 0 amps	10.5 volts/ .85 amps	end de-poarization survey	JT

TANK # 402	DATE	BASE	"ON"	"INSTANT OFF"	DELTA V	COMMENTS	SURVEYOR

Reference Electrode 1	3/19/09	-0.650	-3.450			initial start-up	JT
Reference Electrode 2	3/19/09	-0.629	-4.460			initial start-up	JT
Reference Electrode 1	3/20/09		-3.610	-1.090	0.440	24 hour polarization	JT
Reference Electrode 2	3/20/09		-4.680	-1.060	0.431	24 hour polarization	JT
Reference Electrode 1	3/23/09		-3.590	-1.080	0.430	72 hour polarization	DB
Reference Electrode 2	3/23/09		-4.640	-1.050	0.421	72 hour polarization	DB
Reference Electrode 1	4/9/09		-3.582	-1.061	0.411	efficiency testing	LM
Reference Electrode 2	4/9/09		-4.620	-1.030	0.401	efficiency testing	LM
Reference Electrode 1	5/12/09		-3.460	-1.014	0.364	periodic check	JT
Reference Electrode 2	5/12/09		-4.630	-1.026	0.397	periodic check	JT
Reference Electrode 1	6/29/09		-3.390	-.940	0.290	periodic check	JT
Reference Electrode 2	6/29/09		-4.280	-.960	0.331	periodic check	JT
Reference Electrode 1	10/5/09		-3.440	-1.010	0.360	de-polarization survey	JT
Reference Electrode 2	10/5/09		-4.390	-1.000	0.371	de-polarization survey	JT
Reference Electrode 1	10/8/09		-3.690	-.740	0.090	red- depolarized potential	JT
Reference Electrode 2	10/8/09		-4.590	-.740	0.111	red- depolarized potential	JT
Reference Electrode 1	12/4/09		-3.360	-1.030	0.380	periodic check	JT
Reference Electrode 2	12/4/09		-3.990	-1.020	0.391	periodic check	JT
Reference Electrode 1	3/14/10		-3.320	-1.030	0.380	de-polarization survey	JT
Reference Electrode 2	3/14/10		-4.160	-1.010	0.381	de-polarization survey	JT
Reference Electrode 1	3/18/10		-3.450	-.789	0.139	red- depolarized potential	JT
Reference Electrode 2	3/18/10		-4.420	-.788	0.159	red- depolarized potential	JT

TANK # 402

Current(amp)	Anode 1	Anode 2	Anode 3	Anode 4	Anode 5	Anode 6	Anode 7	Anode 8	Anode 9	Anode 10	Anode 11	Anode 12	Anode 13	Anode 14	Anode 15	Anode 16	Anode 17	Anode 18	Surveyed by
3/19/2009	0.07	0.06	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.05	JT
TOTAL	0.92																		
5/12/2009	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	JT
TOTAL	0.68																		
6/29/2009	0.07	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.05	JT
TOTAL	0.95																		
10/5/2009	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	JT
TOTAL	0.65																		
12/4/2009	0.06	0.05	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.03	0.03	0.04	0.04	0.04	0.04	JT
TOTAL	0.81																		
3/14/2010																			JT
TOTAL																			

Appendix C: Cost Breakdown for Economic Analysis

HELCO rates, January 2009 – January 2010

Cost Adjustment	Rate	Total
11.387	19	30.387
7.958	15.57	23.528
8.64	16.25	24.89
6.647	14.26	20.907
6.529	14.14	20.669
6.67	14.28	20.95
8.041	15.65	23.691
9.236	16.85	26.086
10.524	18.13	28.654
11.143	18.75	29.893
10.214	17.82	28.034
9.97	17.58	27.55
11.485	19.1	30.585
Average Rate		25.83261538

System costs

PV-CP System	$82,766.00
Shipping	$1,500.00
Equipment Rental	$1,740.00
Labor & Travel	$77,547.00
Total	$163,533.00
ICCP System	$47,474.00
Shipping	$1,500.00
Equipment Rental	$1,740.00
Labor & Travel	$49,524.00
Total	$100,238.00

System cost savings

Energy Savings	$347.74
Powerline Right-of-Way Maint	$7,500.00
Total	$7,847.74

ICCP Power	10	3	30	W
Duty Cycle			24	h
Power Generated			720	Wh
			0.72	kWh per day
			262.8	kWh per year

Annual Rate Increase		15.00%	
Year	Rate	Power Use	Cost
1	25.83261538	262.8	$67.89
2	29.70750769	262.8	$78.07
3	34.16363385	262.8	$89.78
4	39.28817892	262.8	$103.25
5	45.18140576	262.8	$118.74
6	51.95861663	262.8	$136.55
7	59.75240912	262.8	$157.03
8	68.71527049	262.8	$180.58
9	79.02256106	262.8	$207.67
10	90.87594522	262.8	$238.82
11	104.507337	262.8	$274.65
12	120.1834376	262.8	$315.84
13	138.2109532	262.8	$363.22
14	158.9425962	262.8	$417.70
15	182.7839856	262.8	$480.36
16	210.2015834	262.8	$552.41
17	241.7318209	262.8	$635.27
18	277.9915941	262.8	$730.56
19	319.6903332	262.8	$840.15
20	367.6438832	262.8	$966.17
		20-year total	$6,954.70
		Annual average	$347.74

HELCO Power Lines Installation		
Cost	$9,000.00	per 300 feet
	$30.00	per foot
Distance	1	mile
	5,280	feet
Total Cost	$158,400.00	

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14. ABSTRACT

This project demonstrated an application of photovoltaic (PV) technology to power cathodic protection (CP) systems for water tanks at Pohakuloa Training Area (PTA), HI. An impressed-current CP system was installed on each of three water tanks in isolated locations, where connecting with the local power grid would be expensive. The demonstrated system, powered only by PV arrays with a battery backup, uses ceramic anodes and includes a satellite-based remote-monitoring capability. This system provides uniform and reliable cathodic protection in the water tanks interior below the water line. Data collected by the remote monitoring system can be loaded into a spreadsheet, and performance can then be analyzed on a pass-fail basis.

The installed PV-powered CP systems operate as designed and conform to NACE SP 0169 criteria. It is expected that little maintenance will be needed to keep the system operating properly. Required maintenance will include periodic cleaning solar arrays and monthly recording of electrical output using a digital meter. Once every year, a qualified CP specialist should survey the system to ensure proper CP levels.

15. SUBJECT TERMS
corrosion prevention, cathodic protection, photovoltaic technology, evaluation, energy conservation, Pohakuloa Training Area

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