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Demonstration of Dehumidification for Corrosion Control in Earth Covered Magazines

Final Report on Project F07-ARCTC02

Michael K. McInerney, Orange S. Marshall Jr.,
and Lawrence A. Gintert

October 2018

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Demonstration of Dehumidification for Corrosion Control in Earth Covered Magazines

Final Report on Project F07-ARCTC02

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Final report

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Under CPC Project F07-ARCTC02, "Dehumidification for Enhancement of Electro-
Osmotic Pulse Technology at Fort A.P. Hill, VA"

Abstract

Earth-covered magazines (ECMs) are used by the Army to store a wide variety of explosive ordinance. These munitions are subject to corrosion under humid conditions and during heavy rainfall. The objective of this project was to install dehumidification (DH) technology in two Earth Covered Magazines at Fort A.P. Hill, Virginia, to enhance the performance of the Electro-Osmotic Pulse (EOP) systems and collect performance and cost data to evaluate their combined efficacy during a one-year demonstration period. Controlling relative humidity (RH) would reduce the expense, damage, and impairment to readiness imposed by corrosion on stored munitions and could increase the design life of the ECM itself.

EOP technology was previously installed in ECMs at Fort A.P Hill for corrosion control under a separate project. During the current project, the RH inside the two magazines was measured and recorded. An EOP system was operating in conjunction with a DH system in one bunker for part of the study's duration. However, no conclusion can be made whether EOP added to the reduction in RH. The 30-year return on investment is projected to be 4.53, and using DH systems is recommended for critical storage facilities where high RH promotes corrosion or other degradation.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Corrosion Prevention and Control (CPC) Project FO7-ARCTCo2 “Dehumidification Technology for Enhancement of Electro-Osmotic Pulse Technology for Prevention of Corrosion of Munitions and Equipment in Ammunition Bunkers at Fort A.P. Hill” The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Ismael Melendez (IMPW-E), and Valerie D. Hines (DAIM-ODF).

The project was performed by the Materials and Structures Branch (CEERD-CFM), Facilities Division (CF), U.S. Army Engineer Research Center, Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL. Significant portions of this work were performed by Concurrent Technologies Corporation (CTC), Logis-Tech, Inc., and Mandaree Enterprise Corporation (MEC). Dr. Bill Abbott of Battelle provided atmospheric corrosion measurement data under a separate effort. 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.

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- Tim Beverly, Fire Inspector

The Commander of ERDC was COL Ivan P. Beckman, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters

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1 Introduction

1.1 Problem statement

U.S. Army installations worldwide maintain hundreds of earth-covered magazines (ECMs) that store a wide variety of ordnance used in everyday military training. Many ECM interiors have serious moisture-intrusion problems due to water seepage or inflow through concrete walls, floors, wall/ceiling joints, and door seals. Water in ECMs can corrode and penetrate metal storage boxes, causing their contents to become damp and degraded. Cracks in floors and walls of older ECMs continually deteriorate through freeze/thaw cycling, which fractures and spalls concrete and exposes lengths of steel rebar to corrosion processes. In addition to facilitating more water intrusion, concrete damage will progress over time until affected ECMs are unsafe to use, adding to the Army's increasing maintenance, repair, and replacement burdens.

In places with very high ambient humidity, such as coastal or island installations, water intrusion also contributes to poor interior air quality. ECM interior dampness not only promotes mold growth on walls and stored contents. It also provides favorable conditions for the growth of mold and bacteria inside these confined spaces, which can aggravate health conditions such as asthma and allergies in susceptible personnel. At installations where the ambient temperature often falls below freezing, ice formation on the floors of ECMs creates a safety hazard for forklift operators and interferes with timely delivery of munitions for training activities.

The Army typically does not dehumidify storage structures. To help keep munitions dry, Army personnel pack storage containers with desiccant materials. However, when water penetrates the interior of ECMs, the interior can become too humid for the desiccant to work effectively. The standard method for waterproofing ECMs is to (1) remove the earth cover, (2) replace the waterproofing membrane on the magazine, (3) install a drainage tile system as needed to eliminate any problems with standing water, and (4) replace the earth cover. This process is expensive, labor intensive, and time consuming. In addition, it disrupts facility operations during the work period, and eventually will need to be repeated. In any case, this procedure fails to address water intrusion via the floor by inflow or infiltration, so slab repair is likely to be an expensive additional mitigation cost.

