

**CATHODIC PROTECTION OF A WELL GROUNDED TANK FARM AND PUMP STATION
IN COLOMBIA, S.A.**

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ABSTRACT

In October 1999 the client company started an ambitious project for corrosion control of underground structures and pipelines in its storage and pumping stations by cathodic protection. The program began at Puerto Salgar station with lectures held in the administration building auditorium. These types of projects are part of a technology transfer program under the responsibility of the integrity department of *Vicepresidencia de Transportes*.

This paper presents a brief outline of the information presented at the Technology Transfer Seminar, the gathered field data, the design process, grounding grid complications and additional recommendations.

INTRODUCTION

A corrosion control seminar on cathodic protection (CP) of pumping and terminal stations was conducted on 25-31 October 1999. The seminar consisted of a series of lectures beginning

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with basic corrosion mechanisms and progressing through cathodic protection design considerations. Part of the seminar involved conducting hands-on field work to gather all information necessary to prepare the cathodic protection design for this station. The methodology used in this project has led to the design and construction of cathodic protection systems for additional stations owned by the Company. The technical responsibility for the seminar and the CP design for the facility were assigned to a joint venture of Tecnología Total Ltda, Bogotá – Colombia and ELK Engineering Associates Inc., Fort Worth, Texas, USA.

The Puerto Salgar Station is a combined refined petroleum products pumping station and tank farm. Principally the facility contains twenty-one tanks with bare bottoms in direct soil contact, multiple underground products pipelines, water pipelines and fire protection foam pipelines all electrically common with the plant grounding grid and underground electrical conduit. After evaluation of the gathered information, an integrated impressed cathodic protection system to protect all underground structures was designed for the facility.

This paper discusses the methodology carried out to assist the reader in understanding cathodic protection principles and design considerations for similar facilities. More than two years after construction of the CP system, it has performed extremely well. This cathodic protection methodology has been applied to other ECOPETROL facilities in Colombia including Guadua, Villeta y Alban and Pozos Colorados, also with excellent results after construction.

BASIC CORROSION MECHANISM

Cathodic Protection is a corrosion control method for structures such as underground pipes, tanks, etc., understanding the principles of cathodic protection systems requires an understanding of the nature of the corrosion process. Corrosion is an electrochemical process in which a current leaves a structure at an anodic site, passes through an electrolyte and re-enters the structure at cathodic sites. The required components and characteristics of a corrosion cell are⁽¹⁾:

- Anode:** The anode is the site where metal is lost and electrons are produced.
- Cathode:** The cathode is the site where the electrons, produced at the anode, are reduced.
- Metallic Path:** The metallic path conducts electrons from the anodic sites to cathodic sites.
- Electrolyte:** Provides reactants for the cathodic reactions and allows the flow of ions.

See Figure 1, Corrosion Cell.

The function of coatings is to isolate the metal from direct contact with the surrounding electrolyte, but in reality, all coatings, regardless of overall quality have some degree of permeability and contain holes, referred to as holidays, that are formed during application, transportation or installation. Holidays in coatings also develop in service as a result of degradation of the coating, soil stresses, or movement of the pipe in the ground. Degradation of the coating in service also can lead to disbonding from the pipe surface, and further exposing metal to the underground environment. A high corrosion rate at a holiday or within a disbonded region can result in a leak or rupture, hence cathodic protection is required to control corrosion in these bare areas.

Cathodic Protection is a technique to reduce the corrosion rate of a metal surface by making it the cathode of an electrochemical cell, this is accomplished by shifting the potential of a metal in a negative direction by the use of an external power (referred to as impressed current CP) or by utilizing a sacrificial anode(s).

In light of the above, it becomes clear that the rate of corrosion could be reduced if every bit of exposed metal on the surface of a pipeline could be made to collect current. This is exactly what cathodic protection does. Direct Current (DC) is forced onto all surfaces of the pipeline and buried structures, when the amount of current flowing is adjusted properly or enough, it will overpower the

corrosion current discharging from the anodic areas on the buried structures, and there will be a net current flow onto these points. The entire surface then will be a cathode and the corrosion rate will be reduced.

