DEMONSTRATION OF ELECTRO-OSMOTIC PULSE TECHNOLOGY FOR GROUNDWATER INTRUSION CONTROL IN CONCRETE STRUCTURES

Vincent Hock
CECER-FL-M
217-373-6753

Michael McInerney, P.E.
CECER-FL-P
217-373-6759

Erik Kirstein
CECER-FL-M
217-352-6511

ABSTRACT

Groundwater intrusion through a building's foundation can cause serious damage. Basement dampness can ruin expensive mechanical equipment which is often located in basement space, can increase maintenance requirements, and can make affected areas uninhabitable or even unusable. A system, based on electro-osmosis, has been developed to prevent water intrusion through concrete structures by applying a pulsating electric field between the structure and the surrounding soil. Electro-Osmotic Pulse (EOP) technology can mitigate some water-related problems from the interior of affected areas without the cost of excavation. The EOP alternative can further mitigate corrosion damage to mechanical equipment and lessen mold problems by lowering the indoor humidity.

INTRODUCTION

Groundwater intrusion through a building’s foundation can cause serious damage. Basement dampness can ruin expensive equipment, e.g., Heating Ventilation, and Air-Conditioning (HVAC) equipment, which is often located in basement space; can increase maintenance requirements (frequent repainting or cleaning to combat mold growth); and can make affected areas uninhabitable or even unusable (e.g., poor air quality).

In older buildings, such as those common on U.S. Army installations, severe damp-basement problems call for immediate action to mitigate water damage. In selective problem areas, the usual approach is to ‘trench and drain’, in other words, to excavate and expose the wall area and the base of the foundation, to replace dampproofing on the wall surface, and to install a drain tile system around the building or affected area. This expensive process is further complicated by the fact that most contractors limit their warrantees against future seepage in areas with high water tables.

Electro-osmotic pulse (EOP) technology offers an alternative that can mitigate some water-related problems from the interior of affected areas without the cost of excavation. The EOP alternative can further mitigate corrosion damage to mechanical equipment and lessen mold problems by reducing the indoor humidity.

Although new applications are still being developed, electro-osmosis is not a recently discovered phenomenon. In 1809, F.F. Reuss originally described electro-osmosis in an experiment that showed that water could be forced to flow through a clay-water system when an external electric field was applied to the soil. Research since then has shown that flow is initiated by the movement of cations (positively charged ions) present in the pore fluid of clay, or similar porous medium such as concrete; and the water surrounding the cations moves with them. Electro-osmosis can be used to arrest or cause flow of water as well as the ions in it. Electro-osmosis has been used in civil engineering to dewater dredgings and other high-water content waste solids, consolidate clays, strengthen soft sensitive clays, and increase the capacity of pile foundations. It has also received significant attention in the last five years as a method to remove hazardous contaminants from groundwater or to arrest water flow.

A system has been developed to apply electro-osmosis commercially within concrete structures by applying a pulsating direct electric field combined with an off-period. It is called electro-osmotic pulse (EOP). The pulse sequence consists of a pulse of positive voltage (as seen from the dry side of the concrete wall), a pulse of negative voltage, and a period of rest when no voltage is applied. The pulse of positive voltage has the greatest time duration. The amplitude of the signal is typically on the order of 20 to 40 Volts DC (VDC). The electrical pulse causes cations (e.g., Ca^{++}) and associated water molecules to move from the dry side (anode) towards the wet side (cathode) against the direction of flow induced by the hydraulic gradient, thus preventing water penetration through the buried concrete structure. One of the most critical aspects of this technology is the negative voltage pulse. This allows control of the amount of moisture within the concrete which prevents overdrying of the concrete matrix and subsequent degradation. Field tests were conducted to assess the feasibility and cost effectiveness of EOP technology at selected Army installations.

BACKGROUND

If ions of one sign are preferentially adsorbed[1] at a solid-solution interface, a net charge or electric potential difference develops across the interface. This phenomenon is referred to as *electro-osmosis*. (The basic physics and chemistry of electro-osmosis can be found in several textbooks and treatises. [1, 2, 3]) It was found that when a potential difference is applied to electrodes immersed into an electrolyte solution on opposite sides of a porous plug or fine capillary tube, a flow of the solution results. Similarly, when a solution is forced through such a barrier by hydrostatic pressure, a potential difference develops between the solution on one side of the barrier and that on the other. This is called the *streaming potential*.

Descriptions of these phenomena are based on the concept of electric double layer. A layer of ions, which is approximately a single ion in thickness, of one sign is firmly adsorbed on the solid surface or particle, the sign of the charge depending on the nature of the surface and other conditions. The region as a whole is electrically neutral, and an equal number of opposite electric charges are present in an adjacent ionic atmosphere which, as the term implies, becomes more attenuated as distance from the surface increases. This is called the diffuse layer. When the solid surface and fluid are in relative motion, there exists a velocity gradient, and a thin film of solution, together with the ions it contains, is immobilized near the wall. Part of the ion atmosphere moves with the solution, and part (together with adsorbed ions) effectively belongs to the surface. As a result, the liquid phase and the wall have different net electric charge, and the application of an external electric field produces relative motion.

For example, electro-osmosis occurs in clay soils when cations in the diffuse layer are driven by the application of an external electric field. As a result, a velocity field in the pore fluid develops (Figure 1). The velocity distribution changes rapidly near the particle’s surface, but then becomes flat at the edge of the diffuse layer. Hence, electro-osmotic flow appears as plug flow through the pores of soil.

---

[1] To adsorb is to collect in condensed form on a surface.

