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DoD Corrosion Prevention and Control Program

Demonstration of Electro-Osmotic Pulse and Dehumidification Technologies to Mitigate Corrosion in Earth-Covered Magazines

Final Report on Project F08-AR23

Michael K. McInerney, Orange S. Marshall Jr., Lawrence Clark,
Christopher Olaes, Paul Noyce and Patrick Reedy

September 2019

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Demonstration of Electro-Osmotic Pulse and Dehumidification Technologies to Mitigate Corrosion in Earth Covered Magazines

Final Report on Project F08-AR23

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Final report

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Under Project F08-AR23, "Demonstration of EOP and DH Technologies to Mitigate
Corrosion in Earth Covered Magazines"

Abstract

The Department of Defense (DoD) maintains many earth covered magazines (ECMs) on its installations including tropical coastal marine properties. ECMs are used to store a wide variety of explosive ordnance. Coastal marine locations are exposed to extreme humidity, high rainfall, and a chloride-infused atmosphere. These conditions create a damp, highly corrosive environment inside ECMs and can severely damage the structures and their contents, and promote mold growth that is hazardous to human health. The objective of this demonstration project was to install and evaluate electro-osmotic pulse (EOP) and dehumidification (DH) technologies in an Army ECM on Guam to mitigate water intrusion and excessively high interior relative humidity (RH), respectively. The demonstration was intended to evaluate how effective this technology combination is at reducing corrosive and unhealthy conditions inside an ECM.

Demonstration results were promising but mixed. The DH system held interior RH to 40%–60% while outdoor RH ranged from 85%–95%. However, the demonstration period was not long enough for the EOP system to reach equilibrium and fully stop seepage. Because the EOP success metric could not be validated for purposes of calculating the project return on investment, the reported return is based only on DH system performance.

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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 FO8-AR23, “Electro-Osmotic Pulse and Dehumidification Technologies for Prevention of Corrosion of Munitions and Equipment in Ammunition Bunkers in Kawakami, Japan and in Guam.” The technical monitor was Robert A. Herron (OUSD(A&S), Materiel Readiness, Corrosion Policy and Oversight).

The project was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research Center, Construction Engineering Research Laboratory (ERDC-CERL). Significant portions of this work were performed by Mandaree Enterprise Corporation (MEC), Warner Robins, GA; Electro Tech CP; and J&B Modern Tech, Harmon, Guam. At the time this report was prepared, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Michael K. McInerney, CEERD-CFM, was the ERDC CPC Program Coordinator. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Lance D. Hansen.

The following personnel at U.S. Navy Ordnance Station, Guam, are gratefully acknowledged for their support and assistance in this project:

- Mr. Larry E. Reisher, Explosives Safety Officer, Navy Munitions Command, East Asia Division, Headquarters
- Mr. Camarin M. Salas, Ordnance Facilities Manager, Navy Munitions Command, East Asia Division, Unit Guam

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

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1 Introduction

1.1 Problem statement

The Department of Defense (DoD) operates and maintains hundreds of earth-covered magazines (ECMs) in many locations worldwide. These structures are designed for storage of a wide variety of explosive ordnance, including bullets, artillery rounds, artillery rockets, fuzes, shaped charges, hand grenades, pyrotechnics, and air defense artillery. The general form of a representative ECM is shown in Figure 1. Military personnel sometimes refer to ECMs as *igloos* or *bunkers*.

Figure 1. ECM 12AC20 at Guam.

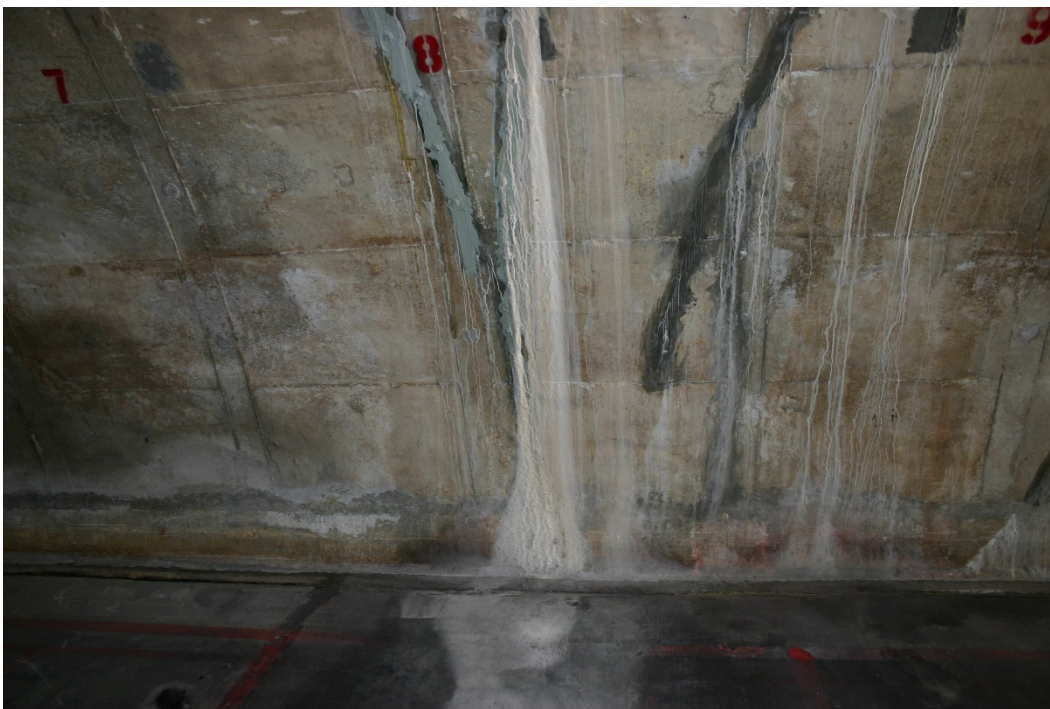


Military installations located in warm marine coastal environments are continually exposed to very high ambient humidity, a chloride-infused atmosphere, and high annual rainfall. These combined conditions promote accelerated corrosion that is highly destructive both to reinforced concrete ECMs and their military-critical contents. This damage is caused by water intrusion through ECM floors, walls, and seams, and by the high ambient humidity that is captured inside the unconditioned structures; ambient high temperatures can accelerate the damage. Aggressive corrosion of a magazine's steel reinforcement materials weaken it enough over time to require premature structural rehabilitation. Figure 2 and Figure 3 illustrate water-intrusion problems in ECMs.

Figure 2. Water intrusion on floor, at left and background, in ECM 12AC20 at Guam.



Figure 3. Water intrusion through cracks in ECM 12AC20 at Guam.



The high interior humidity also contributes to poor air quality for military personnel, civilian employees, and contractors working in these confined spaces. Mold and bacteria growth are promoted, which can aggravate asthma, allergies, or other respiratory conditions. Interior moisture also attracts termites, which can quickly consume wooden pallets and packaging stored in the ECMs.

To keep stored munitions dry, the Army uses desiccant material in shipping and storage containers. Army practice does not typically specify the use of DH technology in storage structures, and often the ECM interior environment becomes too humid for the provided desiccant to effectively control. Munitions stored in such conditions may become inoperable or unsafe for use in the field.

The conventional solution for preventing seepage into ECMs is to encapsulate them with waterproof membranes before placing soil over them. In a previous study of ECM water intrusion, the cost of performing this task was estimated to be \$500K for three ECMs at Fort A.P. Hill, VA (Marshall 2009). Those ECMs are smaller than many operated by DoD, including the ones that were originally included in the demonstration proposal for the current project. Furthermore, it was estimated that the membranes at Fort A.P. Hill would have to be replaced every 15 years.

Electro-osmotic pulse (EOP) and DH technologies offer the potential to actively reduce atmospheric corrosion of munitions and ECM structures. Previously, two ECM moisture reduction projects were conducted at Fort A.P. Hill: one to evaluate EOP technology (Marshall 2009), and one to evaluate dehumidification technology (McInerney, Marshall, and Gintert 2018). The results of those projects were inconclusive because Fort A.P. Hill was determined not to be a highly corrosive environment. In the demonstration/validation project reported here, the research team proposed to install both an EOP and DH system in a selected ECM in a highly corrosive marine environment to demonstrate and validate the efficacy of using both technologies concurrently to reduce magazine interior RH and stop moisture seepage into the structural concrete.

The ECM selected for the initial project proposal was located at Kawakami Ammunition Depot, on the southern mainland of Japan. However, this ECM was found to be unsuitable for demonstrating EOP technology. The concrete floor was found to be electrically conductive due to metal content,

which would cause a short circuit between anodes and prevent the system from producing an electric field with its paired cathode. Therefore, a new demonstration ECM had to be selected. A more detailed explanation of this issue is provided below under “Scope” (section 1.5).

1.2 Objective

The objective of this project was to demonstrate and validate the capabilities of EOP and DH systems, used in combination, to keep ECM structural concrete and interior spaces dry where the environment is very wet, humid, and aggressively corrosive.

1.3 Approach

After an unsuccessful attempt to apply this technology combination at Kakawami Ammunition Depot in Japan, the project was begun again at the Guam Ordnance Annex with the installation of EOP and DH systems in ECM 12AC20. Temperature and humidity probes also were installed in the ECM and monitored by a master control unit (MCU) at 24-hour intervals. Surface moisture data were collected at several locations inside the ECM.

1.4 Metrics

The metric for validation of this technology solution is informed by practical expert guidance (Lloyd n.d.) for preventing corrosion of stored materials through control of relative humidity (RH):

Most atmospheric corrosion can be prevented by maintaining RH below 60%. Desiccators and dehumidified stores can therefore be used for storage. In storerooms and warehouses it is important to maintain the air temperature at a reasonable level and to avoid large variations in temperature; a fall in temperature overnight or at the weekend may lead to heavy condensation of moisture. Condensation may also occur if massive metal parts are placed while cold into a warm room if the air is not saturated at the prevailing temperature. Stoves and gas heaters must be provided with adequate flues. The air in store cupboards may be dried by the use of desiccants or by refrigerating plant. For special purposes, including display cabinets, where it is essential to ensure immediate access to complex equipment refrigerated surfaces may be the most practical means of protection.

From these observations, the research team set the upper range of acceptable interior RH at 60% for purposes of corrosion prevention. Based on the authors' expertise in electrical and electronics engineering, the lower range for interior RH was set at 40%; if the RH falls below that limit, the possibility of electrostatic charge buildup begins to increase, and that would create the possibility of electrostatic discharges that could damage ECM contents or create an explosion hazard. The target RH range is also optimal for human health because it makes the ECM interior less favorable for the growth of molds, fungi, and bacteria inside.

The moisture content of the interior concrete was measured with a Protimeter* moisture probe, an instrument that determines the moisture of building materials using electrical conduction. The device used for this project was a two-pin model that allows the user to either push the pins deep into a material or lightly press the pins against the surface. In a previous ERDC study (McInerney, et. al. 2002) the Protimeter was shown to be an effective quantitative measurement device for concrete moisture, and a relationship was developed between Protimeter readings and actual % moisture content. The target range for Protimeter concrete measurements is below 17%.

The metrics for success are a reduction in the interior %RH and of moisture content of the interior concrete as measured in terms of electrical continuity using the Protimeter device.

1.5 Scope

The demonstration of EOP and DH at Kawakami had to be terminated early because the selected ECM was found to have an electrically conductive floor. Metal content in the floor interfered with activation of the electro-osmosis process by short-circuiting the anodes before they could establish an electric field with the cathodic electrodes. Attempts by the research team to mitigate or resolve the problem were not successful, so the demonstration at Kawakami was concluded early to focus on the demonstration at Guam.

* Protimeter is a product line of Amphenol Advanced Sensors, Wallingford, CT.

2 Technical Investigation

2.1 Project overview

EOP technology has previously been demonstrated to mitigate water intrusion into ECMs (Marshall 2009). A summary of the results of that demonstration is shown in Table 1. In addition to evaluating moisture intrusion, a series of explosives safety tests was performed following recommendations of the Army Technical Center for Explosives Safety and EOP operational and design requirements.

Table 1. Summary of EOP evaluation results.

Metric	Result
Spark potential of steel arch	None
Spark potential of metal pallets on floor	None
Spark potential between metal pallets and steel arch	None
Hydrogen generation potential	None
Cathodic protection of steel-reinforcing	Protected when majority of current is to rebar
Lightning protection	No adverse interference
Electromagnetic frequency production	Not detectable
Radio frequency production	Not detectable
Water intrusion	None

The effectiveness of DH technology in reducing interior humidity in ECMs has also previously been evaluated (McInerney, Marshall, and Gintert 2018). The performance of the DH systems was evaluated by recording the moisture levels inside the test ECMs for a period of one year. The demonstration confirmed that the DH systems could control the ECM interior RH, limiting it to a relatively constant value of about 40% while the outdoor RH was usually well above 60%. In the magazines without DH, used as an experimental control, the RH fluctuated greatly and many times rose above 60%.

2.2 EOP technology

EOP technology exploits the phenomenon of electro-osmosis to move water contained in concrete by applying a pulsating electric field to the structure. One set of electrodes is embedded just below the surface of a structure's concrete floors, walls, or ceilings, and another set is placed either in the surrounding soil or—if the concrete is thick—deep in the concrete itself. A pulsing direct current (DC) voltage is applied to anodic electrodes, which establishes an electric field that permeates the concrete cross-section in reaching the cathodic electrodes. The positive electrical pulse causes cations (e.g., Ca^{++}) and water molecules surrounding them to move from the dry, interior side (anode) toward the wet, exterior side (cathode). The system is designed to move water against the direction of flow driven by the local hydraulic gradient, thus preventing water penetration through a buried or submerged concrete structure. Figure 4 illustrates the general electro-osmotic process, and Figure 5 illustrates what occurs at the pore level.

Figure 4. Diagram of EOP process in a concrete structure.

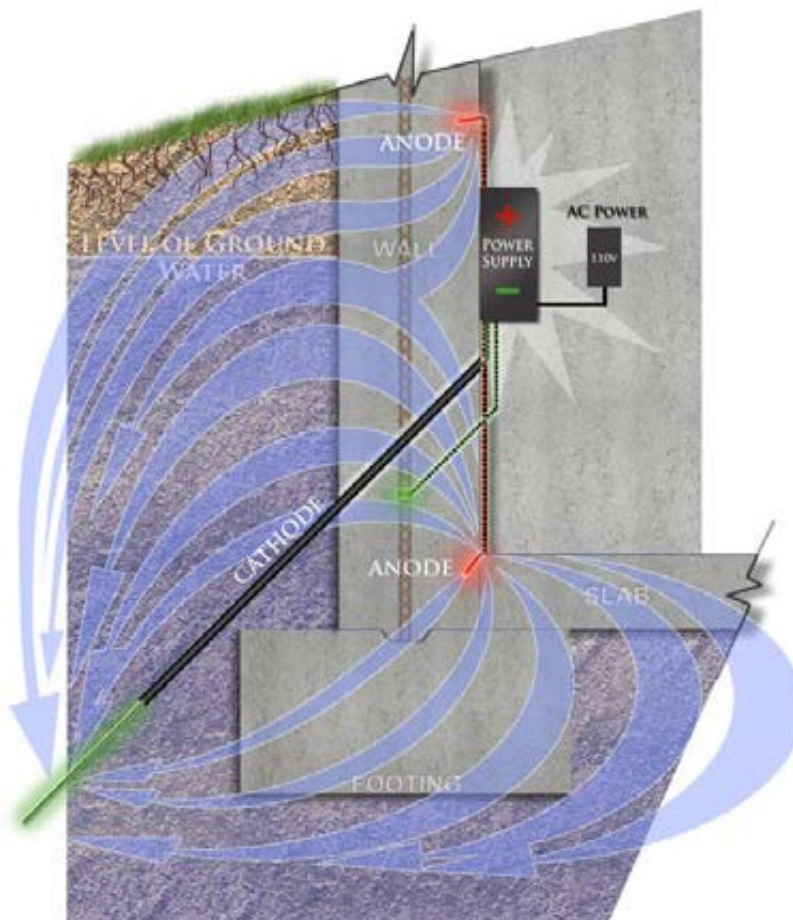
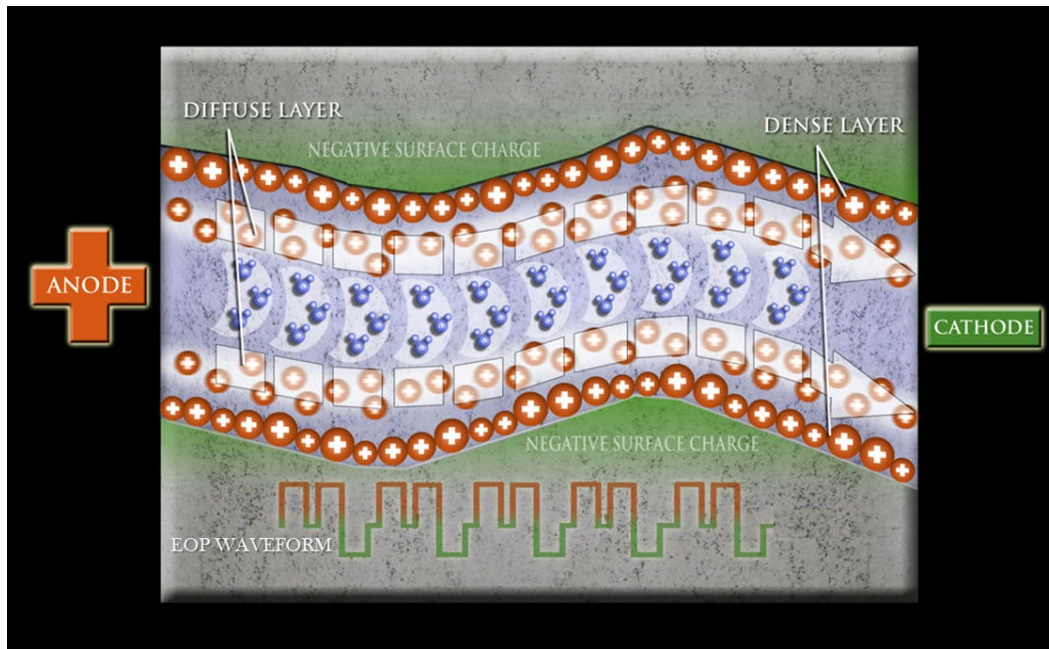


Figure 5. Illustration of electro-osmotic process in a concrete pore. During the electrical positive pulses (highlighted in orange on the EOP waveform) the water is moved from the anode to the cathode.