Successful and cost-effective control of moisture seepage into subgrade concrete structures has been demonstrated by using a technology called electro-osmotic pulse (EOP). This technology has specifically been shown to be effective in reducing moisture intrusion through concrete in ECMs (Marshall 2007, 2008, 2009), but it cannot remove interior humidity that has entered through open air vents or poorly sealed doors. It seems reasonable to expect that using a dehumidification system in combination with EOP technology may provide superior results in keeping ECM interiors drier than using either technology individually.

The use of dehumidification (DH) systems in ECMs to date has been limited, and no data are available on the combined performance and effectiveness of DH and EOP systems in ECMs. The U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) was funded to test and validate this combination of technologies with support and funding from the Department of Defense (DoD) Corrosion Prevention and Control (CPC) Program.

1.2 Objective

The objective of this project was to install DH systems in two ECMs to collect and evaluate performance and cost data to determine the effectiveness of DH in combination with EOP technology for reducing interior relative humidity (RH) and improving corrosion control for stored munitions and munition containers.

1.3 Approach

Fort A.P. Hill, VA, was selected as the site for this project. This Army installation has reported a severe problem with large amounts of water seeping through the concrete walls, floors, and wall/ceiling joints of ECMs. During periods of high rainfall, the water depth inside magazines can reach 1.5 in. During humid periods when the temperature changes from cool to hot each day, interior humidity condenses on the cold metal surfaces inside the magazines, aggravating corrosive conditions already affecting ECM contents.

These earth-covered structures have concrete walls at the front and back, with corrugated steel arch ceilings mounted on top of 15 in. high concrete sidewalls. As part of a previous study (Marshall 2009), the demonstration magazines had been repaired by fixing floor cracks and sealing any other

sources for water intrusion so that standing water that would have elevated RH levels was no longer a factor.

In the same previous study (Marshall 2009), an ECM was emptied and used to evaluate the ability of EOP technology to stop water intrusion and to determine whether using EOP created an explosion risk. The following conclusions were made after analyzing that study's results:

- Implementation of EOP technology stops water intrusion through concrete into ECMs.
- The EOP system will maintain a dry interior concrete surface.
- An operating EOP system does not have any impact on existing lightning-protection systems.
- There is no danger of a spark being generated in an ECM due to the operation of an EOP system.

For the current study, DH systems had been installed in two ammunition storage magazines at Fort A.P. Hill, Virginia. At the time this study began, however, the EOP system was operating in only the empty magazine because ERDC-CERL had not received approval from the U.S. Army Technical Center for Explosives Safety (USATCES) to operate the EOP system in the other ECM. Performance of the DH systems was monitored via RH, and temperature sensors were installed inside each magazine (see section 2.3 for details). Section 1.5 (below) describes a limitation on execution of the demonstration as the result of a lightning strike at the demonstration site.

1.4 Metrics

The following observations by Lloyd (2017, 6) describe the general framework pertaining to RH and the interior conditions required for controlling the corrosion of stored metal materials:

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 satu-

rated 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.

The Department of the Army Pamphlet (DA-Pam) 385–64, “Ammunition and Explosives Safety Standards,” does not specify a minimum or maximum value for RH. However, it does state that static electricity accumulations but subsequent discharges are usually impossible if the RH is above 60%. According to Lloyd (2017), however, 60% is an unacceptable RH level for corrosion prevention. To define the minimum RH value as 40%, we referred to the electronics industry standard for electrostatic discharge protection, (JEDEC 1999). This standard is also applicable to explosives safety because the goal of both industries is prevention of electrostatic discharge, and the methods used are the same.

The metric for success of this demonstration/validation (dem/val) project was that the DH system be able to maintain interior RH between 40% and 60%. This target humidity range is also preferred for protecting human health and preserving the quality of nonmetal ECM contents because it reduces the growth of bacteria, molds, and fungi.

1.5 Scope

As stated above, the original plan noted that previously installed EOP systems were operative in only one of the two DH project ECMs at Fort A.P. Hill. Five months into the performance period (May 2008), a lightning strike disabled the one operative EOP power supply and control unit. Consequently, the research team was not able to collect a full year of both DH and EOP operational data from the ECM in which the EOP system was supposed to be operating.