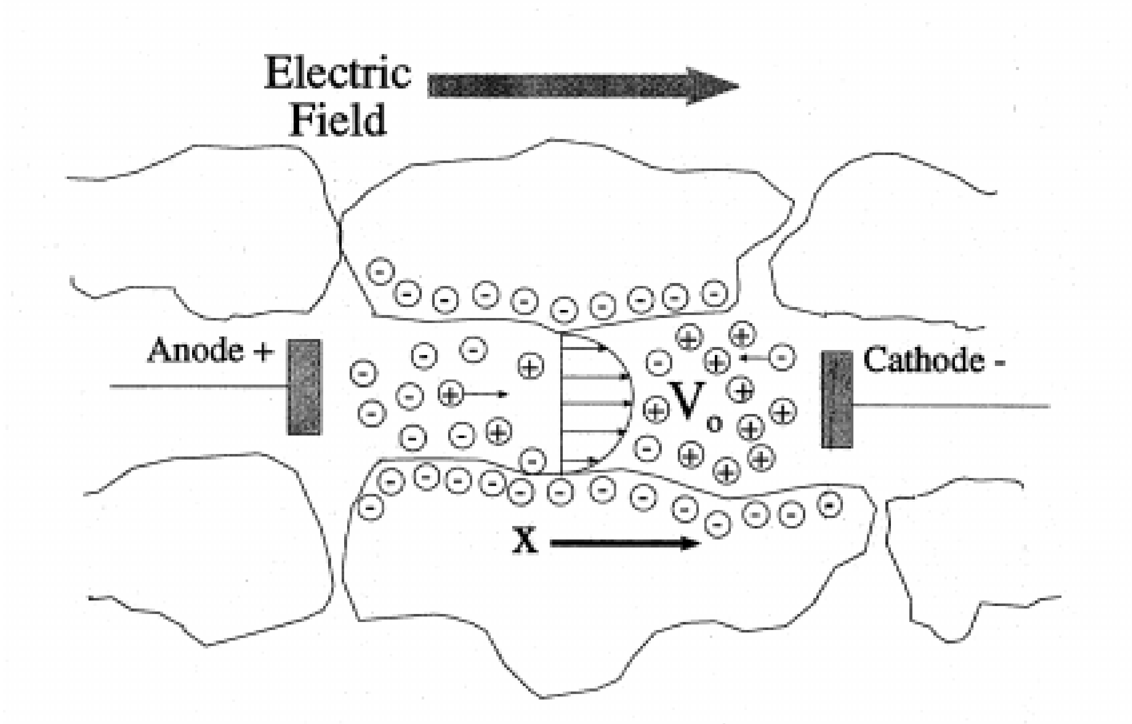

FIGURE 1. Movement of cations in a soil pore by electro-osmosis.

The velocity profile reaches a constant value (V_o) a short distance from the particle's surface. To determine V_o, a steady-state equation of motion is written as:

$$\mu \frac{\partial^2 V_x}{\partial y^2} + E_x \varepsilon \frac{d^2 \phi}{d y^2} = 0 \qquad (1)$$

where:

μ	=	the viscosity of the solution;
V_x	=	the velocity of the solution parallel to the particle surface;
y	=	the distance orthogonal to the particle surface;
E_x	=	the externally applied electric field gradient;
ε	=	the permitivity of the solution; and,
ϕ	=	the electrical potential gradient.

By the Debye-Hückel approximation, ϕ is written as

$$\phi = \xi \exp\left(- y \sqrt{\frac{2 n_i^{\infty} Z_i^2 F^2}{\varepsilon RT}} \right) \qquad (2)$$

where:

ξ	=	the zeta potential[2];
n_i^{∞}	=	the concentration of constituent i in free solution;
Z_i	=	the equivalents/mole of constituent i;
F	=	Faraday's constant;
R	=	the universal gas constant; and,
T	=	the absolute temperature.

When (1) is solved using the boundary conditions,

$$\begin{aligned} V_x &= 0 \quad at\ y = 0 \\ V_x &= V_0 \quad at\ y \gg 0 \end{aligned} \tag{3}$$

The velocity V_o is then obtained:

$$V_0 = \frac{\varepsilon \xi}{\mu} E_x \tag{4}$$

Of the four independent variables in (4), E_x can be controlled to redirect the movement of the solution.

One example of the pulsating electro-osmotic technique consists of a positive voltage pulse, a negative voltage pulse, and a period of zero voltage. Figure 2 shows this example waveform for the pulsating electro-osmotic pulse or EOP system. The positive voltage pulse has the longest interval and the negative voltage pulse has the shortest interval. As a result of this, the pore fluid moves (on the average) in one direction.

---

[2] The zeta potential is the difference of potential between the plates of a hypothetical capacitor used to model the diffuse layer.

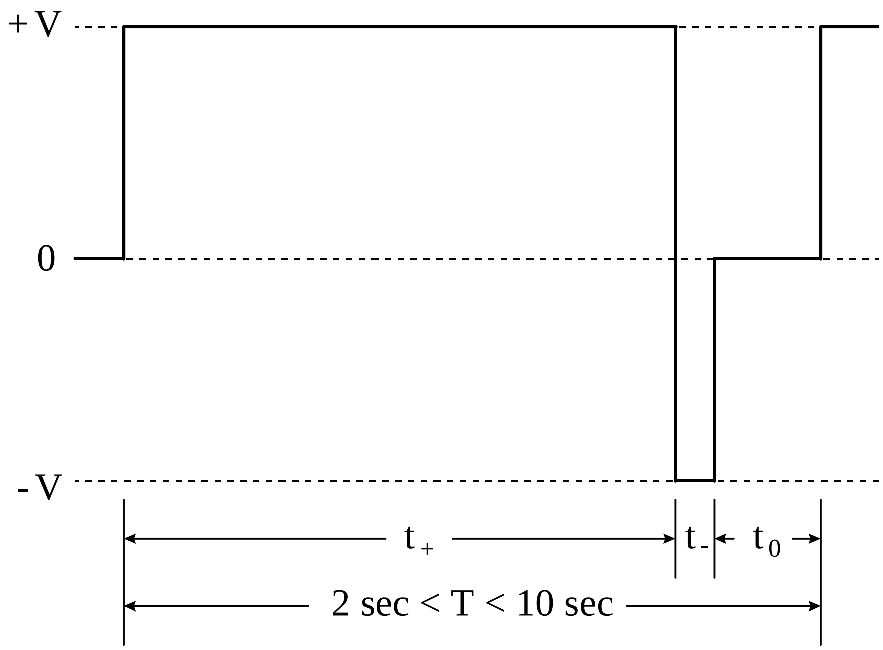

FIGURE 2. Example EOP voltage waveform.

