

Demonstration of Electro-Osmotic Pulse Technology for Groundwater Intrusion Control in Concrete Structures

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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 has been developed to apply electro-osmotic pulse (EOP) technology commercially to concrete structures by applying a pulsating electric field between the structure and the surrounding soil. 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 along with humidity and mold problems.

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).

A properly designed original foundation with appropriate dampproofing will avoid most water problems. However, 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 in order to expose the wall area and the base of the foundation, and then to replace dampproofing on the wall surface and 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 warranties 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 along with humidity and mold problems.

Electro-osmosis is not a new technology although new applications are still being developed. 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 pulsating electro-osmotic 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 greater 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., Cl^-) 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 buried concrete structures. 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, in comparison with conventional dampness mitigation techniques, at selected Army installations.

BACKGROUND

If ions of one sign are preferentially adsorbed 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.

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:

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

where:

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

By the Debye-Hückel approximation, ϕ is written as

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

where:

ξ	is	the zeta potential ¹ ;
n_i^∞	is	the concentration of constituent i in free solution;
Z_i	is	the equivalents/mole of constituent i;
F	is	Faraday's constant;
R	is	the universal gas constant; and,
T	is	the absolute temperature.

When (1) is solved using the boundary conditions,

¹ The difference of potential between the plates of a hypothetical capacitor used to model the diffuse layer.

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

The velocity V_o is then obtained:

$$V_o = \frac{\varepsilon \xi}{\mu} E_x \quad 0 \quad (4)$$

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

The pulsating electro-osmotic technique consists of a positive voltage pulse, a negative voltage pulse, and a period when no voltage is applied. Figure 2 shows an example waveform for the pulsating electro-osmotic pulse or EOP system. This waveform was sampled at one of the demonstration sites. (The vertical scale in Figure 2 is 10 volts/division and the horizontal scale is 1 second/division.) 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.

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 (no applied 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 in the concrete.

TECHNOLOGY DEMONSTRATIONS

Two sites were selected for the EOP technology demonstration, Building 3265 at Fort Jackson, SC and Building 5 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.

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.

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). The reduction of the indoor air humidity through the EOP system is very important, as one of the rooms is the Industrial Hygiene Office, occupied by an individual 40 hours a week.

Rubber-graphite anodes were placed 13 cm above the floor and 28 cm on center. The total number of anodes used was 95. Analysis of the water infiltration revealed that only about the half the basement was leaking, therefore not all of the basement was protected. Five copper-clad steel ground rods (cathodes), 2.44 m long, were driven into the soil adjacent to the exterior concrete wall in selected areas.

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. This 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). 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, since current is inversely proportional to resistance (Ohm's Law). 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.

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 the percent relative humidity of the concrete. 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).

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 the 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 for the rebar specimens, 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.

The level of the water table relative to the basement floor was tracked. A monitoring well was installed just outside the basement wall for this purpose. 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. Figure 3 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, yet because of the EOP system the basement remained dry.

Rainfall data were recorded to track the months when there would be a greater potential for a higher water table. These 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 to May 1996.

McAlester AAP

Many of the same parameters that were recorded at Fort Jackson are being recorded at McAlester AAP. The corrosion potential of rebar is 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 is 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 are monitoring the Industrial Hygiene Office. The level of the water table outside the basement is also being monitored. In addition to these sensors and probes, the electrical power consumption of the EOP system is tracked to determine the power output of the power supply. All these monitoring devices except the rebar corrosion potential are fed into a datalogger that is installed on site and is remotely accessible via modem. The data is 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 are obtained from the Oklahoma Climatological Survey. Data is downloaded monthly from their INTERNET site.

Figure 4 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 4 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 5 shows the water table with respect to the basement floor. (Figure 5 gives the same information for McAlester AAP that Figure 3 gives for Fort Jackson.) Unlike FT Jackson the water table never rises above the basement floor.. Therefore the water intrusion problem at McAlester was mainly associated with the floor to wall cold joints which was associated with periodic saturation of the nearby soil.

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 focus of this estimate is a basement about 2.44-m deep with a concrete exterior. The standard estimate is drawn from construction cost guides, which 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, including the approximation of the cost per linear meter (lm) of the exterior foundation wall. This assumes a contract for the whole building and a standard depth of 2.44 m with average, but wet soil conditions.