2 Technical Investigation

2.1 Project overview

Figure 1 shows examples of water intrusion in a typical ECM, and Figure 2 shows corrosion forming on ammunitions stored in a typical ECM.

Figure 1. Water intrusion problems in ECMs at Fort A.P. Hill.

Figure 2. Ammunition corroding inside a typical ECM.

DH technology was installed in two ECMs, placed into service on 18 December 2007, and operated for one year. Environmental data (i.e., temperature and RH) and EOP system operating data were collected to evaluate system performance and perform an economic analysis. For comparison, RH data was collected in two adjacent ECMs without DH installed.

Contractors designed and installed DH systems for two ECMs at the Fort A.P. Hill Ammunition Supply Point (ASP). The design specifications incorporated a list of 12 detailed requirements from the U.S. Army Technical Center for Explosives Safety at the Defense Ammunition Center, McAlester, OK, that were developed from DA-Pam 385-64 (2011). To comply with those requirements, the DH equipment was installed beyond a 50-foot radius from the ECM and linked to it with ductwork. Also, the low setpoint for RH was specified to be no less than 40% due to the potential ammunition explosion from static electricity that is present in very dry environments. The DH systems were designed as open-loop configurations so that air exhausted from the magazines was not recirculated back to the DH units.

The basic DH technology used in the ECMs is illustrated in Figure 3. Moisture-laden air enters through the process inlet and moves through a rotating container that is packed with a desiccant medium. The desiccant adsorbs the water vapor, and the dehumidified air is delivered through the process outlet directly into the magazine. Then the desiccant medium rotates into the reactivation air stream where the hot reactivation air (heated in the DH unit) enters the rotating container, driving the moisture from the desiccant and exhausting the moisture into the atmosphere outside the magazine. After reactivation, the hot, dry desiccant rotates back into the process air stream where a small portion of the process air cools the desiccant so that it can begin the adsorption process again.

Figure 3. Schematic diagram of the dehumidification process.

The basic blueprints for the equipment are shown in Figure 4 and Figure 5, which are provided by the dehumidification contractor, Logis-Tech Inc. of Manassas, VA.

Figure 4. Dehumidification plan (Logis-Tech, Inc.).

Figure 5. Dehumidification system control and power panel details (Logis-Tech, Inc.).

2.2 Installation of the technology

There were two 300 SCFM (standard cubic feet per minute) DH units* used to dehumidify two ECMs—ECM 1 in building Po2013 (24 x 50 ft) and ECM 2 in building Po2003 (11 x 30 ft). ECM 1 would have DH only (due to lack of permission to operate an EOP system), and ECM 2 would have DH and EOP.

The DH equipment was installed on concrete pads located midway between ECMs Po2003 and Po2013, with ductwork connecting to the roof vents of the ECMs as shown in Figure 6, Figure 7, and Figure 8. A low-voltage temperature and humidity sensor was installed inside each ECM for control and monitoring of DH system performance. The communication

* Munters Cargocaire Model HC-300 dehumidifiers.

lines linking the sensors and the DH system were routed through ductwork to the ECMs. One installed sensor is shown in Figure 9.

Figure 6. DH equipment on concrete pads between the two ECMs.

Figure 7. Duct for delivering dehumidified air from DH system to ECM.

Figure 8. Adapter at ECM roof vent for ductwork interface.

Figure 9. White box on ceiling is an example of the low-voltage temperature and relative humidity sensor in ECM.

No modifications were made to the existing blastproof penetrations of the magazines for the DH ductwork connections and sensor communication lines. The DH units were powered by the AC circuit previously installed for the onsite EOP system.

As part of the DH installation contract, maintenance and repair was included for the DH equipment during the first 2 years of its operation.

2.3 Operation and monitoring

Service support for the DH systems was provided through scheduled quarterly onsite visits. Continuous offsite remote monitoring of performance

parameters (i.e., RH and electrical power use) by the subcontractor, Logis-Tech, was enabled by using a hardwired telephone connection. The project team trained Fort A.P. Hill personnel in simple maintenance tasks necessary for continued systems operation—primarily filter replacement, which is a monthly requirement.