Currently, the reasons for the increased performance of the EOP system over standard dc electro-osmosis for drying concrete are not well understood. However, it is speculated that the change in polarity results in the reversal of some of the chemical reactions occurring during electrolysis. It is also believed that the rest phase (period of zero voltage) allows the system to equilibrate. As a result of these effects, undesirable side effects such as acid production and increased corrosion are avoided. Also, use of a pulse sequence might prevent the concrete from becoming too dry.

An EOP system is realized by inserting anodes (positive electrodes) into the concrete wall or floor on the inside of the structure and by placing cathodes (negative electrodes) in the soil directly outside the structure. The density of the anode and cathode placement is determined from an initial resistivity test of the concrete and soil. The objective is to achieve a certain current density and thus create an electric field gradient in the concrete.

TECHNOLOGY DEMONSTRATIONS

Two sites were selected for EOP technology demonstrations, Building 3265, a guest barracks at Fort Jackson, SC and Building 5, the Health Clinic at McAlester AAP, OK. In both cases, the location of the groundwater intrusion was through the floor and walls of poured concrete basements.

FT JACKSON

Building 3265 had a history of water seepage into the concrete basement mechanical room. The mechanical room had experienced water levels within the structure as high as 36 cm. On the average, there existed about 5 cm of standing water. In addition, there was seepage from cracking in the wall, efflorescence, and poor air quality as a result of the high indoor humidity. This seepage initiated corrosion of the mechanical equipment located in the basement, requiring replacement as often as every two years.

For the EOP system, eighty-three (83) rubber-graphite anodes were coated with a graphite-mortar mixture and inserted into holes drilled into all four walls, approximately 13 cm from the floor and 46 cm apart. Twenty-four feet of rubber-graphite conductive cable was installed around the base of a concrete pad that supported steel water tanks in the room. Three copper-clad steel ground rods (cathodes) were driven into the soil adjacent to the exterior side of the concrete wall. The EOP Control Unit was mounted on one wall and all wiring from the anodes and cathodes was enclosed and wired into the unit. Figure 3 presents a layout of the EOP installation at Ft. Jackson.

MCALESTER AAP

The basement of Building 5 had standing water in several areas. Problems similar to the basement at Fort Jackson were prevalent; water seepage from cracking in the wall, efflorescence and high indoor relative humidity (70 percent). In this case the reduction of the indoor air humidity is very important, as one of the rooms is the Industrial Hygiene Office, occupied by an individual 40 hours a week.

Analysis of water infiltration revealed that only about half the basement was leaking, therefore the EOP system was installed only in the areas of infiltration. Rubber-graphite anodes were installed 13 cm above the floor and 28 cm on center. The total number of anodes used was 95. Four copper-clad steel ground rods (cathodes), 2.44 m long, were driven into the soil in the crawl spaces adjacent to the concrete wall in selected areas. Figure 4 shows the arrangement of the EOP installation at McAlester AAP.