EOP system design, installation, and commissioning for ECM 12AC20 are described in Appendix A. As-built drawings are presented in Appendix B.

2.3 DH technology

DH is a mature technology that has been demonstrated to prevent corrosion of critical assets stored in closed structures. It is commercially available in many different configurations and sizes for various applications. The two common types of DH technology remove water vapor from the space using either mechanical/refrigeration or a desiccant material that absorbs humidity in the conditioned space. Either type of system can be designed to operate as open-cycle or closed-cycle systems.

2.3.1 Compressor-driven refrigeration

Mechanical-refrigeration dehumidifiers are the most common type. They operate by using a fan to draw warm, moist air over a refrigerated evaporator coil, which condenses atmospheric moisture (i.e., humidity) into liquid water that drains away or is otherwise removed. The chilled, dehumidified air is then rewarmed by the condenser coil and released into the conditioned space. This type of dehumidifier differs from a standard air conditioner in that both the evaporator and the condenser are placed in the

same air path. A standard air conditioner transfers heat energy out of the room because its condenser coil releases heat outside. However, since all components of the dehumidifier are in the same room, no heat energy is removed.

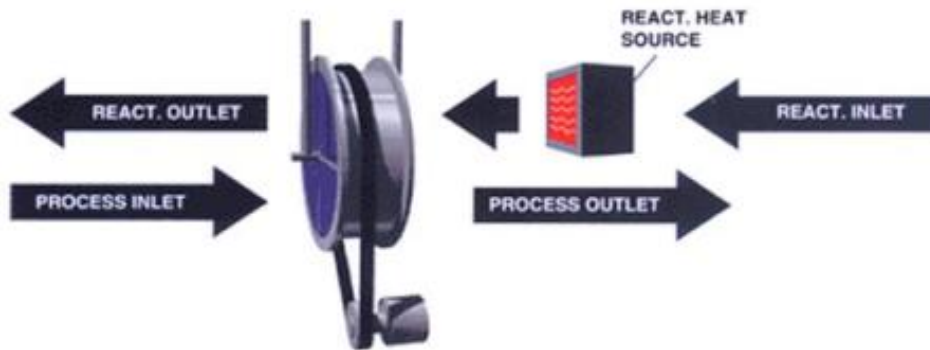
An *open-cycle* refrigeration system draws in air from outside the conditioned facility and removes humidity. A *closed-cycle* system recirculates interior air, removing humidity that may enter through leaks in the building envelope or the use of doors in typical facility operations. An inherent problem with closed-cycle systems is that any outgassing from stored propellants or volatile chemicals will tend to concentrate inside the conditioned space, presenting potential safety or health risks to facility users.

2.3.2 Desiccant systems

Desiccant dehumidifiers do not use compressors, so they are generally lighter and quieter than compressor-driven systems. Desiccant dehumidifiers also can extract humidity from cooler air than can compressor dehumidifiers because they absorb water vapor from air that is below the lowest effective temperature rating for refrigeration DH systems. Therefore, the project team specified a desiccant DH system for this demonstration.

A desiccant system uses a highly effective humidity-absorbing material, such as silica gel, packed into a drumlike cartridge. Because the desiccant material becomes saturated with absorbed moisture during the DH process, the system includes a reactivation capability to dry out the desiccant medium and return it to service. In reactivation, the medium is exposed to a stream of heated air to remove the water before another dehumidification cycle. A typical system will periodically rotate the saturated desiccant out of service using mechanical means and heat to drive off the moisture. After reactivation, the hot, dry desiccant rotates back into the process air stream that cools the desiccant so it can begin the absorption process again. Figure 6 shows a conceptual illustration of the cycle.

Figure 6. Conceptual illustration of desiccant DH process.



The configuration shown in Figure 6 can be used in a closed-cycle system, which is the most efficient design for most desiccant DH applications because it does not bring humid outdoor air into the building. However, a closed-system design was considered undesirable for an ECM due to possible explosive or toxic outgassing from stored ordnance. Consequently, the researchers designed an open-cycle system to prevent the accumulation of hazardous gases inside the ECM. Both the process inlet air source and the desiccant reactivation inlet air is drawn in from outside.

The DH system design, installation, and commissioning for ECM 12AC20 are described in Appendix C.

3 Discussion

3.1 Results

3.1.1 EOP system

Concrete moisture was measured before the EOP system was energized and at two times following system activation—after 6 days and after 363 days. Surface moisture was measured with the Protimeter probe at 32 locations around the interior of the magazine: 16 on the floor (8 each on the left and right sides) and 16 on the walls (8 each on the left and right walls). Moisture measurements for the entire demonstration period are listed in Table 2.

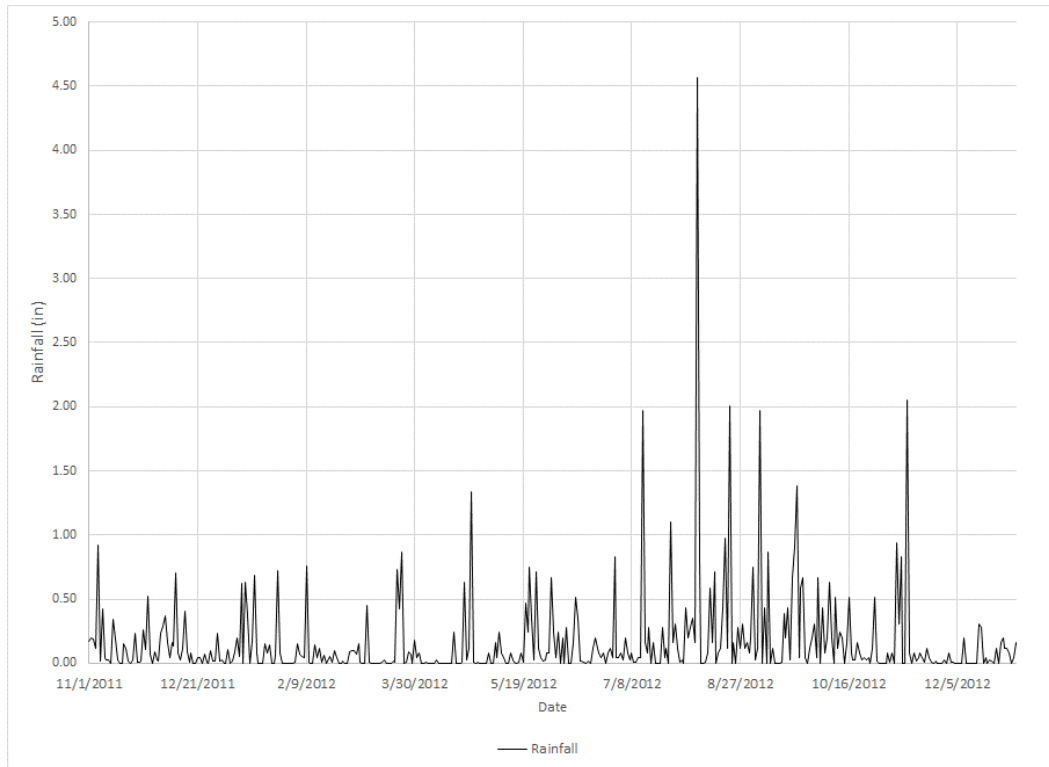
Table 2. Concrete surface moisture data taken on Day 0, Day 6, and Day 363.

Surface Moisture							
ECM 12AC20							
	12/13/2011	12/19/2011	12/10/2012		12/13/2011	12/19/2011	12/10/2012
Location Left				Location Right			
Floor				Floor			
1	22.4	15.7	11.4	1	20.7	16.0	20.8
3	20.8	14.5	20.6	3	23.1	14.2	20.3
5	20.2	15.7	19.8	5	16.9	17.1	20.6
7	20.5	18.1	19.6	7	21.1	18.6	17.0
9	22.4	16.6	20.7	9	21.4	12.7	20.0
11	20.0	15.2	22.5	11	21.3	11.3	11.8
13	18.3	17.3	20.0	13	19.8	17.1	15.7
15	24.4	19.4	22.0	15	22.4	18.4	11.7
Wall				Wall			
1	16.9	14.6	11.7	1	12.5	9.3	11.6
3	13.2	9.6	12.4	3	14.4	9.3	12.1
5	17.1	9.2	15.0	5	12.9	9.4	14.5
7	23.7	20.5	13.0	7	13.3	9.4	17.6
9	24.6	19.5	11.4	9	13.2	9.9	18.3
11	18.1	10.0	11.5	11	12.2	9.3	6.1
13	16.1	9.3	12.4	13	12.4	9.3	12.5
15	18.2	17.1	13.3	15	13.4	10.5	14.5

A plot of local rainfall data from 1 November 2011 through 1 January 2013 for Guam is shown in Figure 7. *

* Weather data are from Weather Underground (www.wunderground.com). The location is Guam Agana, GU-Guam International Airport (PGUM). Guam International Airport is within 13 miles of the naval base and on the same side of the island.

Figure 7. Thirteen-month rainfall data for Guam International Airport.



The moisture measurements in Table 2 indicate a slight reduction in surface moisture over time. The electro-osmotic process is slow and it can take several months to reach equilibrium. Rainfall data show that the area experienced several major rainfalls during the months preceding the December measurements. These rainfall events would have affected the EOP system by increasing the soil moisture around the magazine and, correspondingly, the exterior concrete moisture. The resulting ground saturation would have impeded the EOP moisture-removal process. Also, the December RH measurement values may have climbed due to DH system filter clogging. This problem is described under “DH system” in the next section (3.1.2), and under “Lessons Learned” in section 3.2.

3.1.2 DH system

The ECM temperature and humidity data were downloaded after 6 and 12 months of operation (Figure 8). These data show the system maintaining the RH in the 40% to 60% range until mid-May 2012. During this same period the outdoor humidity ranged from 85% to 95% (Figure 9).

Figure 8. Twelve-month temperature and RH data for ECM 12AC20 interior. Temperature data is black (82 °F to 94 °F), RH data is blue (30% to 100%).

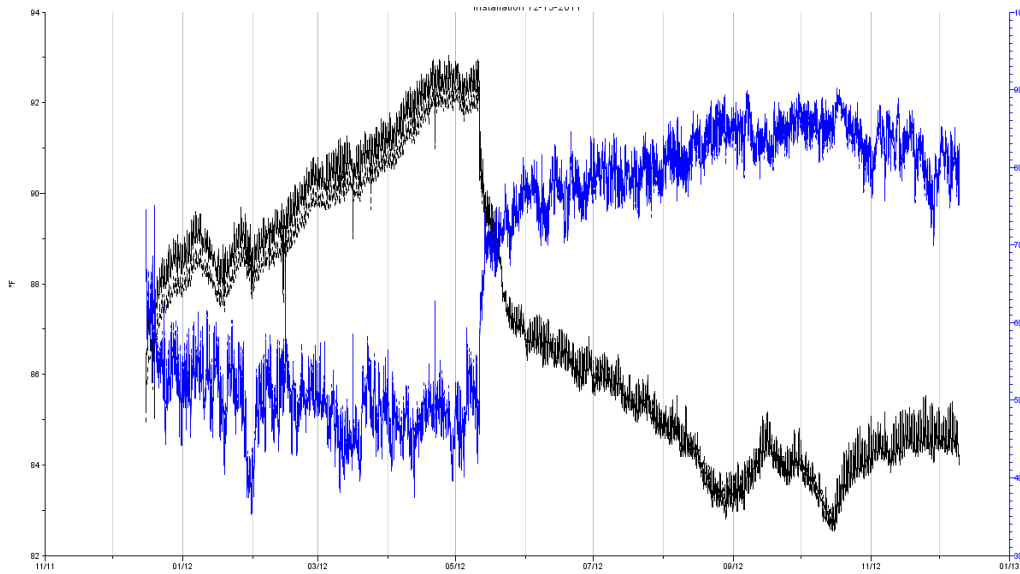
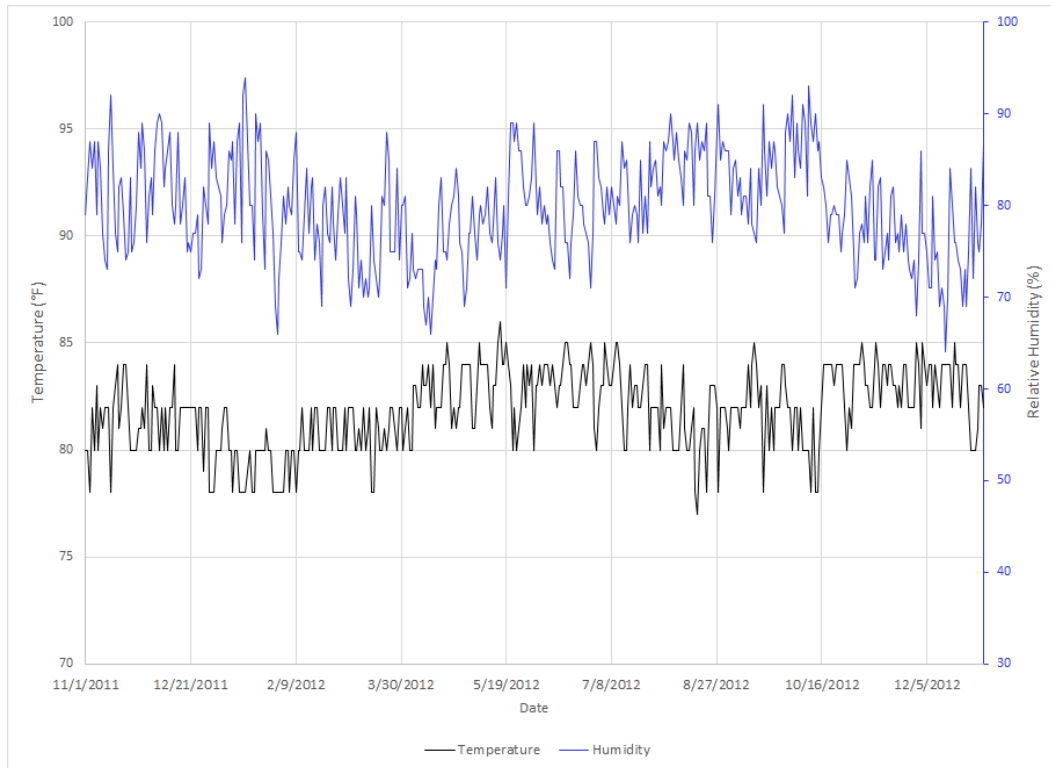


Figure 9. Thirteen-month temperature and RH data for Guam International Airport. Temperature data is black, RH data is blue. *



* Weather data for Guam Agana, GU-Guam International Airport (PGUM). www.weatherunderground.com.

At the six-month interval, the air intake filter (Figure 10 and Figure 11) was found to be clogged. The filter was cleaned, and system performance appeared to recover. Later, at the twelve-month inspection, the air exhaust filter (Figure 12) also was found to be clogged. Since the exhaust filter is in the reactivation air stream, when it clogged it prevented the desiccant material from being reactivated, shutting down the dehumidification process. Both filters were cleaned and the system began to operate properly. The degree the filters were clogged can be seen in Figure 11.

The clogged input filter may also have been affecting the temperature in the magazine. From Figure 8 we see that as the intake filter became clogged the temperature in the magazine rose. Then, after the intake filter was cleaned, the temperature in the magazine returned to being only a few degrees above the outdoor temperature. This change occurred because the DH unit once again began to bring in fresh air without obstruction of the intake filter.

Figure 10. DH unit intake filter shown in operating position.

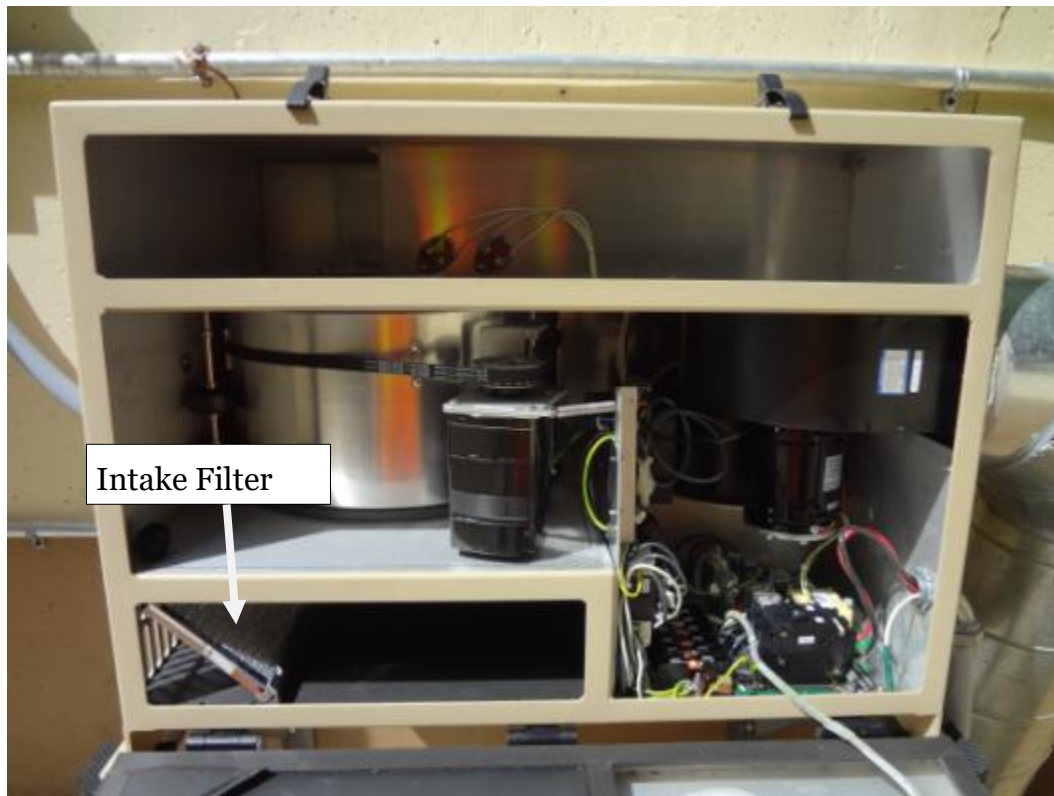


Figure 11. Clogged intake filter (removed for photograph).



Figure 12. Exterior view DH unit exhaust filter (debris accumulated inside filter housing).



The dehumidification system at the Guam ECM was shown to be able to maintain the RH in the magazine between 40% and 60% in an extremely humid environment where the outdoor humidity range is 85% to 95% and system operation was unimpeded by filter clogging.