THE NATURE OF UNDERGROUND CORROSION

Much corrosion of underground piping occurs due to galvanic cell action. In any corrosion cell there must be a metallic cathode, a metallic anode, a metallic path between the two, and a suitable electrolyte. When the cathode and anode are electrically coupled to an electrolyte and to each other, an electric current or flow of electrons is initiated, this continues until: (1) the anode is consumed, (2) the couple is broken, or (3) something retards or arrests the current flow. A common example of a galvanic cell, performing useful work, is the flashlight battery in which there is a zinc anode (case), a carbon rod cathode, and a suitable electrolyte. When the carbon rod and zinc case is electrically coupled with a wire, current flows and eventually consumes enough zinc so that a hole corrodes through the zinc case. At this point the battery would leak, if it were not for the outer case on "leak proof" batteries. See Figure 2, Corrosion Cell, the Dry Cell battery.

A similar galvanic cell action occurs when two dissimilar metals are coupled together underground with the soil as the electrolyte, eventually consuming the anodic metal. For example, if a copper grounding conductor is electrically connected to a product pipeline, a galvanic cell is constructed in which copper is the cathode, the moist soil is the electrolyte, and the steel pipe is the anode. The resultant current flow generated by this galvanic cell eventually would consume the black steel anode. Since pitting attack generally occurs rather than uniform corrosion, a product leak will show up as an isolated hole long before the entire line is consumed.

One ampere of direct current flow for one year will consume approximately 20 pounds of steel or 45.7 pounds of copper.⁽²⁾ This represents a great many individual corrosion failures since this type of corrosion usually appears as individual small pits. A copper-steel couple is one of the more active corrosion cells normally encountered. Mild steel will generally be anodic to and thereby unfavorably affected by a couple to other materials considered more corrosion resistant such as copper, brass, bronze or stainless steel. Galvanic couples between steel tank bottoms and copper grounding grids generally cause accelerated corrosion on the outer edges of the tank bottoms.

Bi-metallic galvanic cells are not necessarily the most common types of corrosion cells which affect underground piping. Another type of corrosion cell, and probably the most frequent cause of corrosion on underground metals, is produced by dissimilarity of soils through which the piping passes. This type of corrosion cell is referred to as a concentration cell. Here the soil around the anode generally will conduct electricity more readily than soils around the cathodic area. When part of a steel structure is cast in concrete and part is in direct soil contact, a strong concentration cell is set up. In this case, the high pH concrete will passivate the surface of the steel, creating a cathodic region where no corrosion occurs. However, the steel in the soil immediately adjacent to the steel encased in concrete will become quite anodic and will corrode. Significant to severe corrosion will usually be seen on the pipe in the soil within one to three feet of the point of exit from the concrete. Concentration cell corrosion will occur if there is a significant difference in the soil or water electrolyte. Soil resistivity measurements are an indicator that concentration cell corrosion may occur.

Dissimilarity in soils may also result from variations in the quantity of oxygen, different concentrations of the same soluble chemicals, different kinds of chemical ions dissolved in the soil, or other possible causes. Additional causes of galvanic cell action may include dissimilar surface conditions. These types of corrosion cells generally produce random pitting attack at a relatively slow rate.

Differential aeration (oxygen gradient) cells are a special form of concentration cell which are

largely responsible for tank bottom corrosion and for corrosion of under slab piping systems. In this instance, the middle of the tank bottom or pipe central to the slab is oxygen deprived and is anodic to the tank bottom or the pipe at the perimeter of the slab. As a result, the middle of the tank bottom will tend to corrode first.