The DH units were set to maintain the RH level inside the magazines between 40% and 50%. Because the capabilities of the DH systems to remove moisture were unknown, the units were set to the lower half (therefore less corrosive) of the ideal range. Note that the DH units do not humidify (add moisture to the air) in the event that the interior air's natural ambient RH falls below the target levels. In such cases, the DH units simply remain idle until the ambient RH naturally returns to the higher target levels.

2.4 Completion of field work

The field work was completed in January 2009.

3 Discussion

3.1 Results

A typical readout from the data collection system is shown in Figure 10. Ambient RH (outside the magazine), Control RH (inside the magazine), and Ambient Temperature (outside the magazine) are shown for each day of operation and indicate the daily averages.

Figure 10. Typical readout of temperature and humidity data for one month (as supplied by Logis-Tech in final contract report).

RH data are presented in Figure 11. Data were recorded from sensors in the two ECMs with DH, two ECMs without DH, and the outdoor RH sensor. The ability of the DH systems to control the interior RH is evident. The DH systems held the interior RH relatively constant at about 40%, while the outdoor RH was usually well above 60%. In the ECMs without DH, the interior RH fluctuated greatly and many times rose above 60%.

Since the ideal interior RH for corrosion prevention and safety is between 40% and 60%, data show that the DH systems were removing too much moisture during this demonstration. For this demonstration, however, it was decided not to change the settings because that might confound the analysis. In actual operation, the system's settings can be changed to reach the desired humidity level.

Figure 11. Relative humidity data recorded from ECMs with DH, ECMs without DH, and outdoors.

ECM 2 (green line) had EOP operating in addition to DH for part of the demonstration (until May 2008). For this operation period, the addition of EOP appears to assist in lowering the humidity level compared to ECM 1. However, the humidity levels at the end of the demonstration for ECM 2 are also lower than ECM 1, and the EOP was not operational at this time.

A previous study of the use of EOP in ECMs concluded that the EOP system will maintain a dry interior concrete surface in ECMs (Marshall 2009). Therefore EOP assists in reducing the interior humidity by reducing the moisture that travels through the concrete from the outside to appear on the ECM's interior concrete surfaces.

Fort A.P. Hill rainfall data for the demonstration period are listed in Table 1. Note that there were several very wet months when the EOP system was operating (March, April and May), and two very wet months when the EOP system was not operating (July and September). If moisture intrusion through the concrete was contributing significantly to the interior humidity, a couple of spikes in the interior humidity of ECM 2 would be expected in July and September, when the EOP system was not operating. There is a spike in July, but it is due to the ECM doors being opened. In this case, it appears that concrete moisture intrusion does not significantly influence the interior humidity, either because the moisture intrusion is very small or because air leakage through the door seals and penetrations dominates. Therefore, no conclusion can be made whether EOP is assisting with the reduction in humidity.

Table 1. Average monthly rainfall for Fort A.P. Hill*.

Month/Year	Monthly Total Rainfall (in.)	Maximum Daily Rainfall (in.)	Normal Monthly Total Rainfall (in.)
12/2007	–	0.84	3.18
01/2008	0.61	0.38	2.90
02/2008	–	1.15	2.51
03/2008	4.06	2.24	3.99
04/2008	5.76	2.20	3.35
05/2008	7.52	2.84	4.08
06/2008	–	1.75	3.97
07/2008	3.90	0.98	4.53
08/2008	–	0.13	3.39
09/2008	5.61	3.41	4.32
10/2008	0.91	0.35	3.38
11/2008	2.75	1.11	3.75
12/2008	2.95	0.69	3.18
01/2009	2.61	0.80	2.90
*Data for Fredericksburg, Virginia Sewage which is about 16 miles from Fort A.P. Hill ECMs. Data obtained from the National Weather Service (https://w2.weather.gov/climate/xmacis.php?wfo=lwx) Reporting Station: FEDV2 Network: National Weather Service Cooperative Observer Program Station Name: Fredericksburg Sewage Plant			

Personnel onsite at Fort A.P. Hill observed there were no problems encountered with installation or operation of the DH systems. During humid days, it was noted that one of the adjacent magazines with no DH treatment had water dripping from interior surfaces due to condensation. It was observed that the ductwork had become partially separated at the field expansion joints during cold weather, presumably due to contraction of the materials. This problem was corrected during a maintenance operation.