3.2 Lessons learned

DH units mounted directly to the ECM offer gains in cost effectiveness for installation. For future applications, headwall DH units should be considered as alternatives to central DH units with long ducts. Depending on the number of magazines, size of magazines, and site-specific issues, it may be more cost-effective (either immediately or when operating costs are considered) to mount DH units on the ECM headwall.

The performance difficulty encountered in the Guam DH implementation was not in the installation, but in operations. Windblown debris consisting mostly of twigs and grass clogs the intake and exhaust filters to such an extent that the equipment cannot function according to specifications. The installed DH unit is capable of performing and achieving the required reduction of RH in the demonstration ECM, but the filters require more frequent inspections and maintenance to avoid reduction in system performance.

4 Economic Summary

4.1 Costs and assumptions

Total project costs were \$1,256,000. A rough breakdown of project expenses is presented in Table 3. If the non-contract project costs are spread equally between the Guam and Kawakami locations, then the total costs for Guam are \$204,475 (\$121,800 + \$37,275 + \$45,400) and for Kawakami are \$1,051,525 (\$619,125 + \$387,000 + \$45,400).

Table 3. Breakdown of total project costs.

Description	Amount
Labor	\$50,800
Materials	-----
Contract (Japan EOP)	\$619,125
Contract (Guam EOP)	\$121,800
Contract (Japan DH)	\$387,000
Contract (Guam DH)	\$37,275
Travel	\$20,000
Reporting	\$15,000
Air Force and Navy participation	\$5,000
Total	\$1,256,000

The Guam field demonstration costs for this CPC project are shown in Table 4 and Table 5.

Table 4. Project field demonstration costs for Guam EOP System.

Item	Description	Amount
1	Labor	\$24,850
2	Travel	\$22,500
3	Materials	\$58,300
4	Equipment	\$16,150
	Total	\$121,800

Table 5. Project field demonstration costs for Guam DH System.

Item	Description	Amount
1	Labor	\$6,921
2	DH Unit	\$14,844
3	Materials	\$14,110
4	Equipment	\$1,400
	Total	\$37,275

Two technicians and one supervisor were required to install the EOP system in ECM 12AC20. A project manager and engineer provided technical support. A total of 303 labor hours, including time spent to travel, was used to accomplish the installation. This ECM was 80 ft x 25 ft x 12 ft high. About 659 linear feet of anode material was installed: 185 ft in the floor/footer construction joint, 100 ft in the floor construction joints, 160 ft in the wall/footer construction joint, and 214 ft in the ceiling cracks. The cost of installation was therefore about \$184.83 per linear foot.

Two technicians and one supervisor were required to install the DH system in ECM 12AC20. A project manager was utilized for technical support. The total cost of installation of the DH system at Guam was \$37,275.

Baseline costs (Alternative 1), new system costs (Alternative 2), and new system benefit cost savings (Alternative 2) are listed in Table 6. Description of the costs are given in the following paragraphs.

Table 6. Costs (in \$) used in ROI computation.

	Baseline				New System Cost (EOP)				New System Cost (DH)				New System Benefit				
	Install	Maintain	Replace	Total	Installation	Operate	Maintain	Total	Installation	Operate	Maintain	Total	Replace	Overhaul	Damage	Training	Total
1	278,400			278,400	1,555		1,555		2,270		2,270		10,000		1,000		11,000
2		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
3		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000		1,000	20,000	66,000
4		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
5		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		66,000
6		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
7		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000		1,000	20,000	66,000
8		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
9		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
10		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		68,000
11		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
12		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000	2,000	1,000	20,000	68,000
13		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
14		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
15		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
16	278,400			278,400	1,555	10,000	11,555		20,000	2,270		22,270	45,000		1,000	20,000	66,000
17		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
18		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
19		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
20		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000	2,000	1,000	20,000	13,000
21		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
22		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
23		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
24		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
25		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000		1,000	20,000	66,000
26		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
27		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000		1,000		11,000
28		1,000		1,000	1,555		1,555		2,270	1,500	3,770		10,000	2,000	1,000		13,000
29		1,000		1,000	1,555		1,555		2,270	1,500	3,770		45,000		1,000	20,000	11,000
30	278,400			278,400	1,555	10,000	11,555		20,000	2,270		22,270	10,000	2,000	1,000		13,000

4.1.1 Alternative 1 (Baseline scenario using membrane enclosure)

A membrane protective system is assumed to prevent the same water intrusion-related corrosion damage as an EOP system. However, humidity-related condensation was observed in untreated magazines, so assumptions about the DH performance of membrane-only systems are likely to be optimistic.

The cost to remove the soil cover and add a moisture-impermeable membrane is estimated to cost about \$278,400. These systems are estimated to have a 15-year service life and \$1,000 in annual maintenance expenses.

4.1.2 Alternative 2 (Installation of EOP and DH systems)

For computing the ROI, the following assumptions are made about EOP system operation costs:

- The estimated annual cost of electricity to operate the EOP system is \$1,555 per year (18,000 kW-hrs per year at \$0.08639/ kW-hr).
- Annual maintenance costs of the EOP system are negligible.
- Major maintenance, including possible power supply replacement, will be necessary every 15 years at a cost of \$10,000.

The following assumptions are made about DH system operation costs:

- The estimated annual cost of electricity to operate the DH system is \$2,270 per year (26,280 kW-hrs per year at \$0.08639/kW-hr).
- The estimated annual DH system maintenance and repair costs are \$1,500 per year.
- The expected service life of a DH unit is 15 years (assuming annual system maintenance as prescribed), and the cost to replace the DH unit and rehabilitate other system components is estimated to be \$20,000.

Initial purchase and installation of the EOP and DH units is not included in year one of the ROI computation because those units are included in the project costs.

Installation of EOP and DH systems will provide \$2,000 of cost avoidance every other year for corrosion-related maintenance and repair of doors and hardware in the magazines, and \$1,000 of cost avoidance every year

for water cleanup and losses to pallets and other dunnage required to keep materiel stored in the magazines dry.

In addition, with the membrane system, heavy prolonged rains could result in up to \$35,000 in losses to materiel stored in the magazines and \$20,000 in delayed or lost training due to moisture infiltration and very high humidity. These losses would be avoided by using EOP and DH systems. It was assumed a heavy rain event occurs about every 5 years.

Annual savings on maintenance and repair of desiccant material and gaskets on storage containers would amount to about \$10,000.

These avoidance costs are listed under New System Benefit in Table 6.

4.2 Projected return on investment

The return on investment (ROI) for this technology was computed using methods prescribed by Office of Management and Budget (OMB) Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Comparing the costs and benefits of the two technology alternatives, the 30-year ROI is projected to be 3.28, as shown in Table 7.

**Table 7. ROI computation.
Return on Investment Calculation**

Investment Required	204,475
Return on Investment Ratio	3.28
Percent	328%
Net Present Value of Costs and Benefits/Savings	78,072
	749,376
	671,304

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	278,400		3,825	11,000	3,575	270,473	266,898
2	1,000		5,325	13,000	4,651	12,228	7,577
3	1,000		5,325	66,000	4,347	54,692	50,345
4	1,000		5,325	13,000	4,062	10,681	6,618
5	1,000		5,325	66,000	3,797	47,771	43,974
6	1,000		5,325	13,000	3,548	9,328	5,780
7	1,000		5,325	66,000	3,316	41,721	38,405
8	1,000		5,325	13,000	3,099	8,148	5,049
9	1,000		5,325	11,000	2,896	6,527	3,631
10	1,000		5,325	68,000	2,707	35,073	32,366
11	1,000		5,325	11,000	2,530	5,701	3,171
12	1,000		5,325	68,000	2,364	30,636	28,272
13	1,000		5,325	11,000	2,210	4,980	2,770
14	1,000		5,325	13,000	2,065	5,429	3,364
15	1,000		5,325	11,000	1,930	4,349	2,419
16	278,400		33,825	66,000	11,457	116,648	105,192
17	1,000		5,325	11,000	1,686	3,799	2,113
18	1,000		5,325	13,000	1,576	4,143	2,567
19	1,000		5,325	11,000	1,472	3,318	1,846
20	1,000		5,325	13,000	1,376	3,618	2,242
21	1,000		5,325	11,000	1,286	2,898	1,612
22	1,000		5,325	13,000	1,202	3,160	1,958
23	1,000		5,325	11,000	1,123	2,531	1,408
24	1,000		5,325	13,000	1,050	2,759	1,710
25	1,000		5,325	66,000	981	12,341	11,361
26	1,000		5,325	13,000	917	2,411	1,494
27	1,000		5,325	11,000	857	1,931	1,074
28	1,000		5,325	13,000	801	2,106	1,305
29	1,000		5,325	11,000	749	1,687	939
30	278,400		33,825	13,000	4,445	38,290	33,845

The original ROI estimate from the Project Management Plan (PMP) was 59.15. All of the calculated new system cost savings in the PMP (such as leak repair, materiel clean-up, loss of materiel, and loss of training) were determined to be highly overestimated. When those cost estimates were recalculated with the benefit of using verified data, the originally estimated ROI value greatly decreased.

5 Conclusions and Recommendations

5.1 Conclusions

The EOP technology demonstrated at Guam measurably reduced concrete moisture, but the demonstration performance period was not long enough for the project team to observe the system reaching equilibrium and moving water out of the concrete to its full potential. More time was needed to reach equilibrium due to the volume of concrete comprising the ECM and the amount of moisture it had absorbed. Consequently, the demonstrated system could not be fully validated in the time allocated for the work and data collection.

The DH system at the Guam ECM was validated in terms of effectiveness in maintaining the interior RH at 40%–60% in an extremely humid locale where ambient humidity ranges from 85%–95%. However, long periods without cleaning the filters can cause the system to lose efficiency and eventually fail to dehumidify. Adjusting maintenance schedules based on the ambient environment is key to mitigating system dehumidification problems. On Guam windblown debris consisting mostly of twigs and grass clogged the intake and exhaust filters to such an extent that the equipment could not function according to specifications.

5.2 Recommendations

5.2.1 Applicability

The results of this demonstration show that EOP technology is capable of drying the interior of subgrade concrete structures affected by water intrusion. Therefore, it is recommended that EOP technology be applied to ECMs where water damage to the storage structure or its contents is known to be caused by water intrusion. The fullest potential ROI for implementing this technology, however, will be realized at locations where ambient atmospheric or interior conditions are known to be highly corrosive due to continually high humidity, temperature, and chloride content.

A previous study and demonstration of EOP technology to mitigate water intrusion into ECMs concluded that EOP was safe for use in ECMs (Marshall 2009).

It is recommended that managers of buildings that house assets that are damaged by accelerated corrosion consider implementing a moisture-controlling system such as a dehumidification system. The DH System used in this project demonstrates the ability to effectively add a system to an existing structure and successfully remove moisture and control RH. The DoD maintains numerous ammunition storage facilities that would benefit from the corrosion protection of a DH system.

5.2.2 Implementation

Implementation of DH technology to enhance EOP will produce improved storage conditions in ECMs for munitions and other materiel. The EOP system can stop water intrusion through the concrete and extend the service life of the structure, and the DH system will maintain a dry interior atmosphere to significantly reduce problems aggravated by high humidity, such as corrosion mitigation and mold growth.

UFC 4-420-01, Ammunition and Explosives Storage Magazines, recommends the use of dehumidification for humidity control in ECMs. It is recommended that this report be added as a reference to the Whole Building Design Guide—Ammunition and Explosives Storage Magazines (http://www.wbdg.org/design/ammo_magazines.php) web page as an example of a successful application of dehumidification to ECMs.

Any changes or additions to a U.S. Navy ammunition storage facility requires approval by the Naval Ordnance Safety and Security Activity (NOSSA) before the facility can be used to store live ordnance. NOSSA approval should be sought to continue implementing DH systems on ammunition storage facilities. Prospective users in other DoD services should refer to safety-approval requirements that pertain to their specific application. It is recommended that a DH system be incorporated into the design of future ammunition storage facilities and considered in other buildings containing corrosion-sensitive assets.

References

- Concurrent Technologies Corporation. 2009. *Dehumidification for Enhancement of Electro-Osmotic Pulse Technology at Fort A.P. Hill, VA*. DoD Corrosion Prevention and Control Program, Corrosion Technologies for Defense Systems and Infrastructure (CTDSI) Task 2.3.
- Lloyd, G.O. n.d. *Guide to the Control of Atmospheric Corrosion*. National Physical Laboratory, Teddington, Middlesex TW11 OLQ, U.K.
<http://www.npl.co.uk/science-technology/advanced-materials/national-corrosion-service/publications/corrosion-guides>, accessed 16 August 2018.
- Marshall, Orange. 2008. *Corrosion Prevention of Pre-Positioned Underground Assets Using Electro-Osmotic Pulse Technology*. Army Corrosion Summit 2007, Clearwater Beach, FL. 14 Feb 2007.
- Marshall, Orange. 2008. "Novel Technologies for Eliminating Moisture in Earth Covered Magazines." Paper presented at Army Corrosion Summit 2008, Clearwater Beach, FL. 14 Feb 2008.
- Marshall, Jr., Orange S. 2009. *Demonstration of Electro-Osmotic Pulse Technology in Earth-Covered Magazines at Fort A.P. Hill, VA*. ERDC/CERL TR-09-23. Champaign, IL: U.S. Army Construction Engineer Research and Development Laboratory.
- McInerney, Michael K., Sean Morefield, Sondra Cooper, Philip Malone, Charles Weiss, Matthew Brady, Jonathan Taylor, and Vincent F. Hock. August 2002. *Electro-Osmotic Pulse (EOP) Technology for Control of Water Seepage in Concrete Structures*. ERDC/CERL TR-02-21. Champaign, IL: US Army Construction Engineer Research and Development Center, Construction Engineering Research Laboratory.
- McInerney, Michael K., Orange S. Marshall, Jr., and Lawrence A. Gintert. October 2018. *Demonstration of Dehumidification for Corrosion Control in Earth Covered Magazines: Final Report on Project F07-ARCTCo2*. ERDC/CERL TR-18-34. Champaign, IL: US Army Construction Engineer Research and Development Center, Construction Engineering Research Laboratory.
- Unified Facilities Criteria (UFC) Section 4-420-01. May 2015. *Ammunition and Explosives Storage Magazines*. Washington, DC: Department of Defense.

Appendix A: Guam EOP System Design, Installation, and Commissioning

Design

Electro-osmotic pulse (EOP) technology exploits the phenomenon of electro-osmosis to move water contained in concrete by applying a pulsating electric field to the structure. The technology uses two sets of electrodes: one set embedded just below the surface of concrete floors, walls, or ceilings; and the other set placed either in the surrounding soil or, if the concrete is thick, deep in the concrete itself. A pulsing direct-current voltage is applied between the electrodes to produce an electric field in the concrete cross-section. The positive electrical pulse causes cations (e.g., Ca^{++}) and adsorbed water molecules to move from the dry side (anode) toward the wet side (cathode) against the direction of flow induced by the hydraulic gradient, thus preventing water penetration through a buried or submerged concrete structure.

The design life of an EOP system is typically 20 years.

Anode system

The anode system has a design working life of 20 years and is constructed of mixed metal oxide coated titanium expanded ribbon mesh anodes (Figure A1). These anodes are expected to exceed the design life as consumption is controlled by current output and the set points will be low.

Figure A1. Anode ribbon connected to lead wire.



Master control unit

The master control unit (MCU) is a microprocessor controlled rectifier that converts the AC power to DC; the DC output pulse waveform is programmable. The MCU also provides for data collection and logging. The EOP system's operating parameters are recorded once every 24 hours.

The units installed are specified for 27 volt direct current (VDC), 5 amp maximum output capability. The input power required for operation of the system is 120 volt alternating current (VAC) at 20 amps. The unit installed at Guam is a two-zone unit with one zone as a spare. Both units are capable of remote monitoring. A unit is shown in Figure A2.

The MCU cabinet for all ECMs is constructed with 316 stainless steel. The cabinets are rated NEMA 3R. The cabinet is weatherproof and effectively sealed to prevent the entry of rain, dust and dirt.

Figure A2. MCU main panel.



Electrical work

The electrical equipment consist of copper-clad steel cathode rods, cables for direct burial, conduits, junction boxes, and monitoring sensors, cabling and equipment. All electrical equipment was installed in accordance with the U.S. National Electric Code (NEC).

The electrical wiring for the EOP circuits and monitoring system within the ECM is installed in grooves cut into the concrete(see Figure A1) or aluminum conduit.

Exterior to the ECM, the EOP circuit and monitoring cables are routed to the MCU within heavy wall galvanized steel pipe, which include fittings and attachment hardware (Figure A3). Junction boxes were installed at the head wall of the structure to allow collection of the DC field cabling. Junction boxes are watertight and constructed of stainless steel. All attachments to the concrete surface use stainless steel anchors. Buried cables are installed in PVC conduits.

Standard 5/8 in by 8 ft copper-clad steel ground rods were used for the cathodes (Figure A4).

The permanent temperature/humidity probes are designed to accurately monitor the temperature and humidity within the concrete.

Figure A3. Galvanized conduit and junction boxes.



Figure A4. Cathode rod being driven into the ground.



Mortar repair

The repair material for the anode encapsulation, excavations and miscellaneous repairs performed was a non-shrink Portland cement concrete repair mortar that met the following requirements:

- electrical resistivity less than 50,000 ohm-cm (at 28 days),
- electrochemically resistant to anode reaction products,
- workability appropriate to the method of placement, and
- shall not crack due to thermal and/or shrinkage effects.

Installation

EOP system installation consisted of the following steps.

1. A depth of cover survey was conducted to determine the depth and placement of the reinforcing steel in the concrete. It was determined during this test that the concrete was slightly conductive.
1. A 3/8 in. x 3/4 in. slot was cut into the ceiling at both sides of the existing cracks to accommodate the anode (
2. Figure A5).
3. A 3/8 in. x 1 1/4 in. slot was cut at the cold joint at the lower wall-floor junction to accommodate the anode.
4. The joint sealer was removed from the control joint around the perimeter of the floor and the concrete was properly prepared to accommodate the anode.
5. A 3/8 in. x 1 1/4 in. slot was cut into the crack that transverses the floor to accommodate the anode.
6. The reinforcing steel was tested for electrical continuity.
7. Slots were cut for the temperature/humidity probes (Figure A6 and Figure A7).
8. The anodes were installed in all slots and lead wires were welded at proper locations (Figure A8 and Figure A9).
9. Lead wires were connected to the reinforcing steel.
10. All lead wires were installed in the slots and routed to the exterior of the ECM through a hole drilled in the front wall.
11. The anodes were grouted using the appropriate repair mortar (Figure A10).
12. Moisture readings were taken at multiple locations within the structure.