SOIL RESISTIVITY

In-situ soil resistivity measurements in selected locations were tested throughout the Puerto Salagar facility using the Wenner four pin method. The pins are driven into the soil in a straight line at the desired spacing. Good contact with the soil is important. The two "C" terminals of the equipment are connected to the two end pins to impress the current in the soil, and the two "P" terminals are connected to the adjacent center pins to obtain the potential reading. (See Figure 3.) The resistivity in ohm-cm of the soil is calculated by using the following abbreviated formula:

$$\rho = 2 \times \pi \times S \times R$$

where π is 3.1415, S is pin spacing in centimeters and R is the resistance of the circuit obtained from the equipment in ohms.^{(3) (4)}

Soil resistivity was measured to depths of 1 to 6 meters at ten (10) selected locations throughout the facility. The measured soil resistivity values ranged from 714. Ohm-centimeters to 2510 Ohm-centimeters at the various depths and locations and are considered to be very corrosive in nature.⁽⁵⁾ These readings present useful information to select the depth of the anodes. A Barnes Layer analysis⁽¹⁾ is recommended to obtain more useful resistivity data for different layers of soil and help in determining the design depth of the anodes.

SOIL BORING LOGS

Soil perforation results available by the time of the study were evaluated to observe the stratum layers of the soil and how deep the anodes could be buried in the station facility. A recommendation was made for future studies where soil boring logs are not available. In that instance, perform geo-electric studies that will define resistivity of the soil strata. However, soil boring logs are still useful to identify rock layers and the water table.

PIPE-TO-SOIL POTENTIALS

The convention established for this project was that all potentials would be reported in millivolts, not in decimal volts. Pipe-to-soil (P/S) potential measurements were made with high input impedance digital FET multimeters, against a standard copper-copper sulfate reference electrode (CRE). Close P/S potentials are used to evaluate the level of cathodic protection on the underground metallic plant piping. For the purposes of this project, 850 millivolts (– 0.85 volts) to CuCuSO_4 reference electrode with the current applied was used as the criterion for cathodic protection.^{(6) (7)} This criterion requires interpretation of the I.R. Drop in the measurement resulting from cathodic protection current flow. Given the very low soil resistivities encountered in the Puerto Salgar Station and the distributed anode configuration, I.R. Drop may be disregarded unless potential measurements are taken in the immediate vicinity of an anode.

CURRENT REQUIREMENT TESTS

Current requirements tests (CRT) provide an accurate assessment of the cathodic protection current required for the protection of complex structures. CRTs also are valuable to determining the degree of electrical continuity between various underground structures. The facility has been provided with a bare copper grounding system consisting of bare stranded horizontal conductors and driven ground rods at regular intervals. By current requirement testing, it was confirmed that all of the plant piping and tank bottoms were electrically continuous with the grounding system.

A current requirement test was conducted at a proposed conventional remote vertical anode ground bed site and at two other locations, one around the perimeter of a large diameter tank.⁽⁷⁾ These CRTs were run to determine the type and size of the cathodic protection system required. All current requirement tests were performed with conditions as found in the station. Thus, the results obtained give an indication of the current requirement with non-isolated conditions and with the grounding system and incoming and out going pipelines attached and electrically continuous to the plant piping and structures.

A temporary cathodic protection system was constructed using a portable rectifier driven copper or steel, ground rods, current interrupter and cables. This allowed us to determine the effect of current applied on the local P/Ss throughout the facility. Existing metallic structures, such as metal fences, culverts, concrete reinforced steel, abandoned pipelines, or abandoned wells can be used as temporary anodes or to supplement installed temporary anodes. If any existing structure is to be used, it should first be tested to be certain that the structure is not shorted to the structure to be tested. It is important not to use any pipelines or tanks for temporary anodes that would be adversely affected if leaks occurred.

The number and driven depth of temporary anodes required depends on the available voltage source, the amount of current desired, and the resistivity of the soil. If the number of anodes is doubled, the amount of current output would be approximately doubled. If the soil resistivity is doubled, the current output would be cut in half. In very low resistivity soil, two or three anodes may be sufficient, while in very high resistivity soil, a large number of temporary anodes may be required.