The electric use and the annual cost of electricity for each DH system are shown in Table 2 and Table 3. ECM 1 is considerably larger than ECM 2 (1,200 sq ft versus 330 sq ft), so the interior volume in the larger structure may account for the extra hours of DH operation in ECM 1.

Table 2. Hourly electric use for each DH system.

ECM	Voltage (V)	Current (A)	Electric Use (kW/hr)
1	240	11.6	2.784
2	240	11.6	2.784

Table 3. Annual electric cost for each DH system.

ECM	Electric Use (kW/hr)	Operating Time (hr/day)	Unit Cost (\$/kW)	Annual Electric Cost (365 days)
1	2.784	6.07	0.095	\$586
2	2.784	5.43	0.095	\$524

3.2 Lessons learned

3.2.1 Site selection

The degree of moisture intrusion during the study period was relatively low, partly due to the repairs made to the ECMs when the EOP system was installed (grouting of concrete cracks and repair of leaky joints).^{*} However, as the corrosivity data indicate, the general atmosphere at this site is not as corrosive as at many other sites where the Army operates ECMs, such as coastal locations, where it is not only humid but the corrosivity of the air is increased due to elevated chloride levels. Therefore, while the installation and operation of the DH equipment has been demonstrated to maintain an acceptable humidity level inside the storage areas of the magazines at a quantifiable cost, the potential benefit of preventing corrosion

^{*} See Marshall (2009) for information on the EOP system installation and demonstration.

of munitions was not as dramatic as it could have been at a site with a more aggressive corrosion environment.

3.2.2 System design

During the project-launch meeting, it was decided that an open system configuration (i.e., no return air from the ECM circulated back through the DH system) was preferred in this application due to potential safety concerns associated with the accumulation of hazardous fumes or gases emanating from ordnance stored in ECMs.

It was also determined that low-voltage sensors with telephone communication lines routed through the ductwork to the interior of the magazines provided an acceptable configuration for maintaining continuous monitoring and control of the DH system. However, there was a minor difficulty in initially establishing communication with the sensors over telephone lines because a data firewall was already in place at the installation. Upon receiving approval to proceed, communications worked flawlessly.

There were minor failures of expansion joints in the ductwork due to separation during cold weather, as shown in Figure 12. These joints were easily reconnected, and configuration of the expansion joints was modified for future installations.

Figure 12. Separation of ductwork expansion joints in cold weather.

3.2.3 Operation

The DH systems operated as expected at minimal operating costs. The systems did not create any difficulties at the ASP, according to installation personnel.

The RH within the magazines was generally maintained between 40% and 60%, with the exception of a few days during the study when the doors of the subject ECMs were open for transfer of munitions and/or testing of the EOP system. Otherwise, the RH was maintained at a steady level. There were isolated instances when interior RH dropped below the optimum level due to the low ambient outdoor humidity. A DH system does not raise the RH on exceptionally dry days; a humidifier must be used in these cases. Setting the interior humidity control to a higher RH value might minimize this problem. (For this effort, the control was set to 40%, the minimum of the optimum range.)

4 Economic Summary

4.1 Costs and assumptions

Total project costs were \$230,000. A rough breakdown of project expenses is presented in Table 4.

Table 4. Breakdown of total project costs.

Description	Amount
Labor	\$110,500
Dehumidification Systems Installation (including equipment and materials)	\$44,100
Two- year maintenance contract (\$1,750 per system)	\$3,500
Monitoring Equipment	\$36,900
Travel	\$20,000
Reporting	\$15,000
Total	\$230,000

The technology was installed in two ECMs at Fort A.P. Hill.

A factor not addressed in the ROI computations was \$100,000 in erratically occurring flood damage during heavy rains. If either system prevented flooding, then the ROI would increase due to cost savings. If a system did not prevent flooding, then its costs would be the same as the status quo and offer no savings, but it would not present an additional liability beyond that affecting unprotected magazines. Thus, the flood damage expense was left out of the calculations.

Baseline costs (Alternative 1), new system costs (Alternative 2), and new system benefit cost savings (Alternative 2) are listed in Table 5.

Table 5. Costs used in ROI computation.