13. The null probes were installed for the stray current analysis and base line readings were recorded prior to energizing.
14. A 1 in. wide x 3 in. deep trench was excavated around the exterior perimeter of the ECM to allow for the installation of the cathode rods (Figure A11 and Figure A12).
15. The cathode rods were installed and the conduit and wiring was routed to the wing wall nearest to the rectifier location.
16. All wiring was tested and terminated within the rectifier (Figure A13).
17. The system was energized with 50% of the current diverted to the reinforcing steel.
18. Stray current testing was completed and the current was increased to 75% current diverted to the reinforcing steel (Figure A14).
19. Stray current testing was completed and no further adjustments were made to the system at this time.
20. Moisture readings were taken at the same points as previous and values were recorded.

Figure A5. Ceiling cut for anode installation.



Figure A6. Moisture sensor.



Figure A7. Moisture sensor.



Figure A8. Floor anodes and lead wire.



Figure A9. Ceiling anodes.



Figure A10. Grouting groove with cement.



Figure A11. Cathode PVC conduit in trench.



Figure A12. Cathode trench backfilled.



Figure A13. Rectifier wiring.

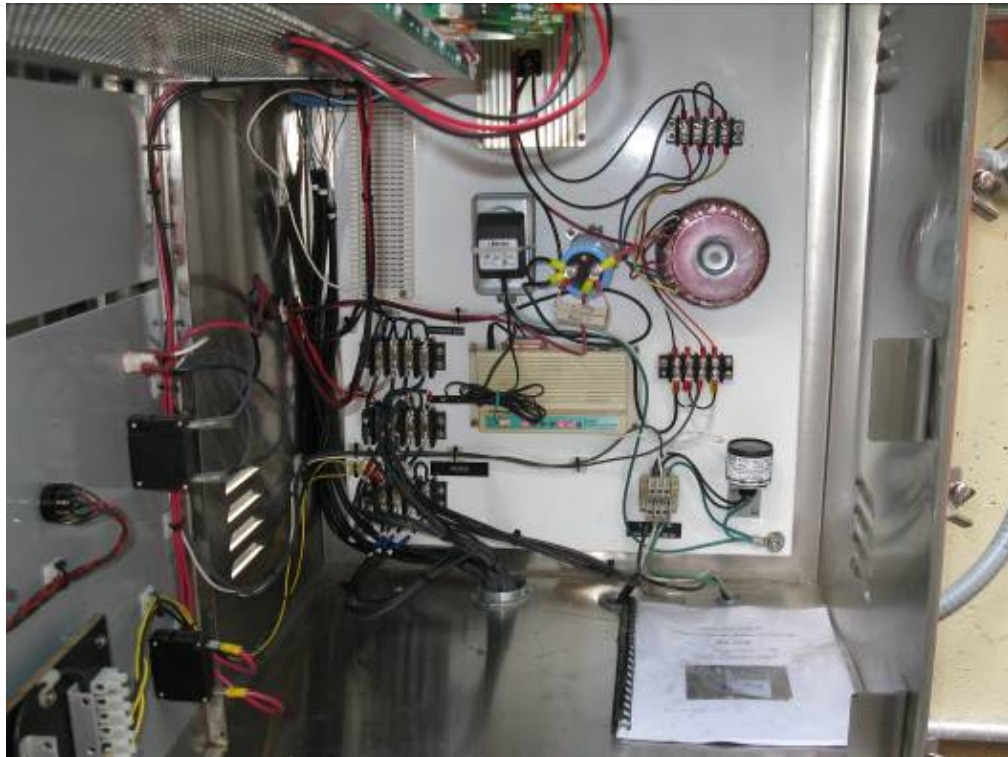


Figure A14. Stray current testing.



Commissioning

Commissioning involves the following system checks prior to operation:

1. Visual inspection of the system,
2. Polarity checks for all circuits,
3. Continuity checks for all circuits,
4. Insulation checks for all circuits,
5. Electrical isolation of DC positive cables from DC negative cables,
6. Energizing of electrical circuits and equipment,
7. Initial adjustment, initial performance assessment, interpretation of performance assessment data and adjustment of rebar protection current,
8. Any adjustments carried out after intermediate performance testing,
9. Performance verification.

Continuity

The continuity test confirms that the steel reinforcement within the structure is electrically continuous. Drawings of reinforcement and other steel elements were checked for continuity which was then verified on site by measuring the electrical resistance and/or potential difference between bars in locations remote from each other across the structure and at all locations where reinforcing bars were exposed.

Electrical isolation

During the installation of the anodes, the system was continuously monitored for short circuits by monitoring the anode/cathode resistance. This allowed for short circuits to be corrected immediately, when the anodes were completely exposed, instead of when the entire system is complete. Startup resistance measurements for the EOP system are listed in Table A1. Resistances are within the expected ranges.

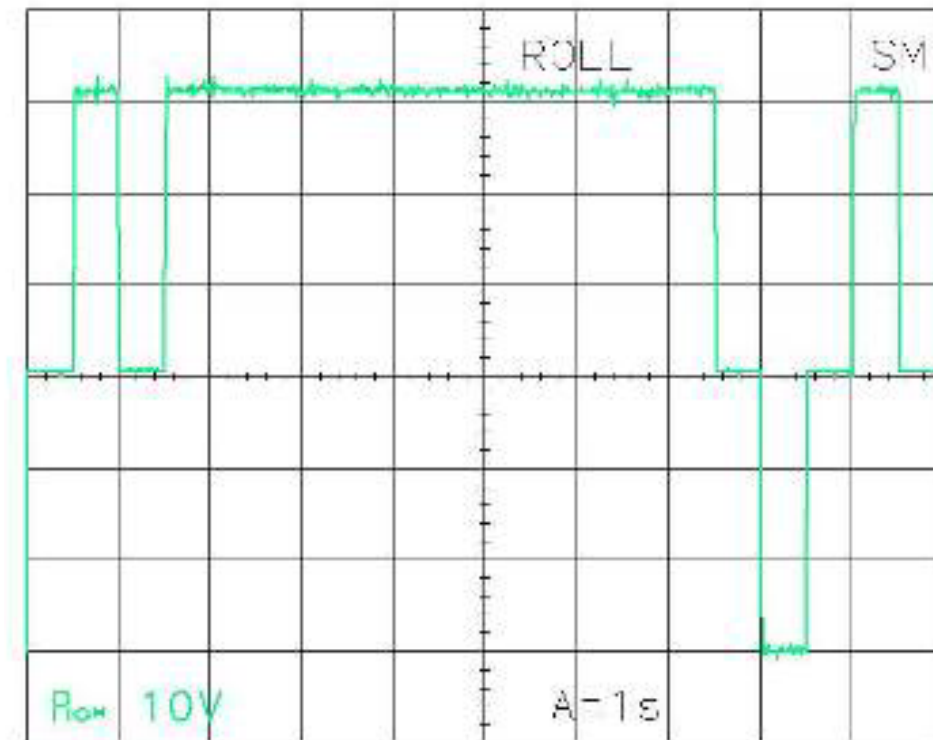
Table A1. Start-up data for ECM 12AC20 (16 December 2011).

Start Up Data						
ECM 12AC20						
Date	12/16/2011					
Rebar to Cathode Resistance			Cathode to Anode Resistance			
	Millivolts	Ohms		Millivolts	Ohms	
1	550.6	5.35	1	154.8	5.86	
2	384.3	6.86	2	410.6	7.28	
3	282.8	6.56	3	577.6	7.18	
4	280.1	19.5	4	56.9	2.2	
Anode to Rebar Resistance						
	Millivolts	Ohms				
	26.1	0.78				
Rectifier Settings						
1 Amp	27 Volt Limit					
Tempature/Humidity Values						
Wall	22 C	100%				
Floor	22 C	74%				

Performance assessment

The power supply output waveform was checked and verified (Figure A15).

Figure A15. EOP wave form for ECM 12AC20.



Rebar protection

When electric current is passed through concrete, there is a possibility for isolated reinforcing steel (or any other metallic element positioned between the anode and cathode) to become a path for stray current. This occurs because the steel is less resistive than the concrete and offers a “path of least resistance.” The current is potentially harmful to the steel since one end of the steel element will become anodic, causing corrosion of the steel. Such corrosion, if sufficient, can result in cracking and spalling, or corrosion of other metallic elements, all leading to eventual structural damage.

Stray current is greatest where there is a double mat of reinforcing steel and where the two or more mats are electrically continuous with each other. Steel closest to the cathode will become anodic and then has the possibility to corrode.

The amount of stray current flowing through the steel is dependent mainly on two parameters, the distance from the current source and the resistivity of the concrete. Both of these parameters profoundly affect the magnitude

of stray current. Stray current may also be significant where the reinforcing steel is connected or grounded to metallic elements in the soil surrounding the structure, in which case, stray current corrosion may become severe.

Stray-current corrosion can be mitigated by connecting the reinforcing steel to the cathode of the EOP system and passing a portion of the cathodic current through the steel.

Figure A16 through Figure A27 show the results of stray current tests with 50% of the EOP current diverted to the reinforcing steel. Figure A28 through Figure A39 show the results of stray current tests with 75% of the EOP current diverted to the reinforcing steel. The data indicate that by increasing the current diverted to 75% the stray current is reliably minimized for all probes.

Figure A16. Guam 12AC20 stray current results probe 1 50% current not shorted.

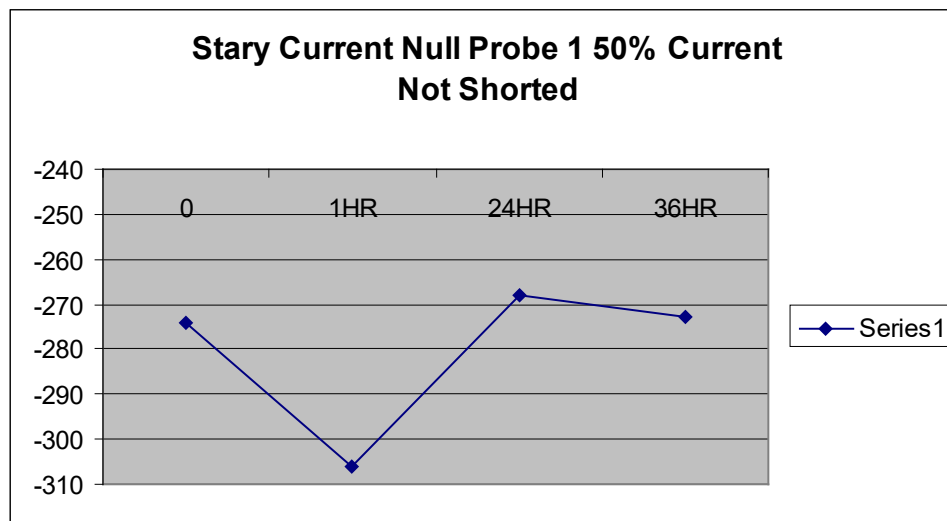


Figure A17. Guam 12AC20 stray current results probe 1 50% current shorted.

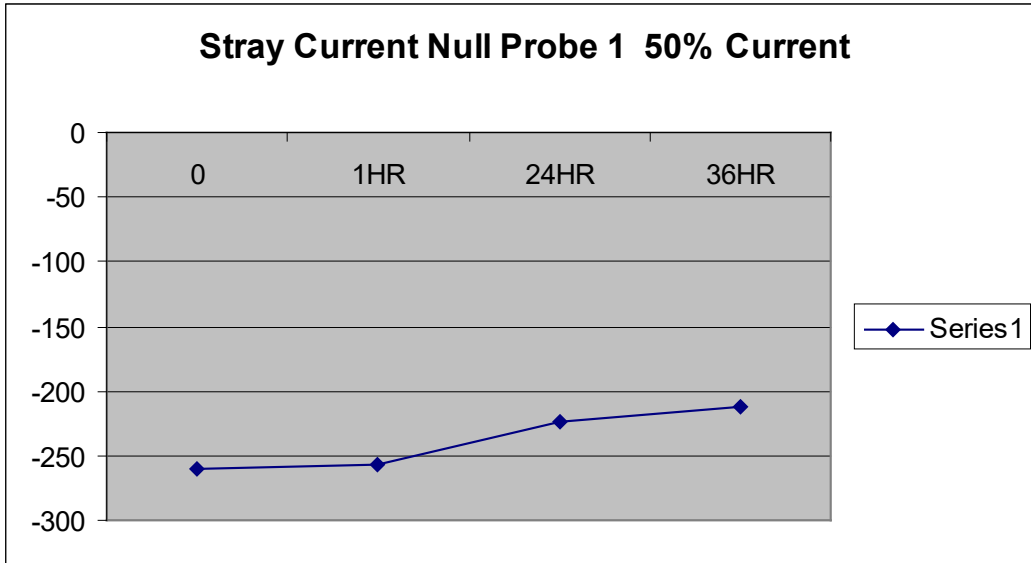


Figure A18. Guam 12AC20 stray current results probe 2 50% current not shorted.

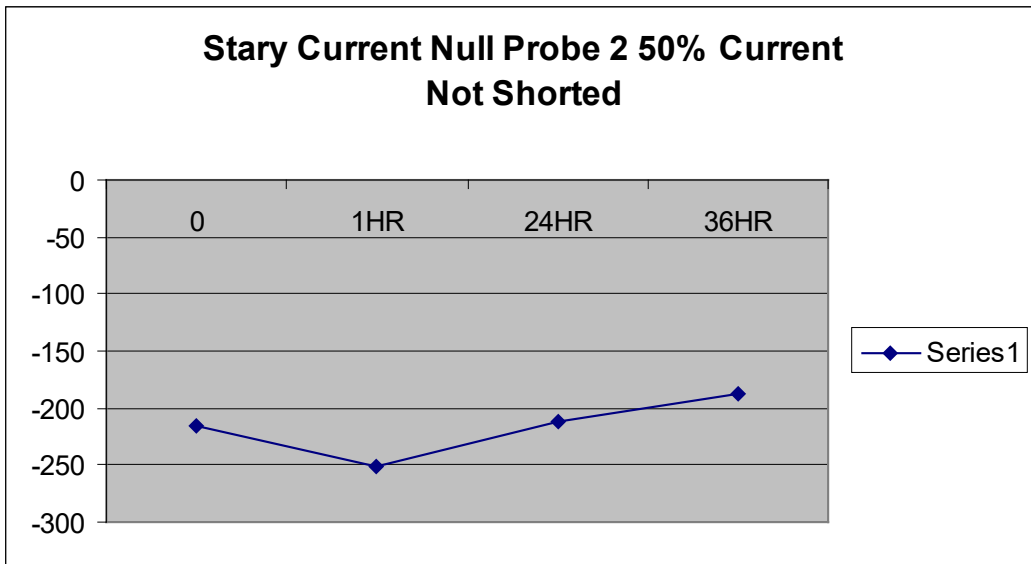


Figure A19. Guam 12AC20 stray current results probe 2 50% current shorted.

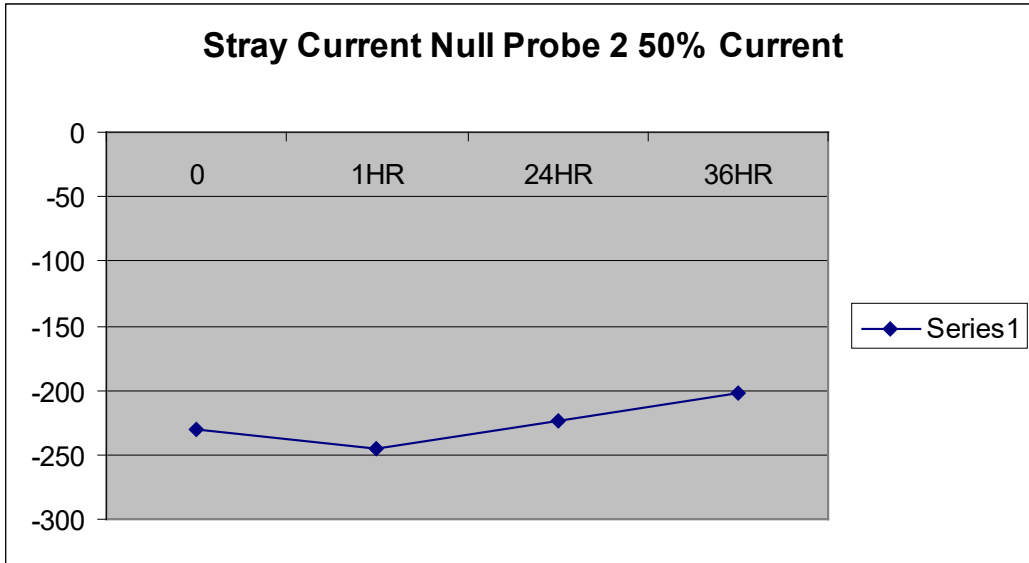


Figure A20. Guam 12AC20 stray current results probe 3 50% current not shorted.

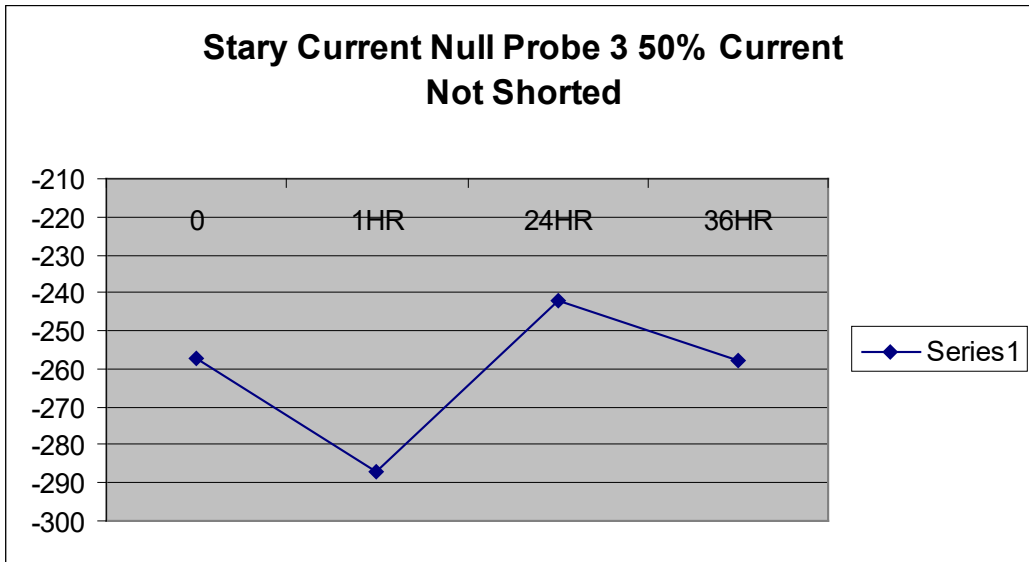


Figure A21. Guam 12AC20 stray current results probe 3 50% current shorted.