The amount of current required depends primarily on the exposed surface area of the copper grounding grid. To a lesser extent, the surface area and the quality of the coating on the steel structures being tested affects the current requirement. Electrically isolated, very well-coated structures will exhibit a noticeable potential change with a small amount of current (1 or 2 amperes or less), while poorly-coated structures will not exhibit a noticeable potential change except with a large amount of current in the range of 10 to 20 amperes, or more. Sufficient current is applied when a substantial section of the structure to be tested has achieved a noticeable potential shift or when full protection is achieved. If full protection is achieved, the current requirement is approximately the same as the test current. If full protection is not achieved with the temporary groundbed, further calculations are required. See Figure 4, Typical Current Requirement Test Arrangement.

In the Puerto Salgar station, P/S measured as part of the current requirement tests reflected an average of buried pipelines, bare tanks bottoms and a massive copper grounding system because all these structures were electrically continuous.

ELECTRICAL GROUNDING

Copper grounding systems in any petroleum production, refining, storage and distribution facilities cause accelerated corrosion of adjacent ferrous structures. This includes tank bottoms, buried plant piping (BPP) and support structures that are in direct soil contact. It does not include ferrous metals encased in concrete which will have essentially the same potential as copper. In addition, the presence of bare copper in the soil places a tremendous load on the cathodic protection system, sometimes demanding most of the current output from a rectifier system.⁽⁸⁾

Conversely, steel in concrete has a much lower current demand than steel, in a soil environment. Thus, moderate amounts of steel embedded in concrete may generally be disregarded in current demand calculations. In most facilities, congested BPP with adjacent bare copper grounding conductors becomes the most difficult area to protect. The installed bare copper grounding grid represents a very large load on the proposed cathodic protection system. This was documented in current requirement tests performed in the station.

From the H. B. Dwight equation for a single, vertically installed rod,⁽¹⁾ the resistance-to-remote earth of one 5/8 inch by 10 foot ground-rod in 1,000 ohm-centimeter soil is 3.3 ohms. As soil resistivity decreases, resistance to earth will decrease proportionally. Therefore, it is readily apparent that very few ground-rods are required at the average facility in order to obtain an acceptable ground resistance of one to two ohms.

Bare copper electrical grounding systems have been a world wide standard for decades because of the perception that copper does not corrode underground. This is not always true and copper is a very poor neighbor from a corrosion control standpoint. Copper is always cathodic to other materials for construction. This results in free cathodic protection for the copper at the expense of the other underground engineering materials, including tank bottoms and process piping. On future new facilities, alternative grounding systems should be considered during the preliminary design stage.⁽⁹⁾

TRANSFORMER / RECTIFIER UNITS

Conventional, tap adjusted rectifiers are extremely simple, reliable units requiring very little maintenance. This cannot be said of the control cards employed in today's modern automatic potential controlled units. Even with the best filtering and surge suppression, they are much more troublesome than the basic rectifier assembly. This is particularly true in areas that experience high levels of lightning activity.

In Colombia a large lightning/over voltage activity exists, because of the location of the country in the tropical weather zone. Because of that, we selected, by design, standard tap adjusted transformer/rectifier (T/R) units that are reliable and easy to maintain. The only justification for an automatic potential control unit would be to provide more constant current output at a facility exposed to severe seasonal drying conditions of the ground bed and plant underground piping. Since the station under investigation is a manned facility, it appeared to us that a better choice than automatic potential control units would be to have a trained operator capable of making tap change adjustments as necessary in accordance with a formal written procedure and output guidelines for each rectifier at the facility. We did not believe that many output adjustments would be necessary at the Puerto Salgar facility. That has proven to be the case in practice. Normally, rectifier output adjustments are only made during the annual survey.

GENERAL DESIGN CONSIDERATIONS

Before going into specific design features, general considerations should be addressed. First of all, keep in mind that the objective of an effective corrosion control program is not a zero corrosion rate; rather, it is an acceptable low corrosion rate. For the production facilities in Colombia, it would appear that an acceptable tank bottom corrosion rate would be one (1) to two (2) mils per year in those areas of the bottom with the least protection. Given a ten to twenty year useful life for these facilities, the above stipulated maximum corrosion rate would only result in ten to forty mils of total corrosion loss. This amount of corrosion would be insufficient to penetrate a pipe wall or a tank bottom at any one location during the facilities' useful life. This statement is made as a preamble to the following comments concerning cathodic protection criteria.