	Baseline				New System Cost				New System Benefit				
	Install	Maintain	Replace	Total	Install DH	Operate	Maintain	Total	Replace	Overhaul	Damage	Training	Total
1	334,000	1,000		335,000		1,200		1,200			1,000		1,000
2		1,000		1,000		1,200		1,200		2,000	1,000		3,000
3		1,000		1,000		1,200	1,800	3,000	100,000		1,000	25,000	126,000
4		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
5		1,000		1,000		1,200	1,800	3,000			1,000		126,000
6		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
7		1,000		1,000		1,200	1,800	3,000			1,000		1,000
8		1,000		1,000		1,200	1,800	3,000	100,000	2,000	1,000	25,000	128,000
9		1,000		1,000		1,200	1,800	3,000			1,000		1,000
10		1,000		1,000		1,200	1,800	3,000		2,000	1,000		128,000
11		1,000		1,000		1,200	1,800	3,000			1,000		1,000
12		1,000		1,000		1,200	1,800	3,000	100,000	2,000	1,000	25,000	128,000
13		1,000		1,000		1,200	1,800	3,000			1,000		1,000
14		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
15		1,000		1,000		1,200	1,800	3,000			1,000		126,000
16	334,000	1,000		335,000	44,100	1,200	1,800	47,100			1,000		1,000
17		1,000		1,000		1,200	1,800	3,000	100,000		1,000	25,000	126,000
18		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
19		1,000		1,000		1,200	1,800	3,000			1,000		1,000
20		1,000		1,000		1,200	1,800	3,000		2,000	1,000		128,000
21		1,000		1,000		1,200	1,800	3,000			1,000		1,000
22		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
23		1,000		1,000		1,200	1,800	3,000	100,000		1,000	25,000	1,000
24		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
25		1,000		1,000		1,200	1,800	3,000			1,000		1,000
26		1,000		1,000		1,200	1,800	3,000		2,000	1,000		3,000
27		1,000		1,000		1,200	1,800	3,000			1,000		1,000
28		1,000		1,000		1,200	1,800	3,000	100,000	2,000	1,000	25,000	3,000
29		1,000		1,000		1,200	1,800	3,000			1,000		126,000
30		1,000	900,000	901,000	44100	1,200	1,800	47,100		2,000	1,000		3,000

4.1.1 Alternative 1 (protective membrane system)

The membrane protective system was assumed to prevent the same water intrusion-related corrosion damage as an EOP system. However, humidity-related condensation was observed in untreated magazines, so an assumption that membrane-only systems can maintain the desired interior RH range is probably optimistic.

The cost to remove the soil cover and add a moisture-impermeable membrane is estimated to cost about \$500,000 for three bunkers. Thus, a cost of \$334,000 was used for two magazines.

The membrane system is estimated to have a 15-year service life and \$1,000 per system in annual maintenance expenses.

Because the membrane system is inadequate in preventing deterioration of the bunkers due to corrosion of the structures, the membranes will not prevent needed replacement of the bunkers (at a per-bunker cost of \$450,000). The bunkers are assumed to be replaced in Year 30.

4.1.2 Alternative 2 (dehumidification technology)

The expected life of a DH system is 15 years (assuming yearly maintenance). The cost to install DH systems in two ECMs is \$44,100. This amount is not included in year one of the ROI computation because those units' cost is included in the project costs.

The maintenance and repair agreement for the two DH systems is \$1,800 per year. This amount is not included in year one and two of the ROI computation because the initial two year maintenance and repair agreement costs are included in the project costs.

The electrical cost to operate the two DH systems is \$1,200 per year.

It is assumed that the DH systems will save the cost of bunker replacement at 30 years.

Installation of DH systems will provide a cost materials avoidance for corrosion-related maintenance and repair to doors and hardware in the magazines of \$2,000 every other year and \$1,000 every year for water cleanup and losses to pallets plus other supplies required to keep materiel dry that is stored in the magazines. In addition, heavy prolonged rains could result in \$100K losses in materiel stored in the magazines and \$25,000 of delayed or lost training due to water (or ice if the weather is cold enough) in the magazines. It is assumed that a heavy rain event occurs about every five years.

4.2 Projected return on investment (ROI)

The 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 alternatives, the 30-year return on investment is projected to be about 4.53, as shown in and Table 6.

Table 6. ROI computation.