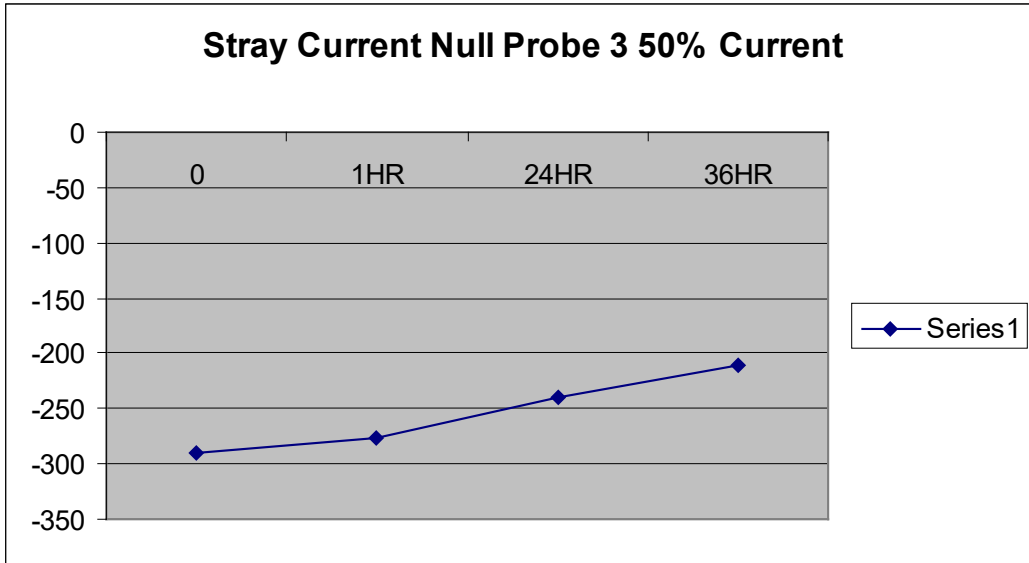


Figure A22. Guam 12AC20 stray current results probe 4 50% current not shorted.

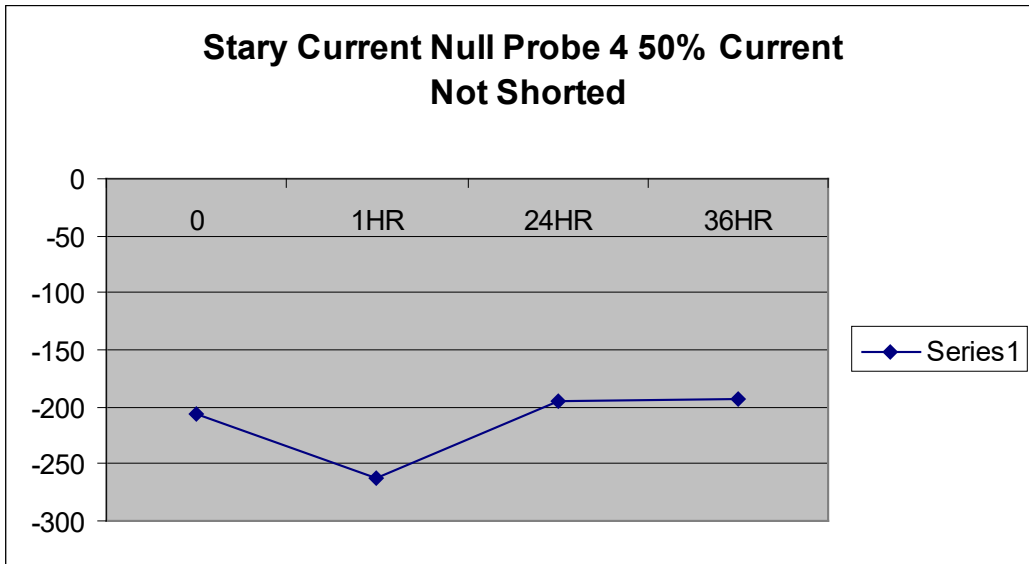


Figure A23. Guam 12AC20 stray current results probe 4 50% current shorted.

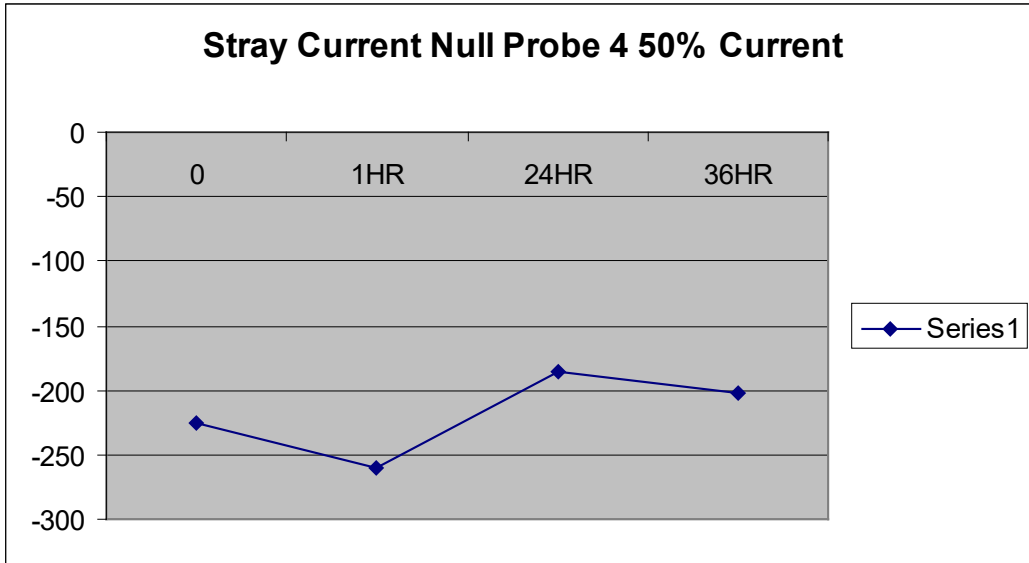


Figure A24. Guam 12AC20 stray current results probe 5 50% current not shorted.

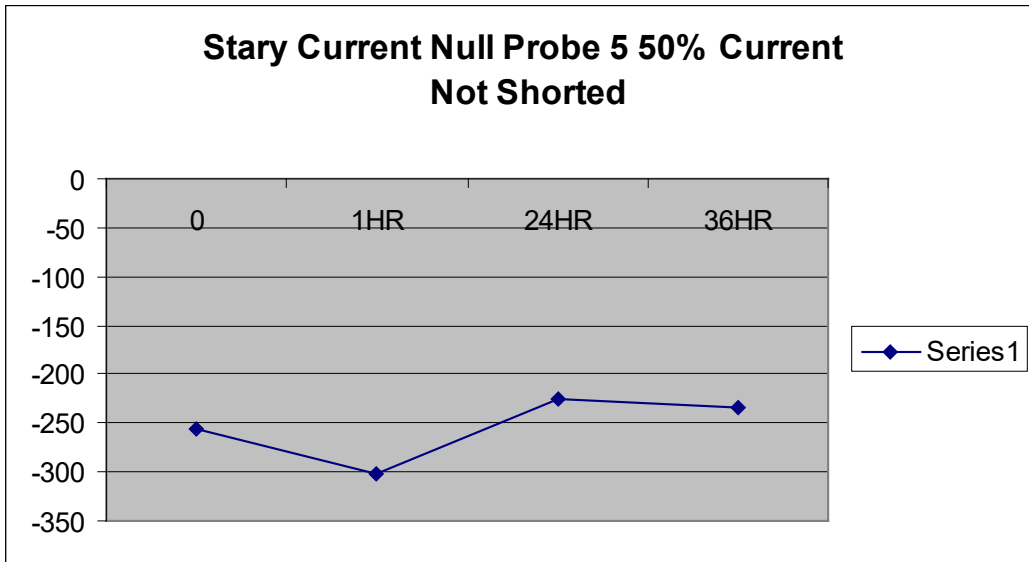


Figure A25. Guam 12AC20 stray current results probe 5 50% current shorted.

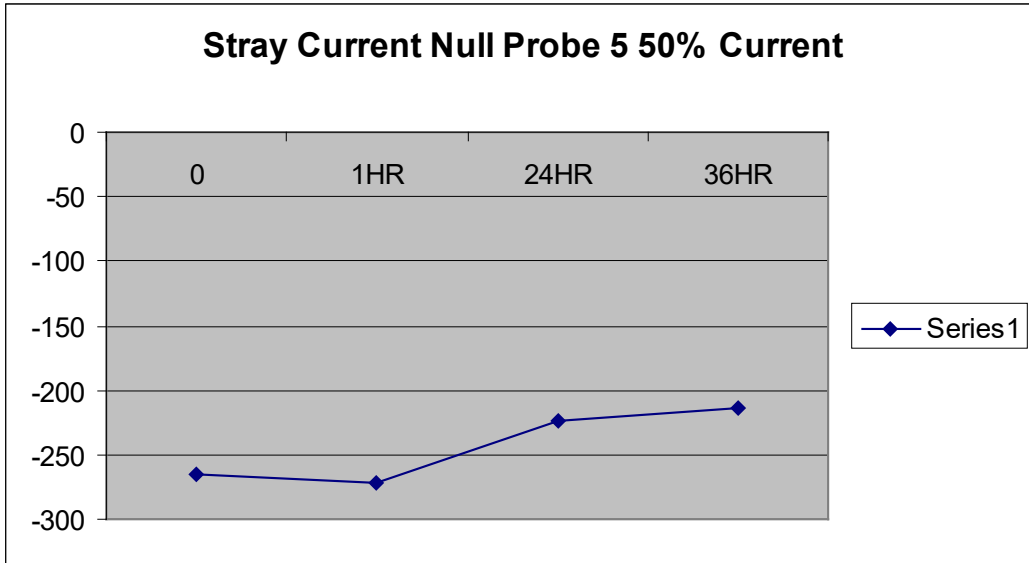


Figure A26. Guam 12AC20 Stray Current Results Probe 6 50% current not shorted.

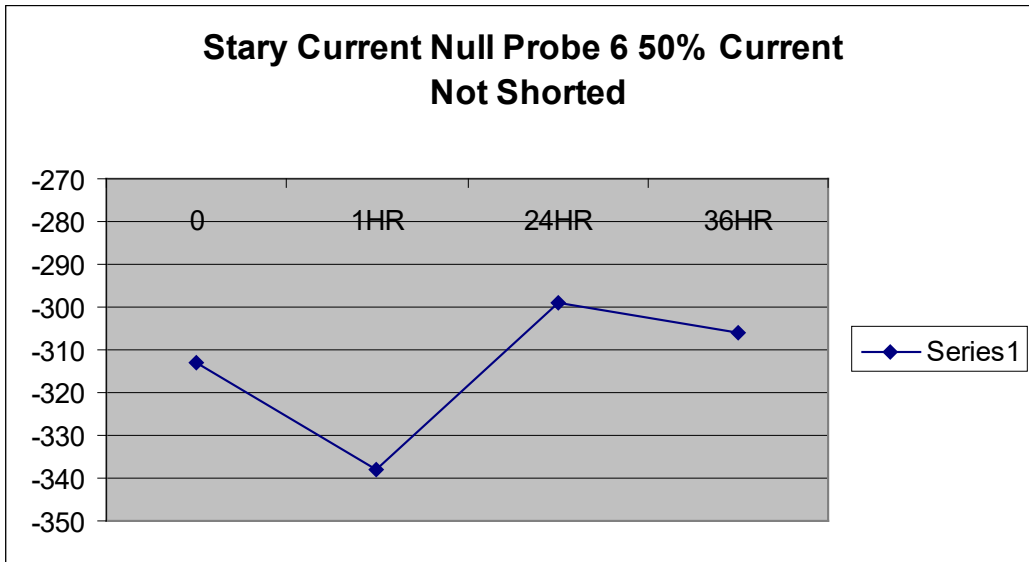


Figure A27. Guam 12AC20 Stray Current Results Probe 6 50% current shorted.

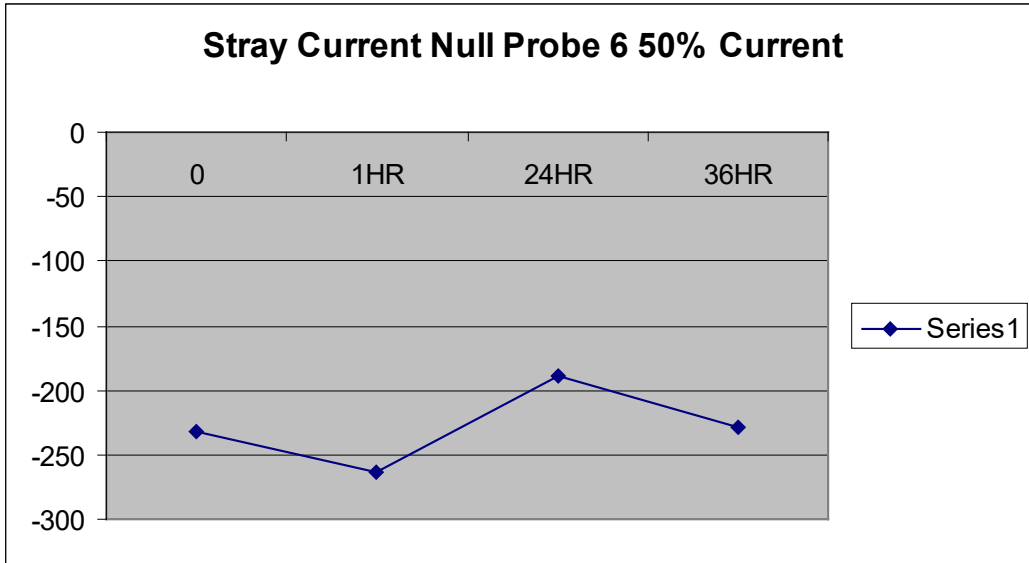


Figure A28. Guam 12AC20 Stray Current Results Probe 1 75% current not shorted.

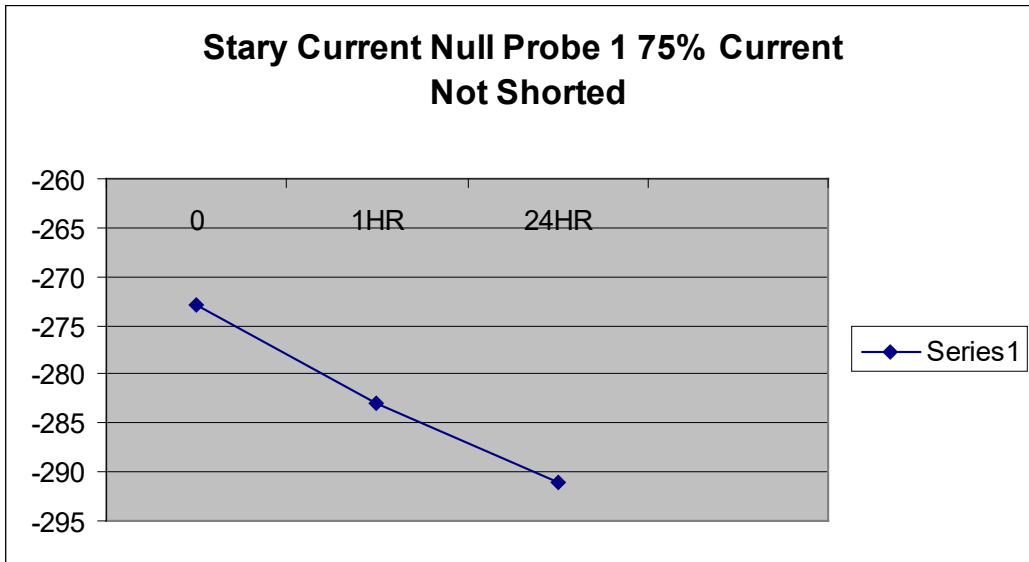


Figure A29. Guam 12AC20 Stray Current Results Probe 1 75% current shorted.

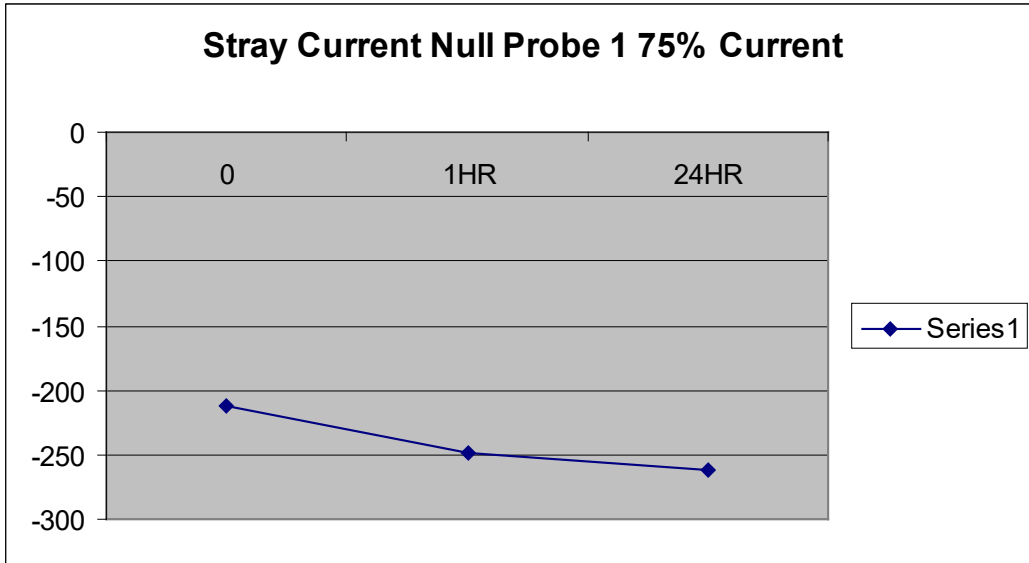


Figure A30. Guam 12AC20 Stray Current Results Probe 2 75% current not shorted.