The original contracts to the EOP manufacturer 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 have been eliminated from the base costs). The price of the EOP system based on installed costs and linear foot of wall was

calculated. As for installation, both sites required some degree of interior access to the basement level, but neither excavation nor dampproofing were required. Installation of the probes is generally based on a 30.5-cm. spacing and about 20 to 30 cm from the floor level. The price includes the EOP Control Unit, the anodes, ground rods, and all the wiring and labor for installation (Table 6).

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 comparison is:

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

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.

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

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. 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 the most important circumstances.

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

This value for P_{OT} should be used only as a guideline because two different sites were combined to determine this estimate.

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 to expose the wall area and the base of the foundation, and then to replace the dampproofing on the wall surface and install a drain tile system around the building or affected area. This is a costly endeavor. Any interior application that can mitigate some of the water-related problems will save the cost of excavation. If the alternative can also mitigate corrosion damage to mechanical equipment and humidity and mold problems 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—equivalent to the expenditure of 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

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TABLES

Table 1. Power supply dc output.

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

Table 2. Concrete moisture readings in Building 3265.

Date of Reading	% Relative Humidity at Surface			
	A	B	C	D
1994/08/23	94	92	98.3	97.6
1995/01/10	44	43	68.3	64.3
1996/08/15	72.5	72.1	76.3	76.8

Table 3. Rebar specimen corrosion potentials.

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

Table 4. Monthly precipitation data for Columbia, SC.

Date	Total Precipitation (cm)	Date	Total Precipitation (cm)
August 1994	13.49	July 1995	19.96
September 1994	8.31	August 1995	16.99
October 1994	12.04	September 1995	14.00
November 1994	7.82	October 1995	9.17
December 1994	14.81	November 1995	7.34
January 1995	11.40	December 1995	5.56
February 1995	17.02	January 1996	7.37
March 1995	4.32	February 1996	2.95
April 1995	2.49	March 1996	16.56
May 1995	4.29	April 1996	6.04
June 1995	27.28	May 1996	6.81

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
Landscaping restoration	\$6.10
Total	\$1,034.41

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

Location	Lineal Meters Installed	Cost per Linear Meter
McAlester AAP	29.0	\$624.07
Fort Jackson	34.5	\$612.69
Average Cost of EOP Installation for Both Sites		\$618.38

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	\$41,973.80

FIGURES

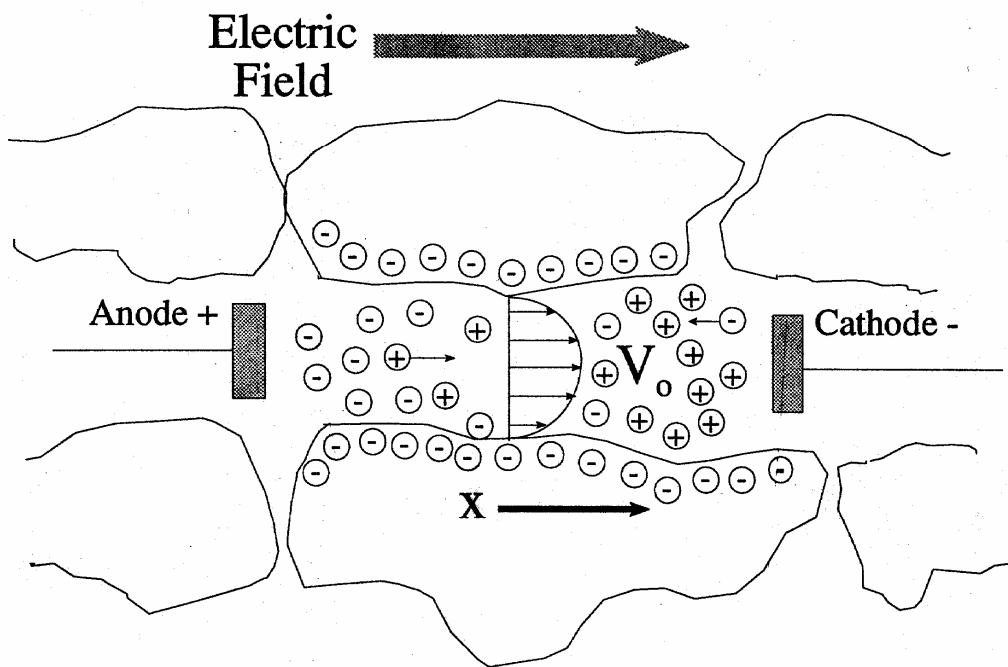


Figure 1. Movement of cations in a soil pore by electro-osmosis.