Investment Required			230,000
Return on Investment Ratio	4.53	Percent	453%
Net Present Value of Costs and Benefits/Savings	54,703	1,097,371	1,042,668

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	335,000		1,200	1,000	1,122	314,026	312,904
2	1,000		1,200	3,000	1,048	3,494	2,446
3	1,000		3,000	126,000	2,449	103,670	101,221
4	1,000		3,000	3,000	2,289	3,052	763
5	1,000		3,000	126,000	2,139	90,551	88,412
6	1,000		3,000	3,000	1,999	2,665	666
7	1,000		3,000	1,000	1,868	1,245	-623
8	1,000		3,000	128,000	1,746	75,078	73,332
9	1,000		3,000	1,000	1,632	1,088	-544
10	1,000		3,000	128,000	1,525	65,571	64,046
11	1,000		3,000	1,000	1,425	950	-475
12	1,000		3,000	128,000	1,332	57,276	55,944
13	1,000		3,000	1,000	1,245	830	-415
14	1,000		3,000	3,000	1,163	1,551	388
15	1,000		3,000	126,000	1,087	46,025	44,938
16	335,000		47,100	1,000	15,953	113,803	97,850
17	1,000		3,000	126,000	950	40,208	39,258
18	1,000		3,000	3,000	888	1,184	296
19	1,000		3,000	1,000	830	553	-277
20	1,000		3,000	128,000	775	33,334	32,558
21	1,000		3,000	1,000	725	483	-242
22	1,000		3,000	3,000	677	903	226
23	1,000		3,000	1,000	633	422	-211
24	1,000		3,000	3,000	591	788	197
25	1,000		3,000	1,000	553	368	-184
26	1,000		3,000	3,000	517	689	172
27	1,000		3,000	1,000	483	322	-161
28	1,000		3,000	3,000	451	602	150
29	1,000		3,000	126,000	422	17,856	17,434
30	901,000		47,100	3,000	6,189	118,786	112,597

The original ROI ratio from the Project Management Plan (PMP) was estimated at 6.26. Many of the cost and benefit estimates used in the PMP were refined during the project, but those changes were minimal. The biggest difference between the original and revised ROI assumptions was the frequency of damaging rain events. The original assumption (one event per year) was revised to reflect a more realistic frequency of one event every 5 years. This revision had the effect of reducing the expected interior damage to ECMs over time.

5 Conclusions and Recommendations

5.1 Conclusions

Dehumidification equipment was installed and operated for a one-year demonstration period. Accurate cost information was recorded, and a very conservative ROI ratio of 4.53 was demonstrated. The RH inside the two magazines under study was measured and recorded, demonstrating operational effectiveness of the equipment and system at maintaining a consistently low, yet safe RH level.

An EOP system was operating in conjunction with a DH system in one bunker for part of the study's duration. However, no conclusion can be made whether EOP added to the reduction in humidity.

The RH within the magazines was generally maintained between 40% and 60%, with the exception of a few days during the study when the doors of the subject ECMs were kept open for munitions purposes. Otherwise, the RH was maintained at a steady level. There were instances where the RH had naturally dropped below the optimum level in this location, due to the outdoor humidity falling below 55%. Because the DH system does not govern the RH to remain above 30% on exceptionally dry days, a humidifier must be used in such cases to suppress the buildup of static electricity. Using a higher interior humidity setpoint for the lower bound of the target range might minimize this problem. In this work, the control was set to 40% RH, which is the minimum of the optimum range.

Based on the results of this project, it is concluded that the application of DH technology to reduce corrosion effects on munitions stored in ECMs in high-humidity areas will produce a positive ROI.

5.2 Recommendations

5.2.1 Applicability

As part of the determination of technology applicability, the specific storage facility should be assessed to determine if the storage areas are exposed to continual high humidity. The Fort A.P. Hill demonstration did not fully test the system in the most severe humid conditions due to the relatively mild climate at that location.

This study demonstrated that DH technology is effective at controlling humidity levels at values that inhibit corrosion, and the technology should be considered for other types of critical storage facilities where high humidity promotes corrosion or other degradation of stored contents.

Also, it is recommended that future installations of DH technology for ECMs use a configuration with DH units mounted on the magazine head-wall so that the ductwork requirement is minimized and the operating efficiency is maximized.

5.2.2 Implementation

It has not been established to what degree DH and EOP technologies contribute to improved conditions via humidity reduction in ECMs. Therefore, guidance for widespread implementation is not yet established due to the limited amount of data on the EOP system.