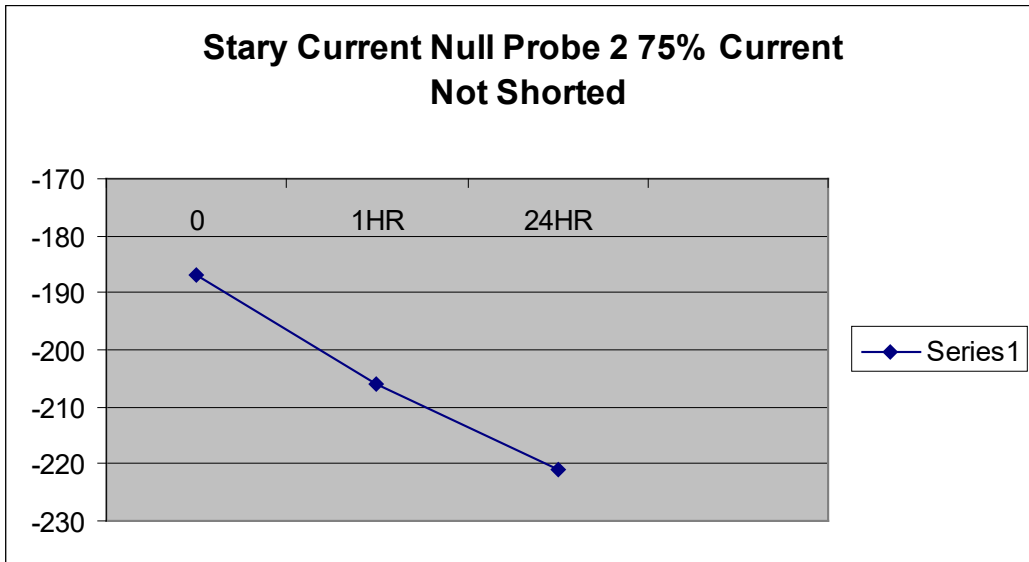


Figure A31. Guam 12AC20 Stray Current Results Probe 2 75% current shorted.

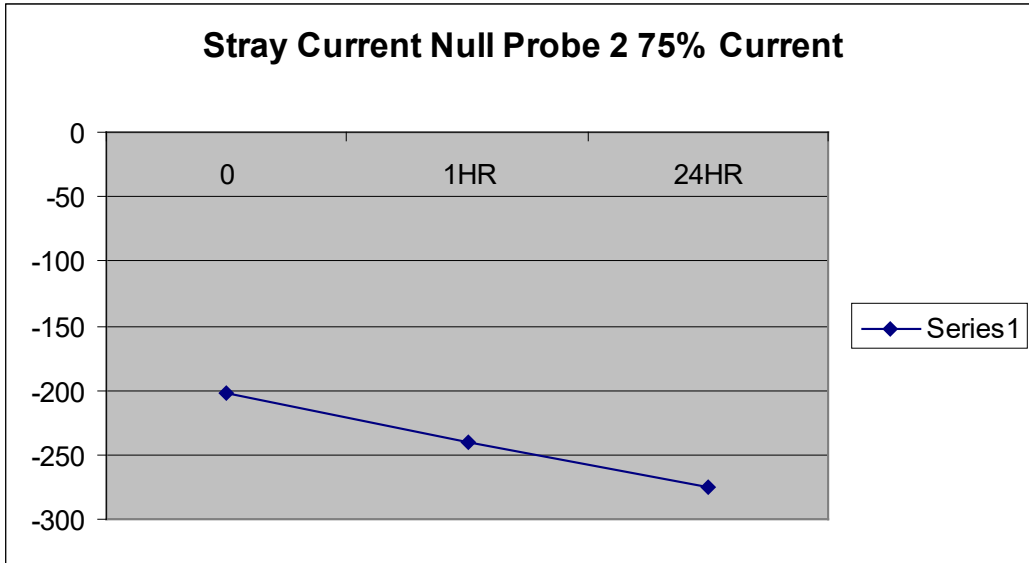


Figure A32. Guam 12AC20 Stray Current Results Probe 3 75% current not shorted.

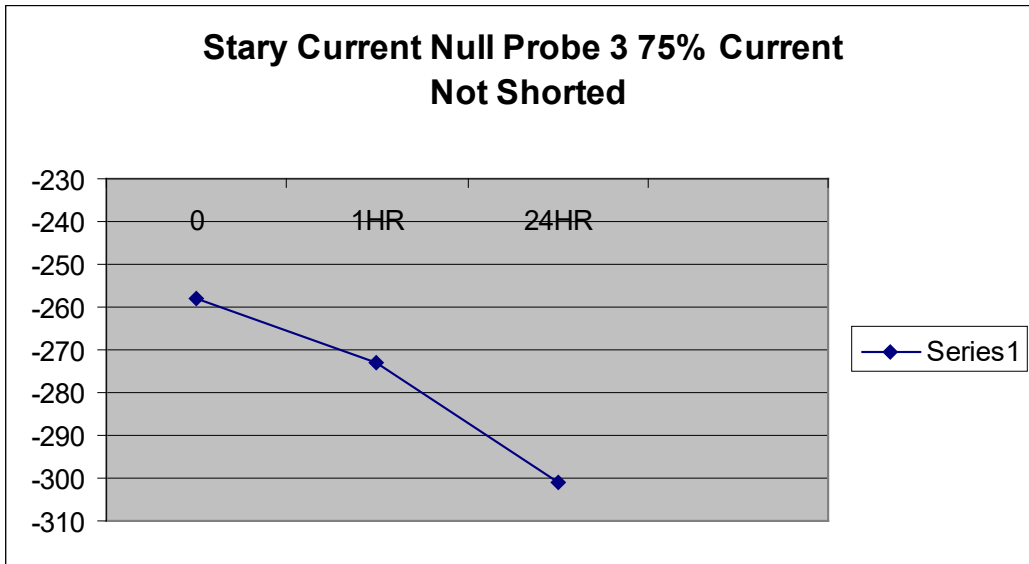


Figure A33. Guam 12AC20 Stray Current Results Probe 3 75% CURRENT SHORTED.

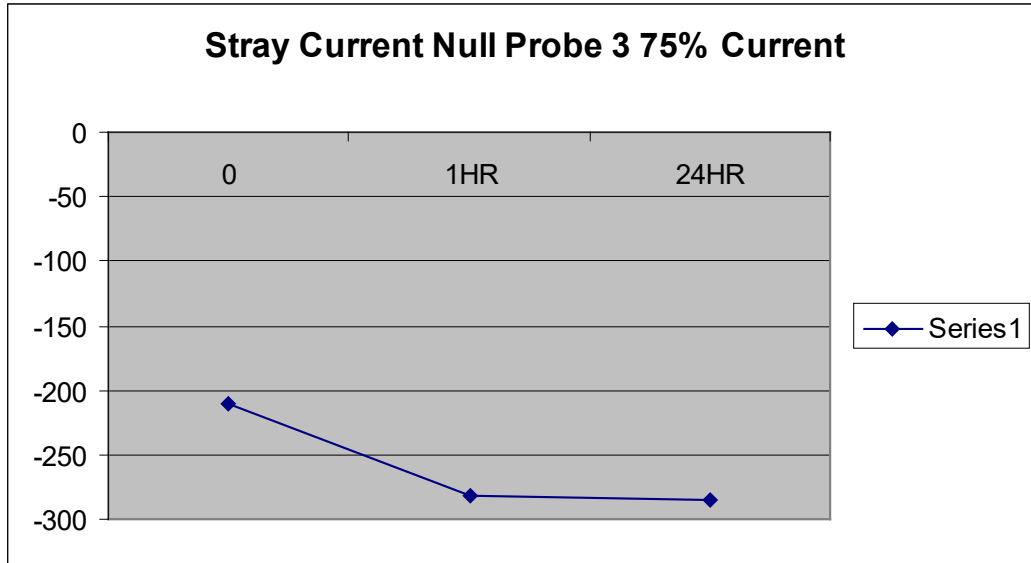


Figure A34. Guam 12AC20 Stray Current Results Probe 4 75% current not shorted.

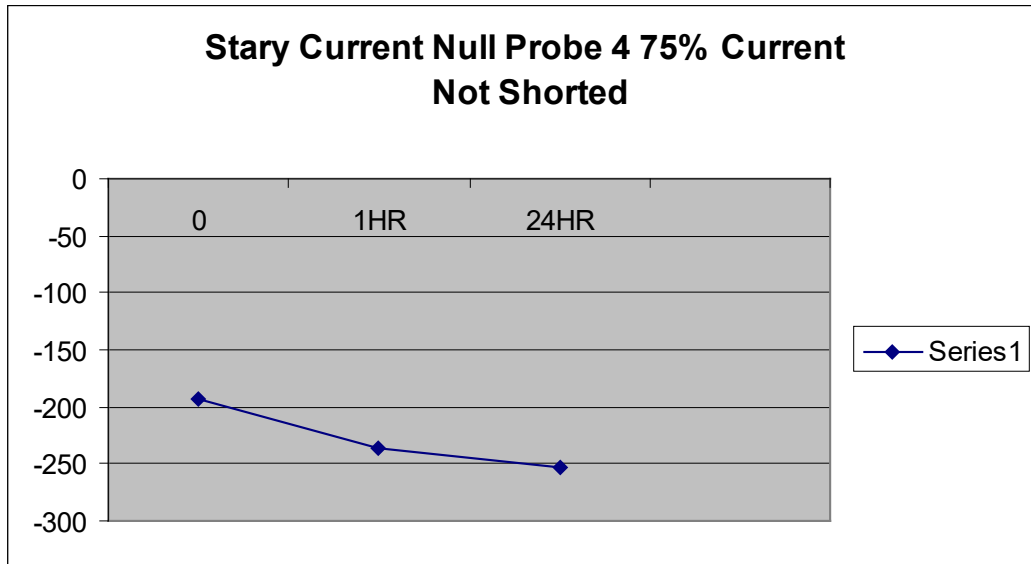


Figure A35. Guam 12AC20 Stray Current Results Probe 4 75% CURRENT Shorted.

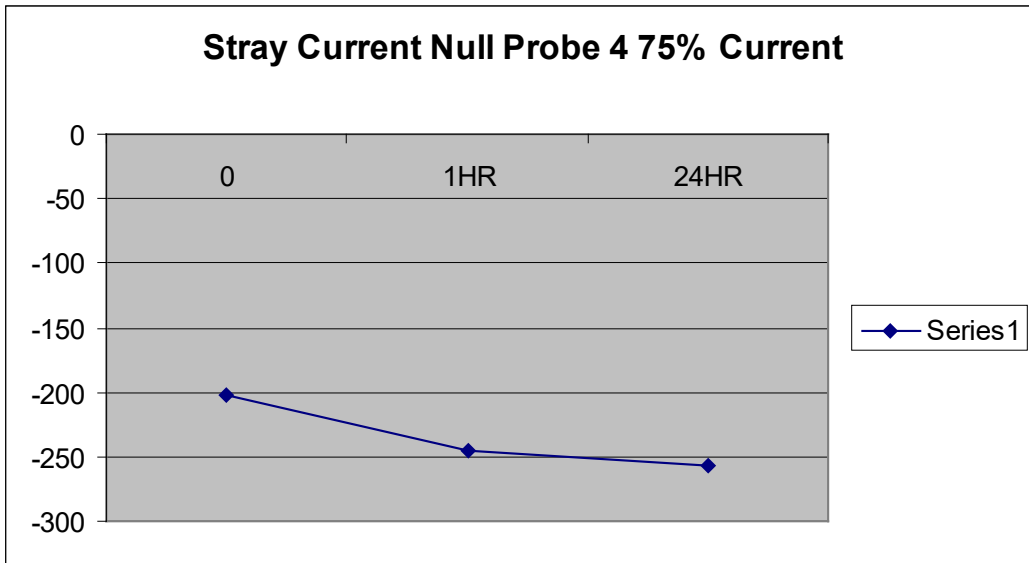


Figure A36. Guam 12AC20 Stray Current Results Probe 5 75% current not shorted.

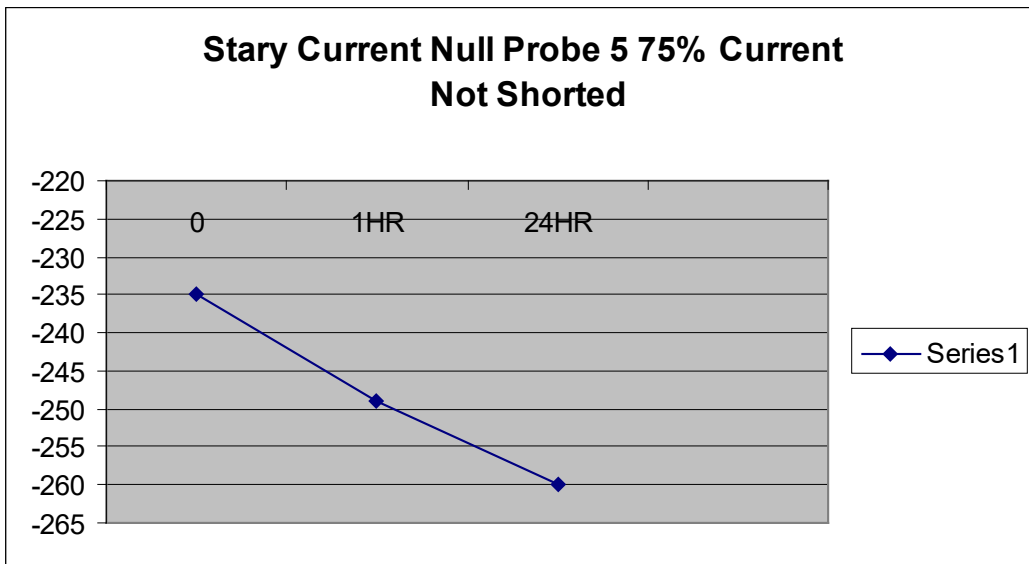


Figure A37. Guam 12AC20 Stray Current Results Probe 5 75% current shorted.

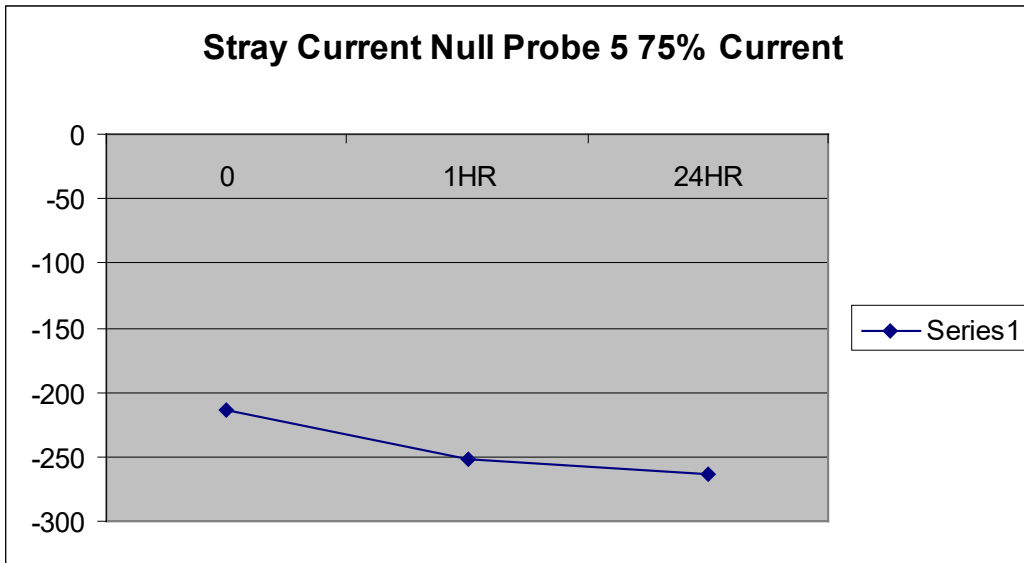


Figure A38. Guam 12AC20 Stray Current Results Probe 6 75% current not shorted.

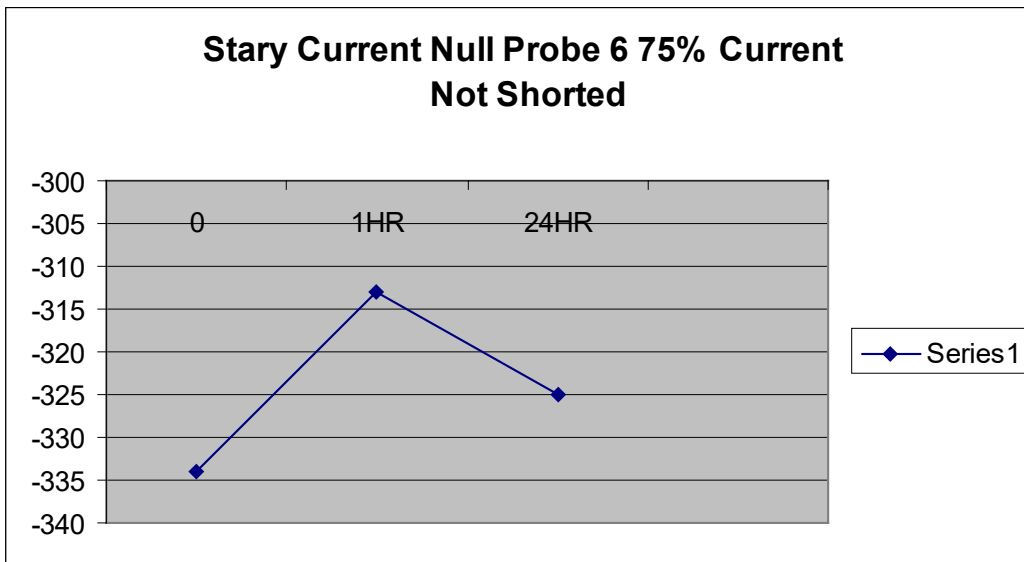
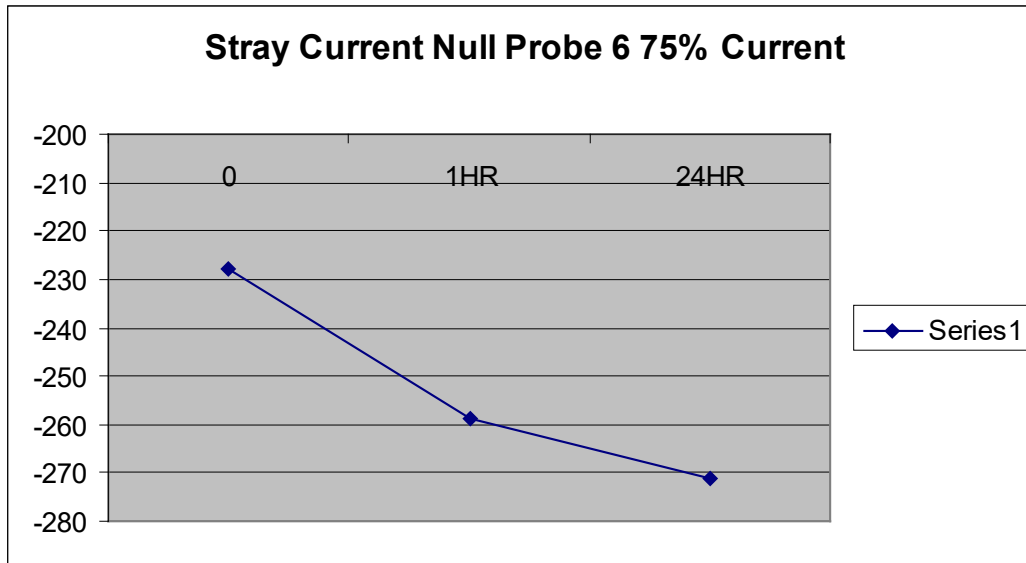


Figure A39. Guam 12AC20 Stray Current Results Probe 6 75% current shorted.