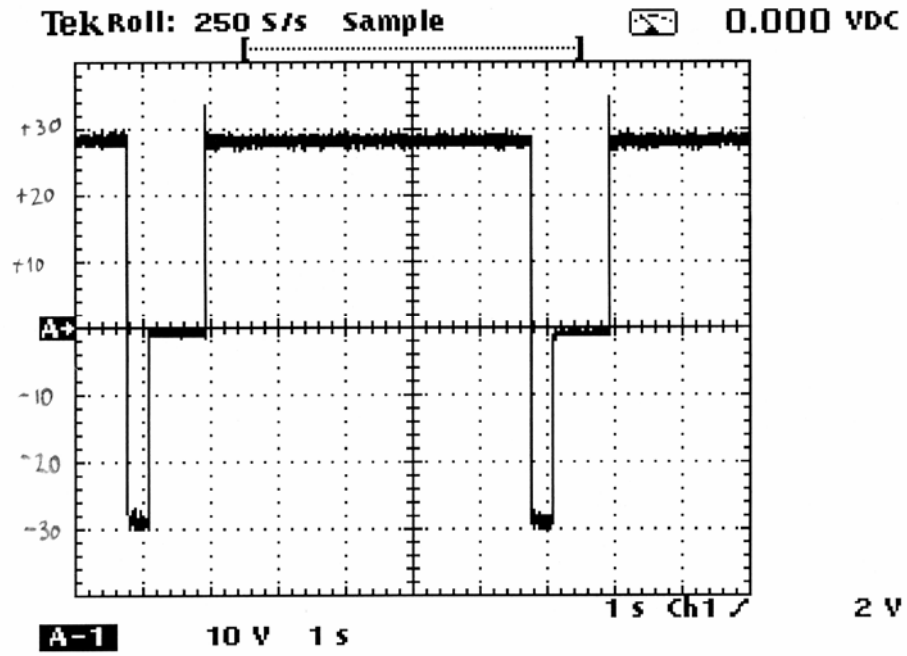


Figure 2. Example EOP voltage waveform.