UFC 4-420-01 (1 May 2015), “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 webpage* as an example of a successful application of dehumidification to control humidity in ECMs. Sections of UFC 4-420-01 relevant to this project are reproduced in the Appendix of this report.

* http://www.wbdg.org/design/ammo_magazines.php

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Appendix: Excerpts from UFC 4-420-01 “Ammunition and Explosives Storage Magazines”

Sections of UFC 4-420-01 (1 May 2015) are relevant to this project—Purpose and Scope (Section 1.1) and Temperature and Humidity Control (Section 3-5.2) are reproduced below.

Section 1.1: Purpose and Scope

This UFC serves as a reference tool to assist in the planning and design of Ammunition and Explosives (AE) storage magazines for the Department of Defense (DoD), by providing definitions and information related to the design, selection, and siting of these unique facilities. This UFC is intended to assist in the selection of a magazine design by providing available options and information related to the use of designs that have been used in the past and have been approved by the Department of Defense Explosives Safety Board (DDESB). The individual DoD Services can also provide additional guidance on the selection of magazine designs.

A web site designed to be a companion resource to this UFC is located on the Whole Buildings Design Guide and can be accessed at: http://www.wbdg.org/design/ammo_magazines.php. This web site provides the following additional information and resources:

- Available electronic copies of referenced military regulations, manuals and standards.
- Available design drawings, approval letters, and specifications for 7-Bar and 3-Bar Earth-Covered Magazines (ECM) that have been approved for new construction.
- Available drawings and related information for the designs of 7-Bar and 3-Bar ECM that are no longer approved for new construction but still in use.
- Available drawings and related information for the designs of ECM and Aboveground magazines (AGM) and containers that have been approved for restricted use.
- A listing of the existing magazine designs that are classified as undefined

- Available drawings for barricade design utilizing various construction materials.
- Links to additional related resources and publications.

This UFC, when used with the companion web site, provides planners and designers of AE storage facilities access to up to date information and resources needed in the selection and design of new storage magazines and in the evaluation of existing facilities.

Section 3-5.2: Temperature and Humidity Control.

In some cases, due to specific criteria or determination that ventilation alone is inadequate, the AE product being stored may require more than just ventilation control. Specific criteria for special storage requirements should be provided by the using activity. For this application, some form of heating and cooling will be required. For cooling, heating, and humidity control systems, the following must be considered:

- Determine location of mechanical equipment. Will mechanical equipment require its own space outside of the magazine?
- Determine acceptable paths of connection from mechanical equipment to interior of magazine. Are penetrations compliant with structural integrity?
- Coordinate lightning protection with mechanical equipment and establish bonding requirements to ensure continuity of duct and piping.
- Mechanical humidity control using mechanical cooling requires some form of reheat. Reheat must be in accordance with ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.
- Mechanical humidity control using a desiccant drying system requires some form of desiccant regeneration (either integral to a package unit or by desiccant replacement). Base final determination on a Life Cycle Cost Analysis.
- Determine the hazardous location classification of the atmosphere within the magazine and select equipment and materials compatible with that classification (e.g. Class1, Division 2).
- Coordinate with the user on the criticality of maintaining the space environmental conditions and determine if sensors and

status points should be provided and connected to the base Energy Monitoring and Control System for remote monitoring or to another central monitoring site.

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14. ABSTRACT Earth-covered magazines (ECMs) are used by the Army to store a wide variety of explosive ordinance. These munitions are subject to corrosion under humid conditions and during heavy rainfall. The objective of this project was to install dehumidification (DH) technology in two Earth Covered Magazines at Fort A.P. Hill, Virginia, to enhance the performance of the Electro-Osmotic Pulse (EOP) systems and collect performance and cost data to evaluate their combined efficacy during a one-year demonstration period. Controlling relative humidity (RH) would reduce the expense, damage, and impairment to readiness imposed by corrosion on stored munitions and could increase the design life of the ECM itself. EOP technology was previously installed in ECMs at Fort A.P Hill for corrosion control under a separate project. During the current project, the RH inside the two magazines was measured and recorded. An EOP system was operating in conjunction with a DH system in one bunker for part of the study's duration. However, no conclusion can be made whether EOP added to the reduction in RH. The 30-year return on investment is projected to be 4.53, and using DH systems is recommended for critical storage facilities where high RH promotes corrosion or other degradation.					
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