Appendix B: Electro-Osmotic Pulse System Drawings

As-built drawings for the EOP system in ECM 12AC20 at Guam are presented in Figure B1 through B7.

Figure B1. Exterior elevation showing locations of EOP system components for Guam ECM 12AC20.

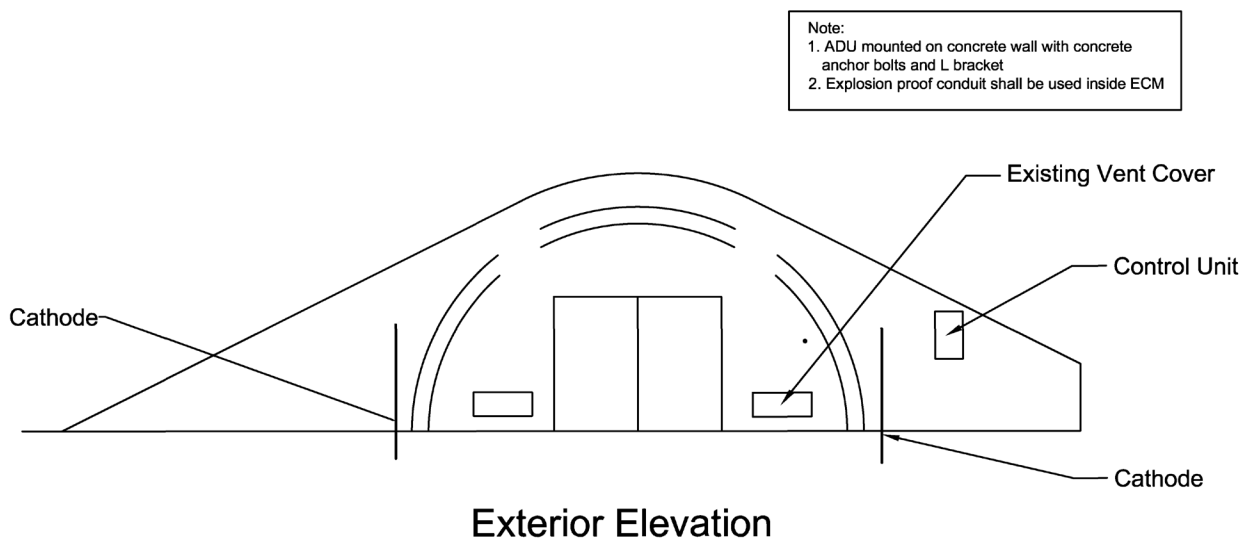
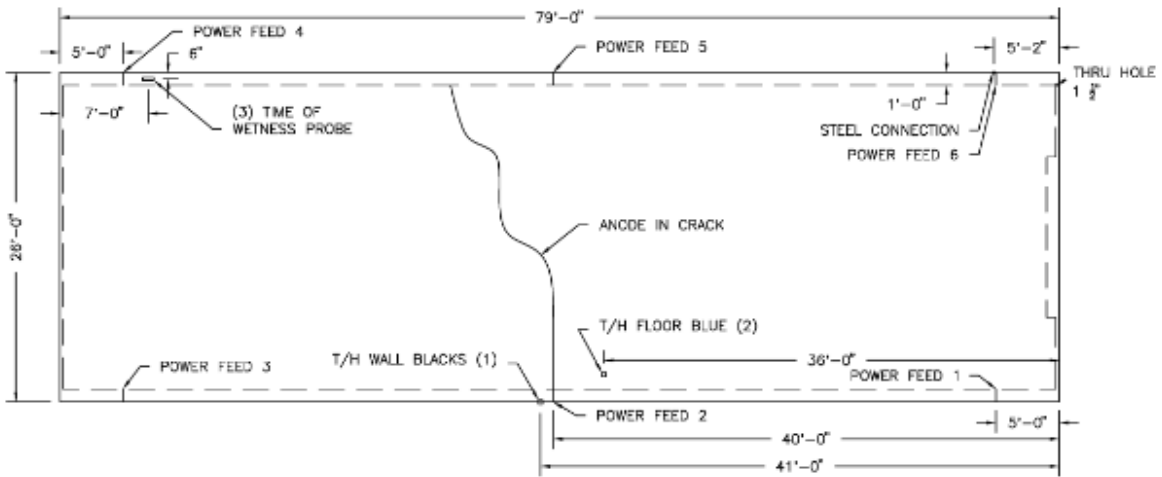


Figure B2. Locations of EOP system anode feeds in the floor and anodes in the ceiling for Guam ECM 12AC20.

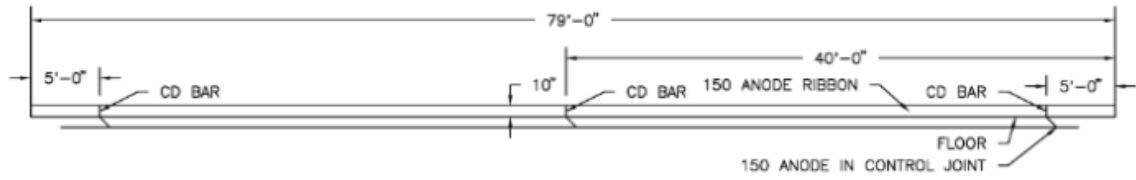


① ECM 12AC20
1/8" = 1'-0"

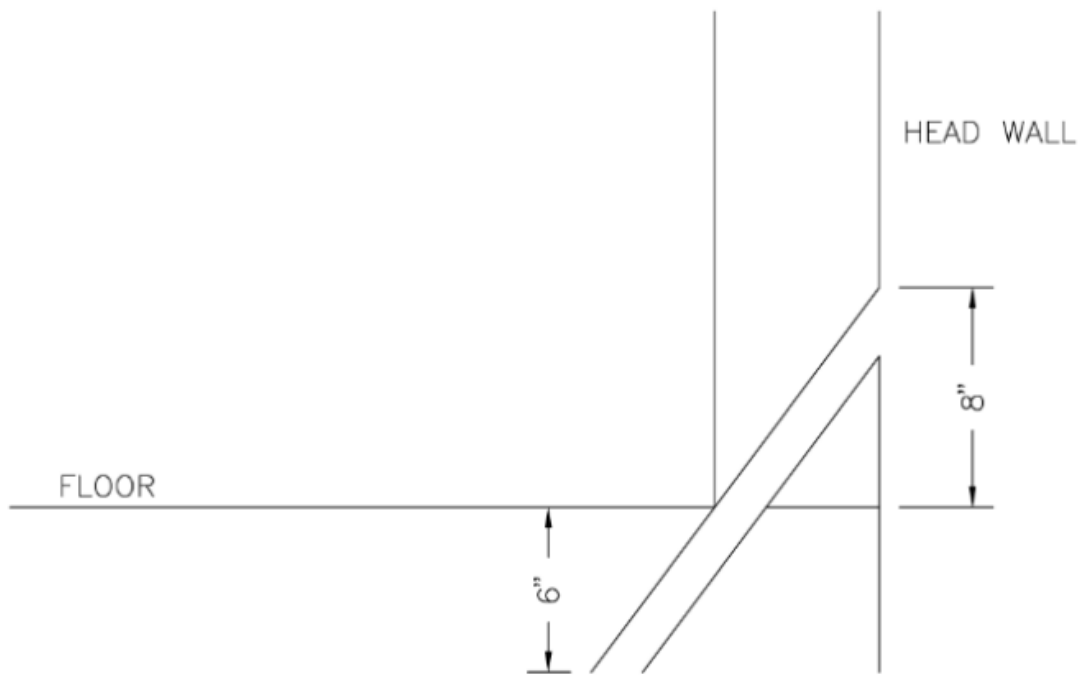


② CEILING ANODE REFLECTED VIEW
1/8" = 1'-0"

Figure B3. Details of anode wall installation and through hole in headwall for Guam ECM 12AC20 EOP system.



ECM 12AC20
WALL DETAIL
① $\frac{1}{8}" = 1'-0"$



THRU HOLE
DETAIL
② $\frac{3}{8}" = 1'-0"$

Figure B4. Plan detail of EOP system floor anodes and exterior cathodes for Guam ECM 12AC20.

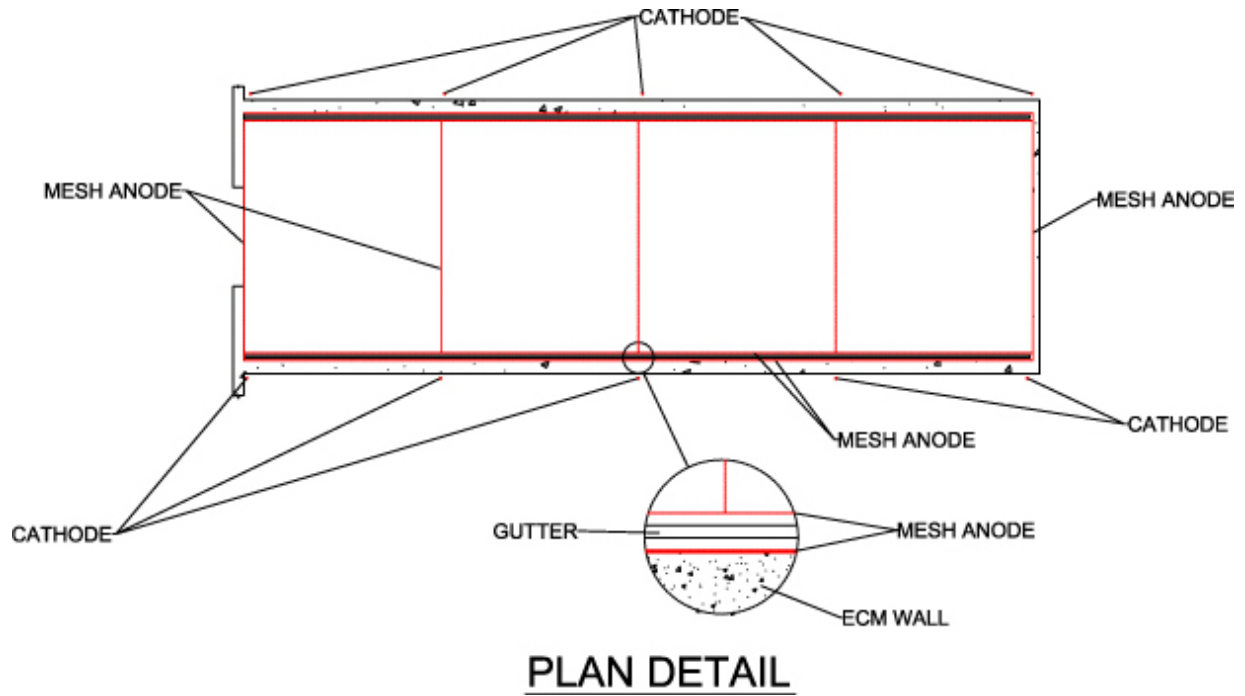


Figure B5. Detail of anode installation in wall footer/gutter for Guam ECM 12AC20 EOP system.

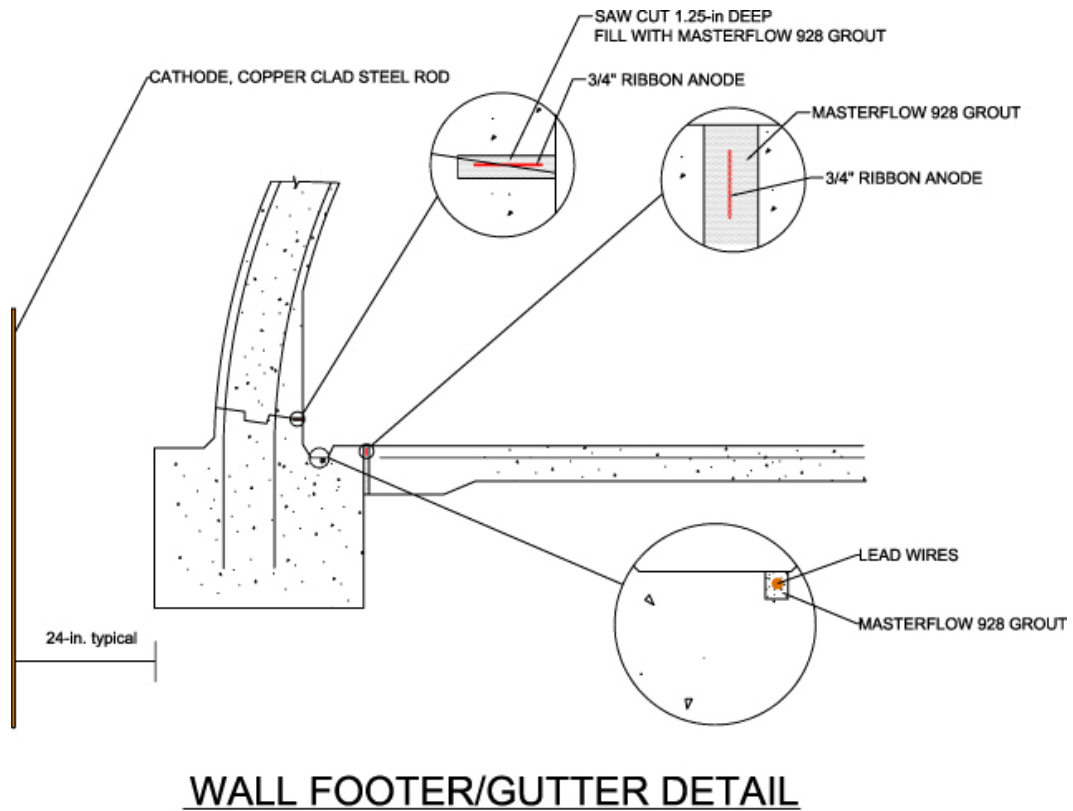
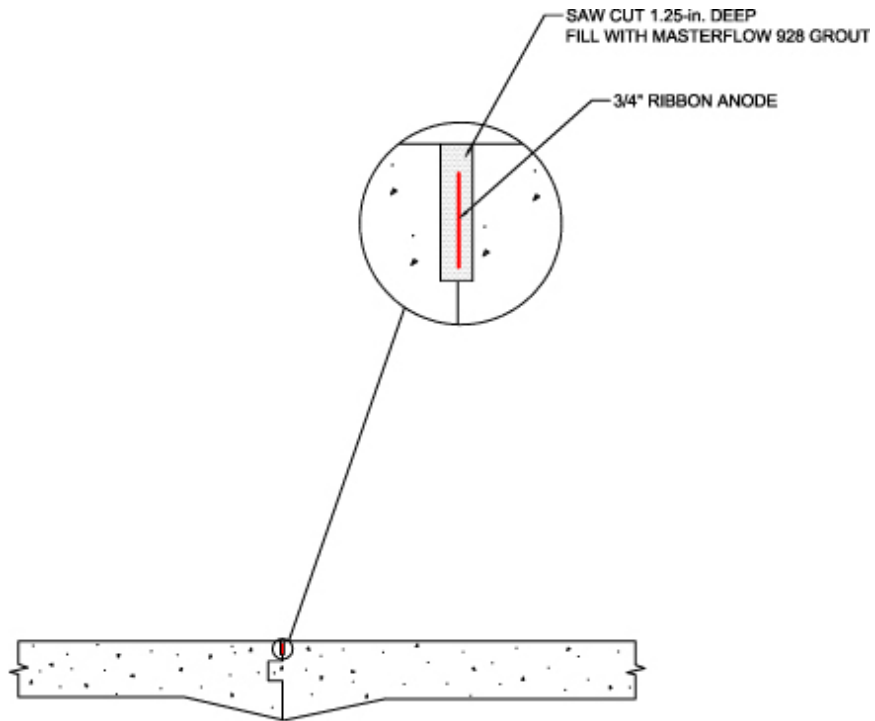
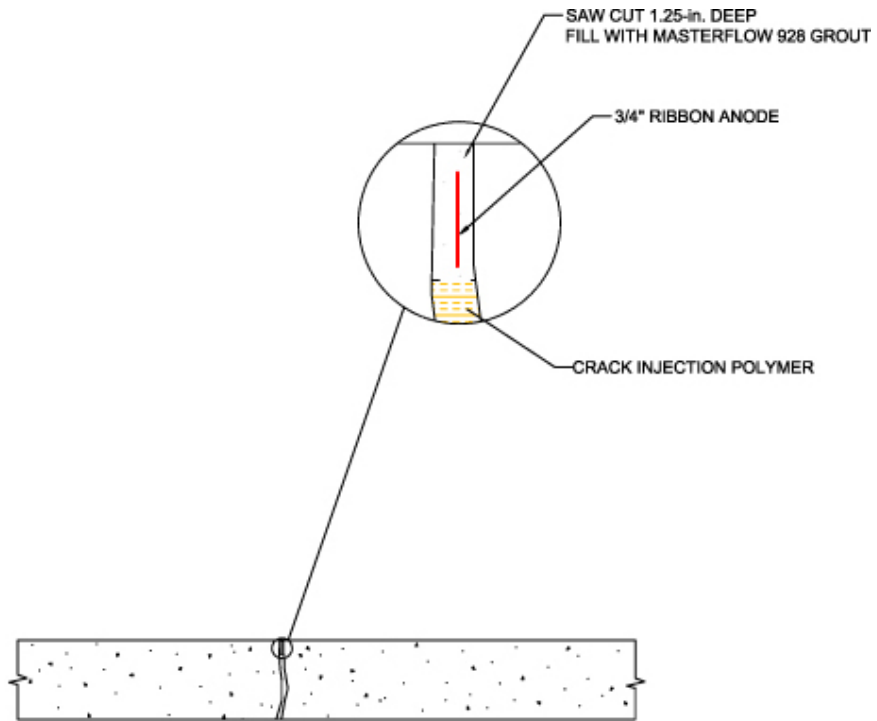


Figure B6. Detail of anode installation in construction joint for Guam ECM 12AC20 EOP system.