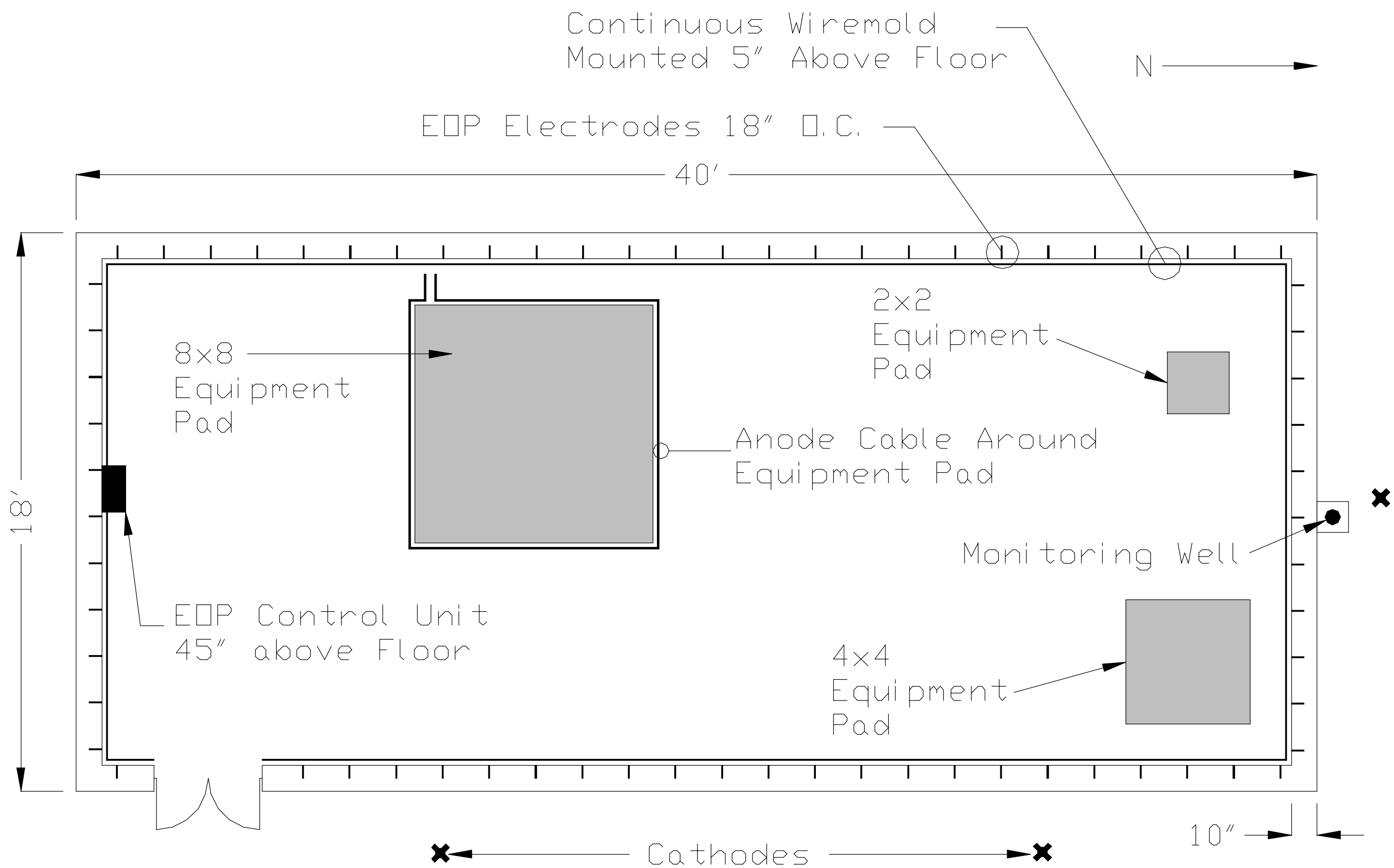

FIGURE 3. Layout of EOP installation at Ft. Jackson.

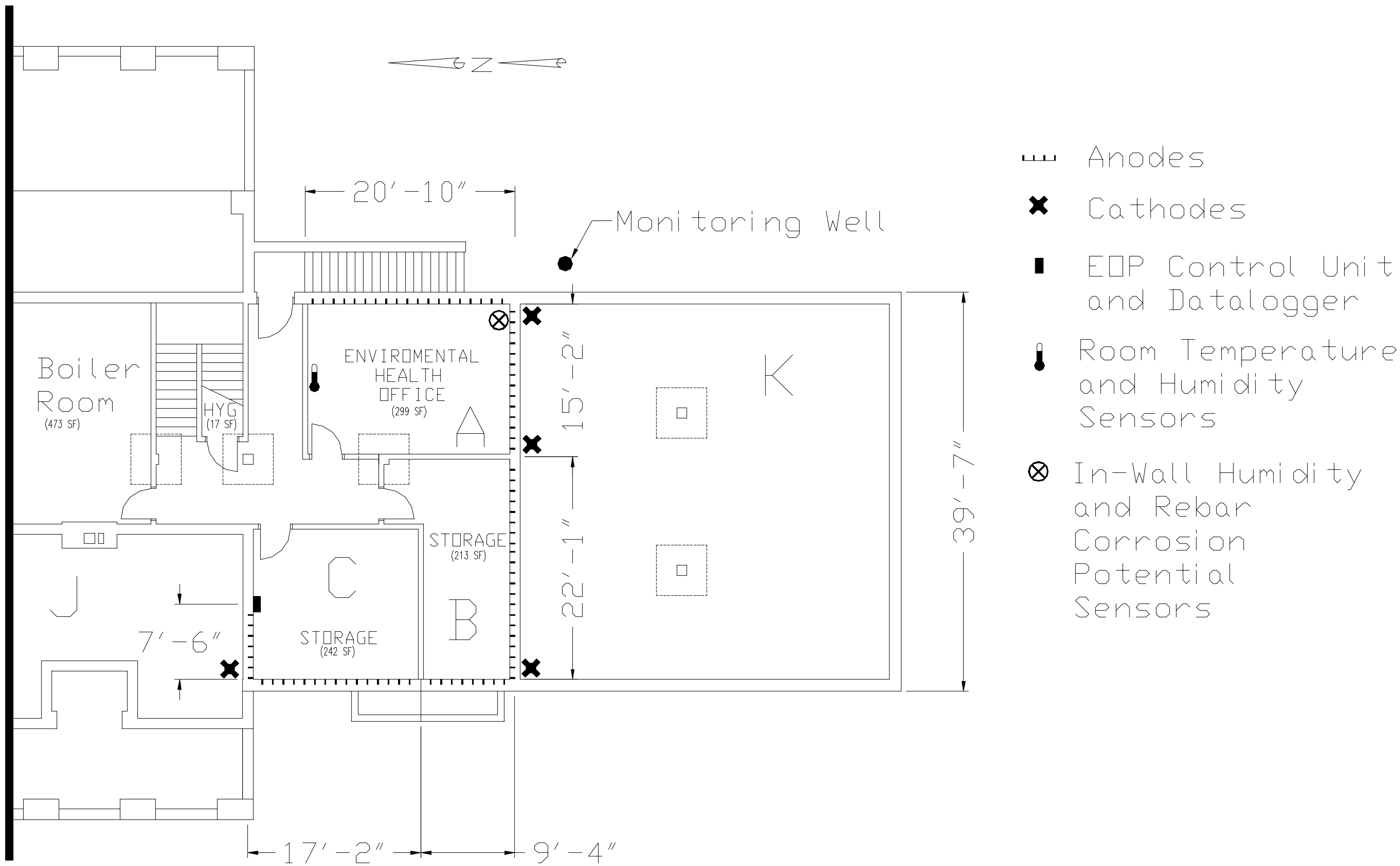

FIGURE 4. Arrangement of EOP installation at McAlester AAP.

EOP OPERATIONAL DATA

FT Jackson

The EOP dc output current was within acceptable limits, varying from 0.75 amps for a high humidity environment to less than 0.2 amps for a low humidity environment. Direct variation of current with humidity is a result of the characteristics of the EOP system. The EOP power supply produces a voltage pulse of constant amplitude (i.e. a constant voltage power supply). Since the resistivity of the concrete is inversely proportional to the amount of water present in the concrete, as the water is slowly driven out, the resistivity of the concrete increases, decreasing the current load of the power supply. (Recall Ohm's Law, current is inversely proportional to resistance.) Table 1 shows measured current and voltage outputs of the EOP power supply. The slight increase in output current is due to the higher water table during July and August 1996.

TABLE 1. Ft. Jackson EOP power supply dc output current.