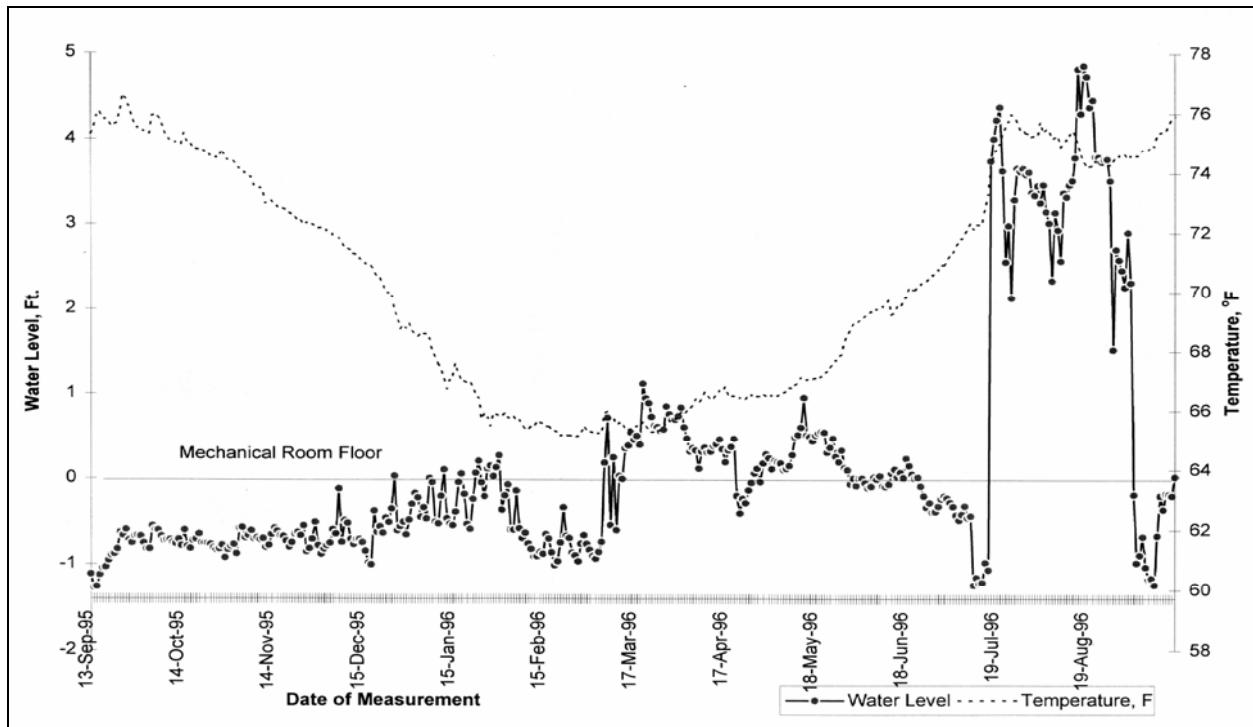


Figure 3. Hydrograph from monitoring well at Fort Jackson, SC.

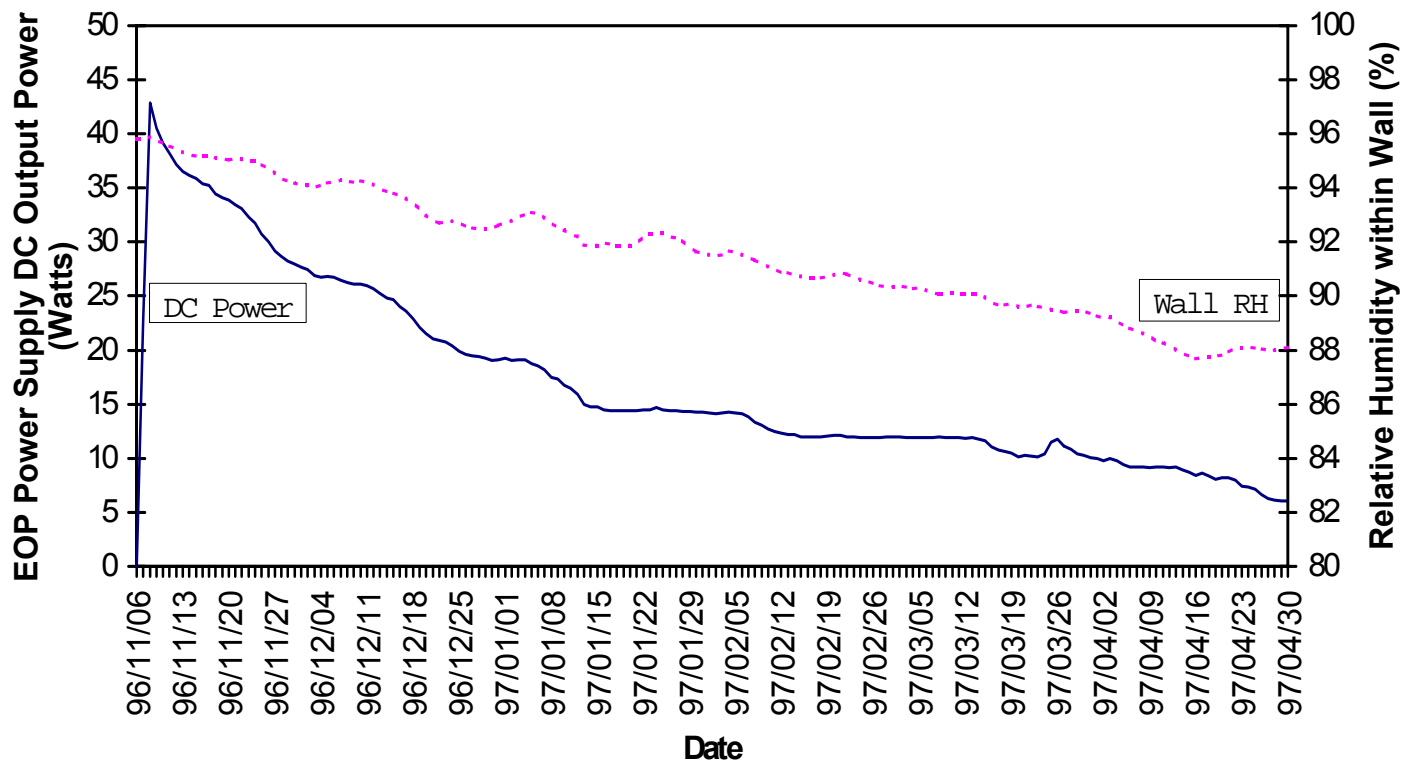


Figure 4. Power consumption of EOP system in relation to relative humidity of the wall.