CONSTRUCTION JOINT DETAIL

Figure B7. Detail of anode installation in concrete cracks for Guam ECM 12AC20 EOP system.



CONCRETE CRACK DETAIL

Appendix C: Guam Desiccant DH System Design, Installation, and Commissioning

Design

1. The equipment was installed on the headwall of the magazine (Figure C1) and DH unit mounting brackets (Figure C2).
2. Fresh air was introduced into the magazines through the headwall blast vents such that there was no requirement to cut or damage the steel reinforcement in the magazine's concrete, and the vents retained their ability to close (Figure C1).
3. Ductwork between the DH equipment and the magazines was designed so that it did not interfere with entry doors to the magazines and had minimal impact on grounds maintenance operations (Figure C1).
4. The system has temperature and humidity sensors in the interior that are connected to a data recording device capable of retaining daily recordings for a minimum of one year. Low voltage data cables in electrical conduit transmits the data to the data logger (Figure C3).
5. The design meets all the safety requirements provided by the Defense Ammunition Center Technical Center of Expertise for Explosives Safety in a manner similar to (if not identical to) the installation at Fort A.P. Hill (McInerney 2017), specifically:
 - a. No class-rated electrical equipment is used. Low-voltage sensors and low-voltage communication cables fed through explosion proof electrical conduit are utilized.
 - b. There are no electrical power lines penetrating the magazine.
 - c. Electrical power is fed to the DH equipment underground for at least the first 50 feet, in order to avoid any above ground conductors.
 - d. An assessment of the location of the DH equipment outside the magazine was completed to verify that it is covered by the existing lightning protection system (LPS) (100-foot rolling sphere method) of the magazine.
 - e. All metallic enclosures, including ductwork, of the DH system was electrically bonded together and bonded to the magazine structure.
 - f. Only UL-certified or other U.S. recognized electrical equipment was used.
 - g. The location of the DH equipment and appurtenances are of the path of munitions handling equipment and operations.

- h. The minimum RH was set at 45% in order to avoid excessively dry air that could present the risk of static generation around any ammunition or explosives.

Figure C1. Exterior elevation showing locations of DH system components for Guam ECM 12AC20.

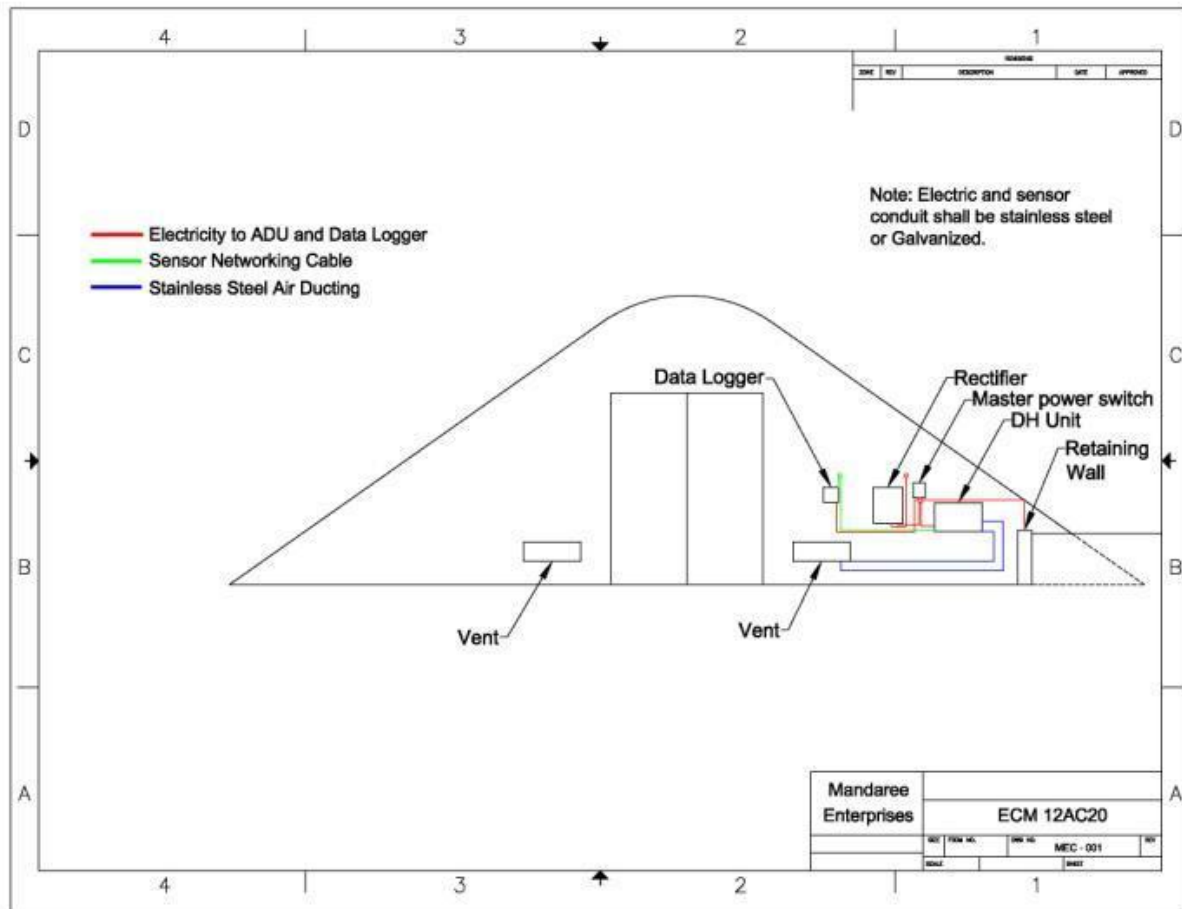


Figure C2. DH unit mounting brackets.

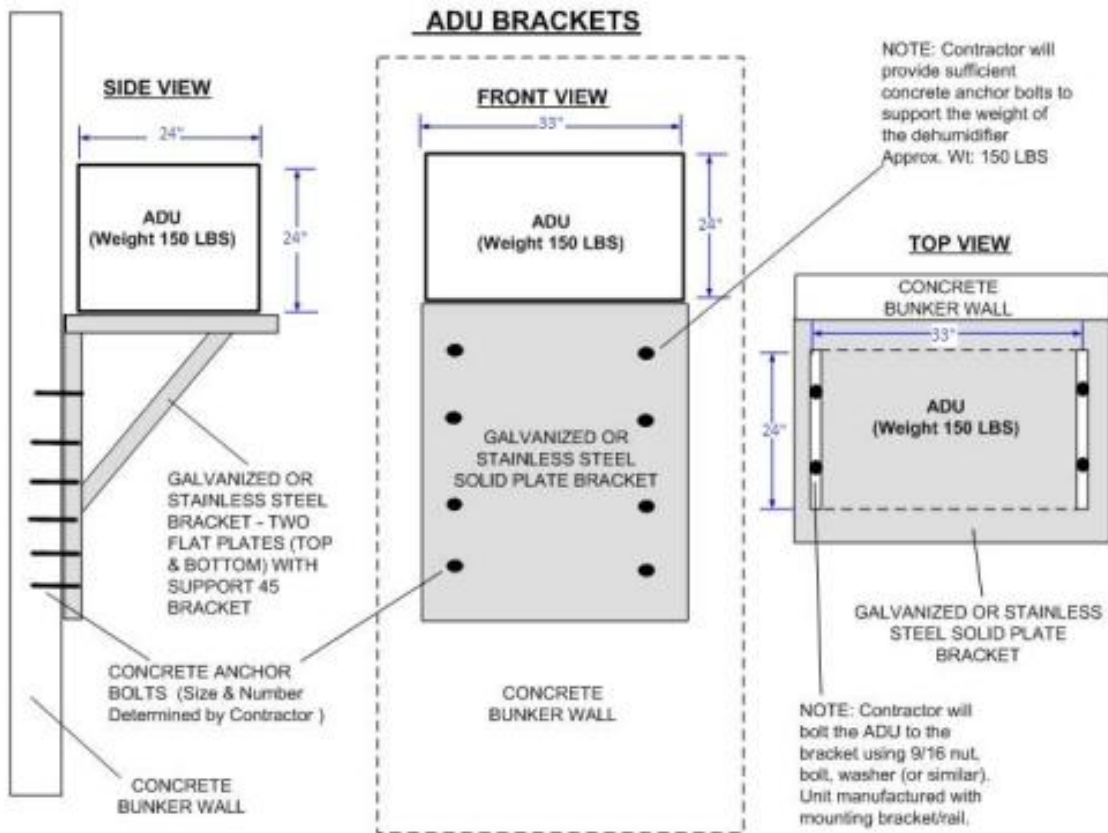
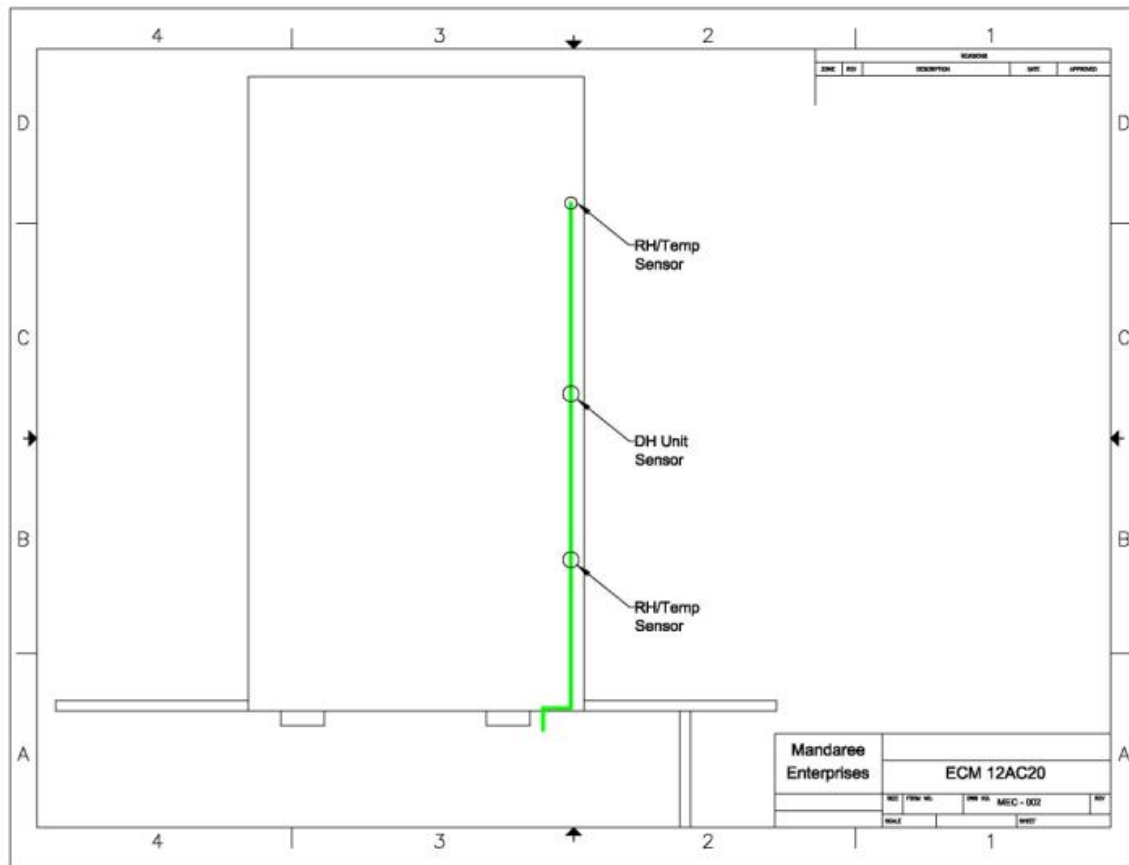


Figure C3. Humidity and temperature sensor locations in Guam ECM 12AC20.



Installation

The DH system is in an open-loop configuration (i.e., the air exhausted from the magazine is not recirculated back into the magazine) to avoid accumulation of any outgasses from the munitions. A Munters DEW-300 DH unit (Figure C4) was installed on the headwall of the ECM for dry air introduction. The mounting system was designed for survival in the earthquake and typhoon environment on Guam. Ductwork between the DH equipment and the magazine was installed to not interfere with magazine entry doors and to have minimal impact on grounds maintenance operations (Figure C5). The DH ducting was installed to preserve the existing blast-proof penetrations into the magazine (Figure C6). A buried electrical cable was run to a junction box mounted on the head wall from a utility pole to power both the EOP and DH systems (Figure C7).

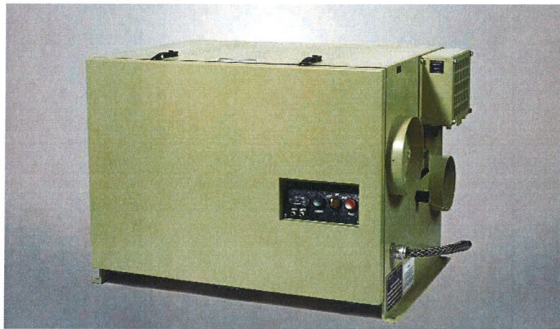
The DH unit was set to maintain the humidity level inside the magazine between 40% and 50%. Note that the DH unit does not reintroduce humidity if the natural ambient RH falls below the low-end target level. In

this case, the units simply remain idle until the ambient air humidity naturally returns to a higher level.

Figure C4. Manufacturer's product-sheet for DH unit installed in ECM 12AC20.

CARGOCAIRE

MODEL DEW-300



OFF-THE-SHELF-DEHUMIDIFIER

ADVANTAGES

Cargocaire off-the-shelf desiccant dehumidifiers combine state-of-the-art desiccant technology with dependability and long operating life for humidity control at virtually any temperature. Advantages include:

- Efficient humidity control for applications including product drying, mold and mildew control, corrosion protection, storage and condensation control.
- Durable unitized body with welded aluminum construction.
- Easy access panel for inspection and maintenance.
- Simple ductwork connections.
- Compact, low profile design.

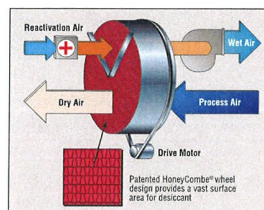
FEATURES

Process Air: Flow rates of 150-300 scfm. Nominal moisture removal: 9.1 lbs/hr at 75°F, 50% RH at 300 scfm. Capable of processing saturated, conditioned or outside air.

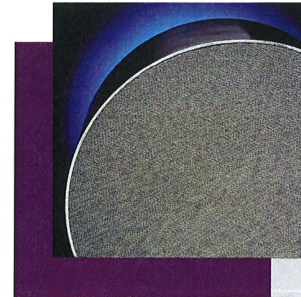
Contact Air Seals: Separate process and reactivation air streams. Compatible with modulating face and bypass systems.

Electrical Controls: Automatic restart after power failure. Contacts for remote run and fault status. Elapsed time meter. Simplified controls using relay logic. 24 VAC signal wiring allows for low voltage wiring of humidistat. Control system monitors and controls unit function.

Drive System: Simple drive belt arrangement, few moving parts.



The Titanium Gel wheel is the most advanced of its kind. It contains an inert, non-corrosive, non-metallic, solid desiccant, manufactured to eliminate erosion, settling and attrition. The HoneyComb® design maximizes the transfer of water in vapor phase and minimizes air friction loss through laminar air flow. The desiccant will not break down even if saturated with water.



 Munters

Figure C5. DH equipment installed at Guam ECM 12AC20.



Figure C6. Stainless steel ducting connecting DH unit to ECM air input.



Figure C7. Installation of buried electrical line for Guam ECM 12AC20.



The collection of data for the DH system performance required that temperature and humidity sensors be placed in selected areas within the magazine (Figure C8 and Figure C9). Two sensors were mounted in the ECM for redundancy, and a third sensor was installed for DH system control. These sensors were interrogated through a data logger mounted on the outside headwall in a corrosion and weather-resistant box (Figure C10). Temperature and relative humidity data was downloaded 6 and 12 months after the commissioning of the DH system.

Service support for the DH systems was conducted on a six month and 12 month visit to the site. On-site personnel were trained in the simple maintenance tasks for system operation. Maintenance and repair of the DH equipment was included for the first two years of operation.

Figure C8. Wall-mounted sensors in ECM 12AC20.



Figure C9. Temperature/RH sensor in ECM 12AC20.



Figure C10. Data logger in a stainless steel weatherproof enclosure outside of ECM 12AC20.



Commissioning

The DH system was commissioned on 13 December 2011.

REPORT DOCUMENTATION PAGE

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					5c. PROGRAM ELEMENT NUMBER Corrosion Prevention and Control	
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14. ABSTRACT The Department of Defense (DoD) maintains many earth covered magazines (ECMs) on its installations including tropical coastal marine properties. ECMs are used to store a wide variety of explosive ordnance. Coastal marine locations are exposed to extreme humidity, high rainfall, and a chloride-infused atmosphere. These conditions create a damp, highly corrosive environment inside ECMs and can severely damage the structures and their contents, and promote rapid, mold growth that is hazardous to human health. The objective of this demonstration project was to install and evaluate electro-osmotic pulse (EOP) and dehumidification (DH) technologies in an Army ECM on Guam to mitigate water intrusion and excessively high interior relative humidity (RH), respectively. The demonstration was intended to evaluate how effective this technology combination is at reducing corrosive and unhealthy conditions inside an ECM. Demonstration results were promising but mixed. The DH system held interior RH to 40%–60% while outdoor RH ranged from 85%–95%. However, the demonstration period was not long enough for the EOP system to reach equilibrium and fully stop seepage. Because the EOP success metric could not be validated for purposes of calculating the project return on investment, the reported return is based only on DH system performance.						
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