Date of Reading	DC Volts	DC Amps
1995/01/10	+37	0.20
1996/08/15	+30	0.75

Concrete moisture readings were taken at different locations on the walls. Table 2 lists the moisture measurements that were taken at three different times; at the time of installation, at the 5-month performance check, and 2 years after installation. The data are presented as percent relative humidity. All measurements were made at the concrete surface, not internally. The most suitable humidity for concrete structures is ≈70 percent. Note the direct correspondence between the power supply current (Table 1) and the concrete humidity (Table 2).

TABLE 2. Concrete moisture readings in Building 3265, Ft. Jackson.

	% Relative Humidity at Surface			
Date of Reading	A	B	C	D
1994/08/23	94	92	98	98
1995/01/10	44	43	68	64
1996/08/15	73	72	76	77

The corrosion potential of rebar specimens was investigated. Several small (~5-cm long) sections of 1.27-cm steel rebar were embedded in various locations in the basement walls. The purpose of these specimens was to document whether any change occurred in the native corrosion potential of rebar that might be embedded in a concrete structure when an EOP system is operating. The corrosion potential of the specimens was tracked and compared to the average corrosion potential for reinforcing steel in concrete, which is approximately -0.2 VDC. Table 3 lists the corrosion potentials for some of the specimens. These potentials were taken at the 5-month performance check on 10 January 1995. This data shows no significant difference in the corrosion potential from the native potential. However, this is just one time sample of a dynamic system, a larger record will be needed to fully document the EOP system effect on rebar corrosion potential.

TABLE 3. Rebar specimen corrosion potentials.

	Potential (Volts DC)		
Specimen	Minimum	Maximum	Average
3	-0.190	-0.200	-0.195
5	-0.204	-0.224	-0.214
9	-0.145	-0.154	-0.150

The water table level is a good indication of EOP system performance: if the water table is above the floor of the basement and the basement remains dry, then the EOP system is fulfilling its purpose. A monitoring well was installed just outside the basement wall for the purpose of tracking the level of the water table relative to the basement floor. (It’s location is shown in Figure 3.) Figure 5 shows the hydrograph for the monitoring well from September 1995 until September 1996. (Groundwater temperature just happened to be included in the standard monitoring well ‘package’, it was not used in this study.) Note there are several times during the recording period when the water table exceeded the basement floor level. In previous years the basement would have flooded during these periods, however now because of the EOP system the basement remains dry.

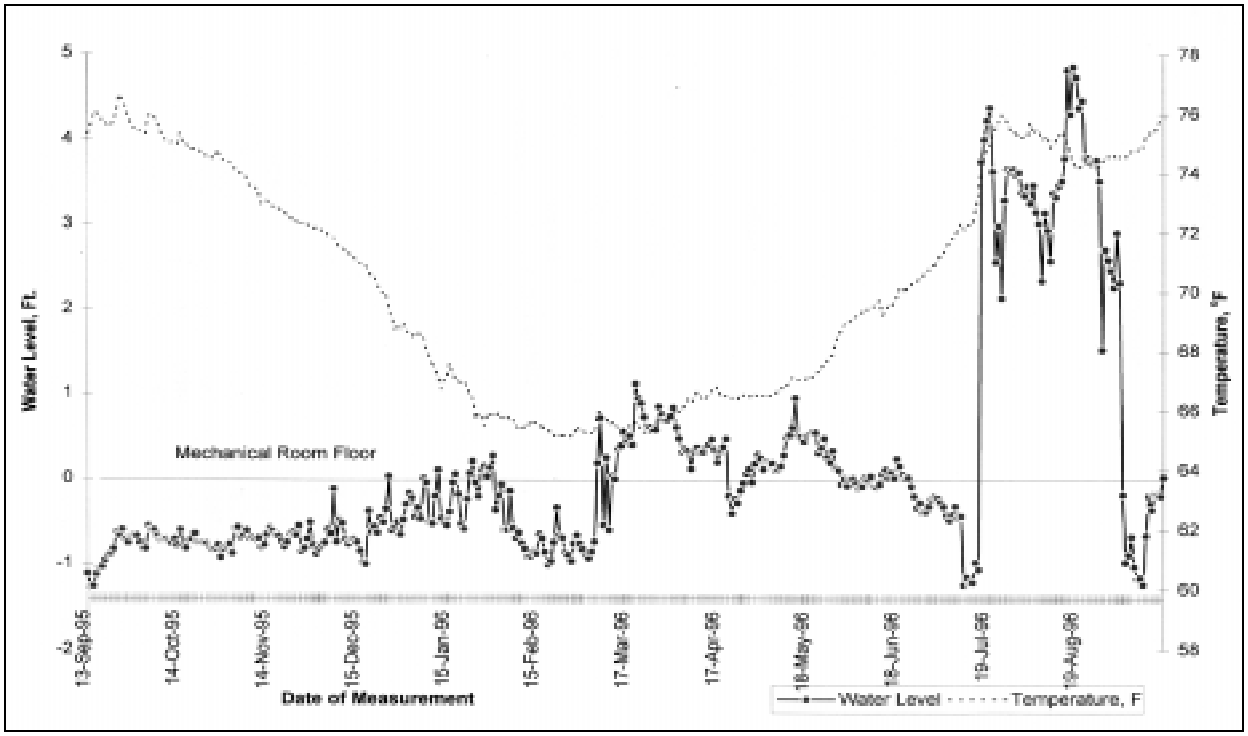

FIGURE 5. Hydrograph from monitoring well at Fort Jackson, SC.

Rainfall data was obtained to track the months when there would be a greater potential for a higher water table. This data can be correlated to the monitoring well data points, specifically, note the correlation between the high rainfall during March 1996 and the rise in the water table during that month. Table 4 shows the rainfall data at Fort Jackson up until May 1996.

TABLE 4. Monthly precipitation data for Columbia, SC.