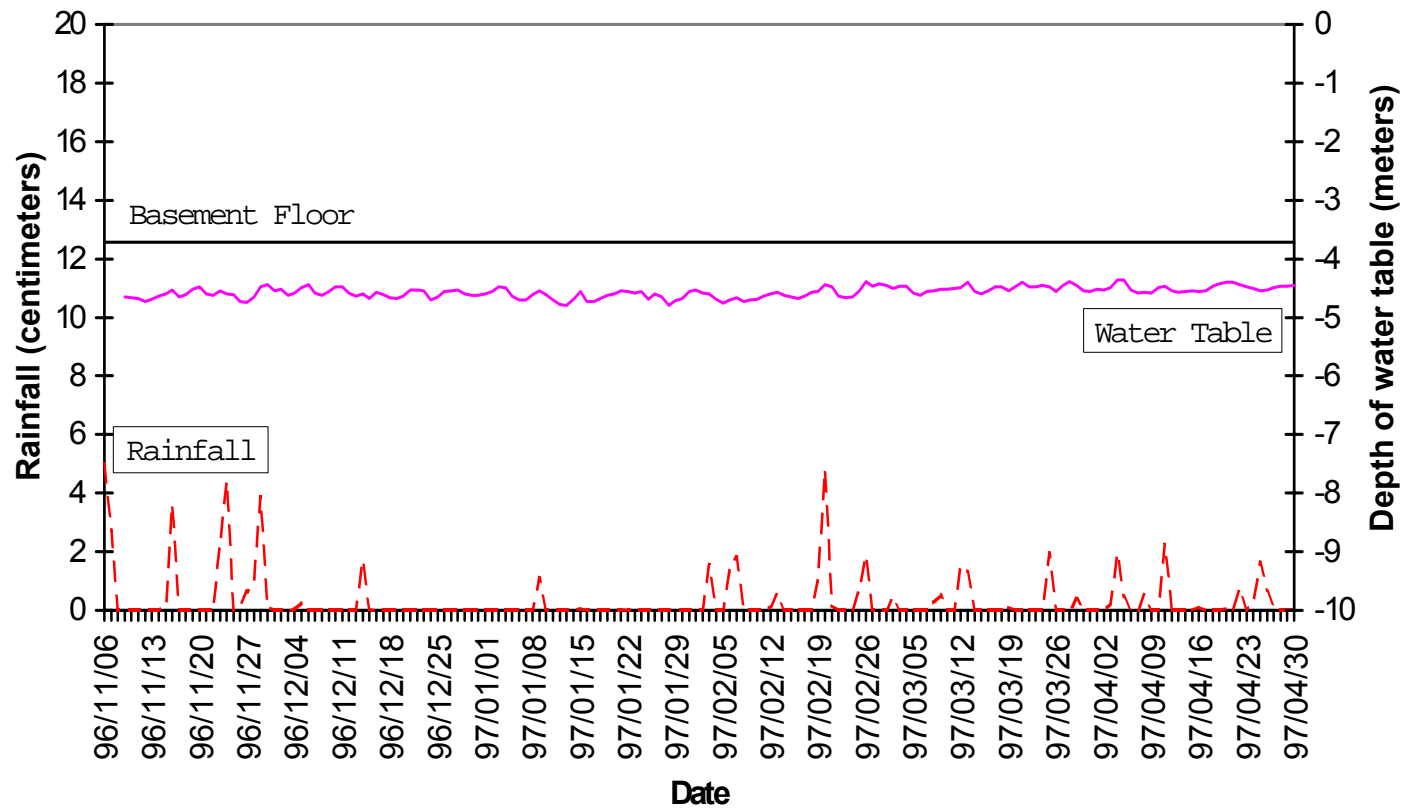


Figure 5. Water table with respect to basement floor, Bldg. 5, McAlester AAP.