Month	Total Precipitation (cm)	Month	Total Precipitation (cm)
1994/08	13.49	1995/07	19.96
1994/09	8.31	1995/08	16.99
1994/10	12.04	1995/09	14.00
1994/11	7.82	1995/10	9.17
1994/12	14.81	1995/11	7.34
1995/01	11.40	1995/12	5.56
1995/02	17.02	1996/01	7.37
1995/03	4.32	1996/02	2.95
1995/04	2.49	1996/03	16.56
1995/05	4.29	1996/04	6.04
1995/06	27.28	1996/05	6.81

McAlester AAP

Many of the same parameters that were documented at Fort Jackson were recorded at McAlester AAP. The corrosion potential of rebar was sampled using a 33-cm long piece of 1.27-cm steel rebar which was grouted into the wall along with a Ag/AgCl reference half cell. The half cell was installed so as to be behind the rebar, and separated from it by about 5 cm of concrete. The humidity of the concrete was sampled using a dual humidity/temperature probe which was sealed in a small cavity in the concrete wall. Since the cavity is sealed, this probe monitors the temperature and humidity of the cavity. The humidity of the cavity should be proportional to the moisture content of the concrete, giving an indication of the effectiveness of the EOP system as it operates. Ambient room humidity and temperature sensors monitored the Industrial Hygiene Office. The level of the water table outside the basement was also monitored. In addition to these sensors and probes, the electrical power consumption of the EOP system was tracked to monitor the power output of the power supply. The locations of these sensors are indicated in Figure 4.

All these monitoring devices except the rebar corrosion potential were fed into a datalogger that was installed on site and was remotely accessible via modem. The data was collected and stored in the datalogger until downloaded to a computer.

The daily rainfall, average outdoor temperature, and average outdoor relative humidity at McAlester AAP were obtained from the Oklahoma Climatological Survey. Data was downloaded monthly from their INTERNET site.

Figure 6 shows some of the recorded data, and highlights the power consumption of the EOP system in relation to the relative humidity of the wall cavity, as measured by the wall probe. Figure 6 shows that, as the power consumption drops (as a result of the decrease in current as the water is driven out), the concrete humidity drops as well. This shows that the EOP system is decreasing the moisture content in the concrete with a corresponding decrease in power requirements, both excellent indicators that the system is working properly.

Figure 7 shows the water table with respect to the basement floor. Unlike FT Jackson the water table never rose above the basement floor, confirming that the water intrusion problem at McAlester was mainly through the floor-wall cold joints, that manifested itself with the periodic saturation of the nearby soil following a heavy rainfall.

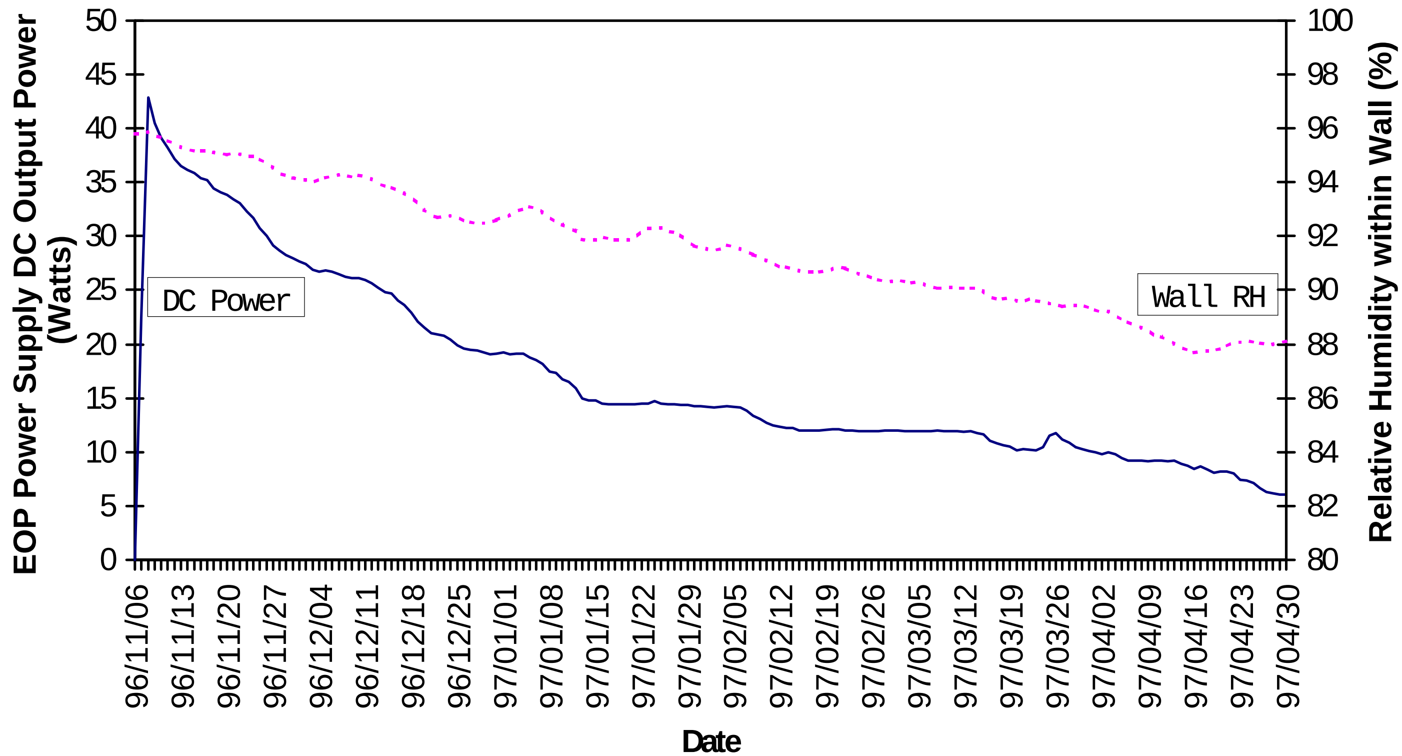

FIGURE 6. Power consumption of EOP system in relation to relative humidity of the wall.

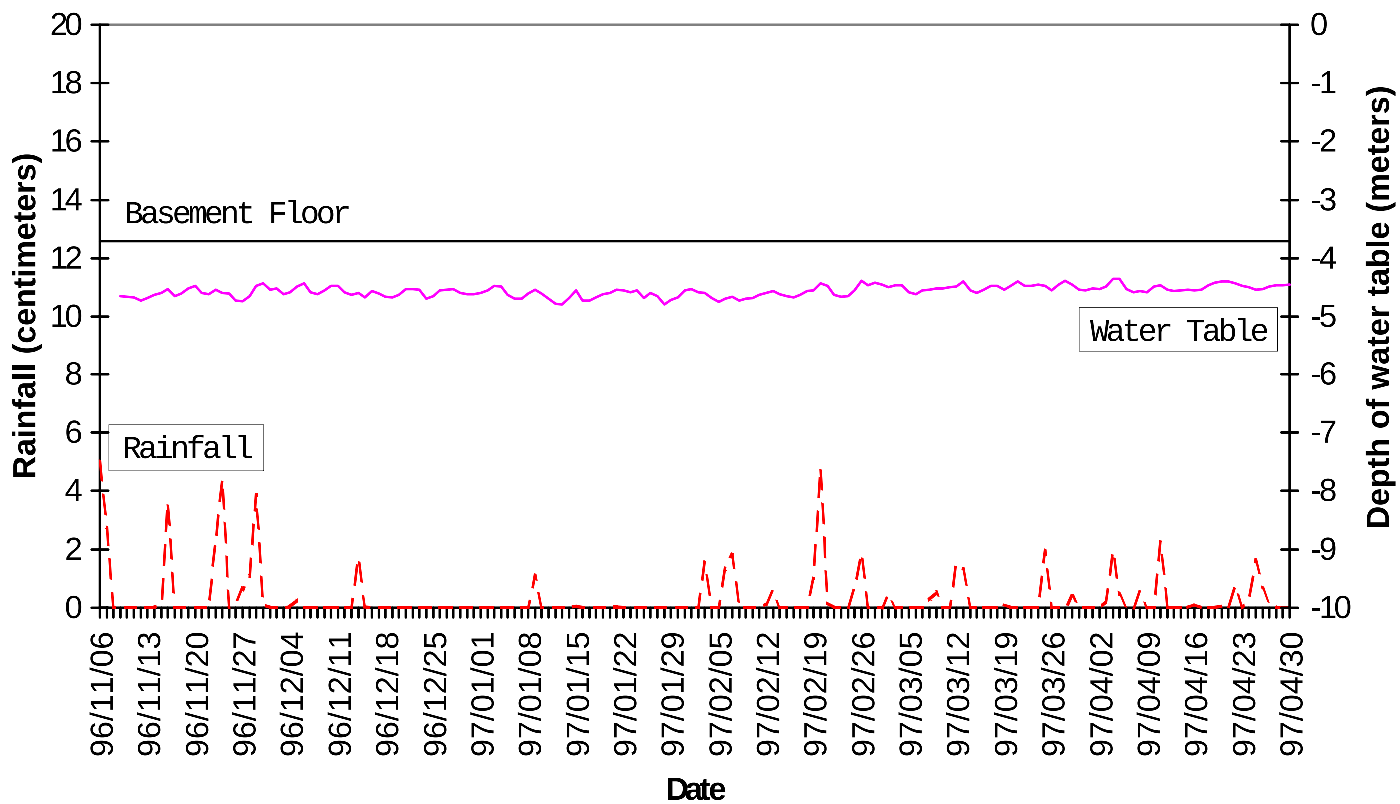

FIGURE 7. Water table with respect to basement floor, Bldg. 5, McAlester AAP.

COST/BENEFIT ANALYSIS

How to best estimate the initial cost savings of EOP over standard dampproofing methods for purposes of decision making must be based on experience and standard construction industry cost-estimating reference guides.[4, 5, 6] The comparison of the standard waterproofing technology to EOP technology is based on field experience at Fort Jackson and at McAlester AAP.

The standard estimate is drawn from construction cost guides, assuming a basement about 2.44 m deep with a concrete exterior. It is then compared to the results of the Army test sites.

Table 5 gives the breakdown of the costs for each facet of the standard dampproofing method, as an approximate cost per linear meter (lm). The assumption is a contract for the whole building and a standard depth of 2.44 m with average, but wet soil conditions.

TABLE 5. Standard approach cost estimate.

Action	Cost per lm ($)
Site dewatering	221.55
Wood shoring	34.78
Excavation and backfill	728.34
Drain tile installation	13.78
Dampproofing	26.25
Backfilling	3.61
Landscape restoration	6.10
Total	1,034.41

The original contracts to the EOP installer were analyzed and adjustments were made to the contract prices to reflect generic installations (i.e., travel, monitoring wells, report requirements, and certain extra experimental requirements were eliminated from the base costs). The price of the EOP system was calculated, based on installed costs, and expressed as linear meter of wall. As for installation, both sites required some degree of interior access to the basement, but neither excavation nor dampproofing were required. The cost includes the EOP Control Unit, the anodes, ground rods, and all the wiring and labor for installation (Table 6).

TABLE 6. Calculation of EOP System Based on Installed Costs and lm of Wall.

Location	Lineal Meters Installed	Cost per lm ($)
McAlester AAP	29.0	624.07
Fort Jackson	34.5	612.69
Average Cost of EOP Installation for Both Sites		618.38

The manufacturer of the EOP system estimates the life cycle of the system be 10 years. Therefore, one could assume a normal cycle with almost zero maintenance for that period of time. However, the system does consume energy roughly equivalent to that of a 60W light bulb left on all the time. This cost is minimal and is neglected in these calculations.

The percent savings based on capital costs is basically a comparison between the cost of trenching, dampproofing, backfilling, and installed EOP technology. The percent savings comparison is computed as:

$$\%\ \text{first cost saved} = 100 \times \left(1 - \frac{\text{EOP per lm}}{\text{Trench \& Drain per lm}}\right) = 100 \times \left(1 - \frac{\$618.38}{\$1{,}034.41}\right) = 40\% \qquad (5)$$

Payback is based on a calculation of time taken to recoup the original investment. This is usually based on the overall reduction in maintenance and repair costs over time. The two possible approaches are *Payback Upon Price Comparison* and *Payback Over Time*. With payback upon price comparison (P_{PC}) one determines how long it would take to save investment moneys for EOP over a comparable expenditure for a trench and drain system.

$$P_{PC} = \frac{1}{\dfrac{\text{Trench \& Drain per lm - EOP per lm}}{\text{EOP per lm}}} = \frac{1}{\dfrac{\$416.03}{\$618.38}} = \frac{1}{0.67} = 1.49\ \text{years} \qquad (6)$$

Note that this is an internal return-on-investment, but does not represent the savings over time.

The payback over time (P_{OT}) calculation very much depends on individual circumstances. Some questions regarding these circumstances are: whether the treated area can be used in the future for habitable area; whether corrosion degradation of valuable mechanical equipment will be stopped; and whether elimination of painting mold will reduce the number of cycles of painting in the future. Table 7 summarizes the savings over ten years at FT Jackson and McAlester AAP for these circumstances.

TABLE 7. Payback over time savings estimates.

Situation	Savings ($)
Usable space return (at McAlester)	21,225.00
Painting avoidance (at McAlester)	748.80
Reduced mechanical maintenance (at Jackson)	20,000.00
Total	41,3973.80

$$P_{OT} = \frac{\text{Total Installation Cost}}{\text{Sum of Annual Cost Avoidances}} = \frac{\$38{,}800.00}{\$41{,}973.80 / 10 \text{ years}} = 9.24 \text{ years} \quad (7)$$

This value for P_{OT} should be used only as a guideline because two different sites were combined to determine this estimate, however it is both a good estimate of final returns, and a reasonable payback over time. Some reasons for this conclusion are:

1) The life cycle for the full return-on-investment is almost equal to the expected life of the system, i.e. any life after ten years will represent a higher return-on-investment.
2) The extended life (i.e. after ten years) will represent a dramatic cost saving in that the initial labor of putting in the probes and wiring has already been expended.
3) If one considers the usable space retrieved from dampness, then there will be at least ten years of productivity beyond the mere acquisition of additional space.
4) Over the expected life of a foundation wall (about 50 years) the payback could be 2-5 times the initial investment, even assuming the purchase of replacement electronics.
5) The estimate was acquired from real-world field test data on existing Army installations.

One might also consider some intangible, or certainly difficult to quantify benefits:

1) There is minimal disruption of the building activity during the drying out process, e.g. no digging, minor noise and a small amount of waste.
2) Illnesses caused by allergies or other sensitivities will

be reduced, thereby increasing health and productivity of the building occupants.

In summary, both the economic benefits based on conservative estimates from field data, and the intangible benefits, point to a very positive return-on-investment for EOP technology.

CONCLUSIONS

In buildings with daily occupancies and mature landscaping, retrofitting a foundation wall by ‘trenching and draining’ is not easy. The common approach to prevent water intrusion is to excavate and expose the wall area and the base of the foundation, to replace the dampproofing on the wall surface, and to install a drain tile system around the building or affected area. This is a costly and disruptive endeavor. Any interior application that can mitigate some of the water-related problems will save both the cost, inconvenience, and disruption of excavation. If the alternative can also mitigate corrosion damage to mechanical equipment and lessen mold problems by lowering the indoor humidity it should be highly rated.

Based on the results of the demonstration and validation, this study concludes that the application of EOP technology for control of moisture in concrete basement structures is an acceptable alternative to conventional trenching and drain.

The EOP technology installed in a facility at Fort Jackson, SC successfully prevented water seepage and reduced the relative humidity of the concrete to 70 percent. The cost of installation has been determined to be 40 percent lower than the cost of the conventional ‘trench and drain’ approach. The operating, or energy cost, of the EOP system is negligible - about that of continuously burning a 60W light bulb.

It is recommended that the EOP technology be transferred for Department of Defense implementation as a cost effective alternative to the ‘trench and drain’ approach for control of moisture in concrete basement structures.

ACKNOWLEDGMENTS

This study was conducted for the U.S. Army Center for Public Works (USACPW) under the Facilities Engineering Application Program (FEAP); Project Title ‘A Demonstration of Electro-Osmotic Pulse (EOP) Technology for Control of Seepage in Concrete Structures’. The assistance provided by Frank Cooper, Fort Jackson, SC; Gary Reasoner, McAlester Army Ammunition Plant; Fidel Rodriguez and Malcolm McLeod, Center for Public Works, Ft. Bevoir, VA; Dr. Charles Lozar of Architects Equities Research

Group; and Roger Hayes, Arild Ottersen, Egil Bjerke, and Micheal Connor, Drytronic (formerly known as Dry-Tec of North America), was essential to the completion of this work.

REFERENCES

1. Hamill, W.H., Williams, R.R. and MacKay, C., *Principles of Physical Chemistry, 2nd edition*, 1966, Prentice-Hall, Inc., Englewood Cliffs, N.J.

2. Glasstone, S., *Textbook of Physical Chemistry, 2nd edition*, 1946, D. Van Nostrand Company, Inc., Princeton, N.J.

3. Tikhomolova, K.P., *Electro-Osmosis*, 1993, Ellis Horwood Limited, Chichester, West Sussex, England.

4. *Means Cost Estimating Guides*

5. *Walker Estimating Guide*

6. *National Construction Estimator Handbook*

AUTHOR'S ADDRESS: U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORIES
ATTN: CECER-FL-M (V. Hock)
P.O. BOX 9005
CHAMPAIGN IL 61826-9005

U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORIES
ATTN: CECER-FL-P (M. McInerney)
P.O. BOX 9005
CHAMPAIGN IL 61826-9005

U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORIES
ATTN: CECER-FL-M (E. Kirstein)
P.O. BOX 9005
CHAMPAIGN IL 61826-9005