The static potential criterion, -850 millivolts, is by far the easiest and most practical to use in essentially all field situations. This was our criterion of choice for this specific project.^(6, 7) When very low soil resistivity exists, less than 1,500 ohm-centimeter, we believe that voltage drops in the bulk electrolyte may be safely disregarded. This is not true for potential measurements taken in the immediate vicinity of an impressed current anode. Significant voltage drops exist in the bulk electrolyte due to current flow away from the anode. However, local cathodic pipe-to-soil potentials in that area are so high, due to excess current pick up from the close by anode, that IR Drops are not a concern. When polarized pipe-to-soil potentials at the pipe-to-soil interface exceed -1.00 volt,

we are not concerned about a few millivolts of IR Drop in the bulk electrolyte. That is why we did not recommend utilization of the "instant off" criterion for this specific facility.

The 100 millivolt cathodic polarization criterion may be applied to areas that are receiving cathodic protection but are not polarized to -0.85 volts CSE. This criterion is much more time consuming and difficult to apply than is the case for the -0.85 CSE criterion. However, its use is justified when the existing cathodic protection systems do not have sufficient capacity to fully polarize the pipeline to the static potential criterion. If 100 millivolts of polarization gain or decay can be demonstrated, properly utilizing the technique, an acceptably low corrosion rate would be assured and no further action would be required.

Pipe-to-soil potential limits should be established to avoid over polarization of coated, cathodically protected structures. As the hydrogen over voltage potential is exceeded, nascent hydrogen will begin to form on the surface of the pipeline steel. If this nascent hydrogen forms underneath a protective coating, cathodic disbonding of the coating can result. Some pipeline coatings are more susceptible than others to this phenomenon. For soil resistivity in the range of 500 to 5000 ohm-centimeter, voltage drops in the bulk electrolyte may become a factor in the pipe-to-soil measurement. For the soils found at this station, the IR drops are only a matter of a few millivolts. In higher resistivity soils, consideration must definitely be given to these voltage drops.

Measurement of tank bottom structure-to-electrolyte potentials becomes more and more difficult as tank diameter becomes greater. Based upon present guidelines, we recommended installing reference potential tubes (RPT) under all large diameter tanks. A nominal 2 inch, Schedule 40 PVC tube was installed under the ring wall beam and terminated at the center of the tank. This permits placing a portable CRE in contact with the soil at the end of the RPT. Two RPTs were called out under the larger diameter tanks, with the second RPT extending about half way to the center of the tank.

CATHODIC PROTECTION DESIGN

Given all of the above discussions and evaluating the field data gathered during the seminar, an integrated impressed current cathodic protection system was proposed to provide protection to:

- All tank bottoms in direct soil contact
- Underground product piping
- Underground water lines
- Underground fire water lines
- Underground foam lines and foam concentrate lines
- Other electrically continuous underground metallic structures like the grounding system.

In an attempt to minimize cathodic interference problems within the facility and to provide more uniform structure-to-soil potentials throughout the facility, each rectifier was provided with a direct negative connection to the adjacent plant grounding grid. Two additional negative connections were made to nearby ferrous structures. This level of redundancy is essential in facilities such as Puerto Salgar. In one sense, we could consider that all of the cathodic protection current expended on the bare copper grounding system is wasted energy. It is not possible to avoid current losses to the bare copper grounding system in a facility such as the Puerto Salgar Station. Therefore, we made a deliberate choice to directly connect each rectifier negative output to the copper grounding grid. This improves the electrical continuity between the various tank bottoms and piping systems and minimizes voltage drops in the piping system. The net result is improved uniformity in overall structure-to-soil potentials throughout the facility. It also greatly minimizes the risks of cathodic interference on short, isolated pipeline segments. However, this type of system mandates that CP must be maintained in the station at all times.

Anodes were first placed around or close to each of the tank bottoms requiring cathodic protection based upon the "Estimated Current Requirement Based on Tank Bottom Surface Area" spreadsheet. Additional anodes were placed close to the process piping areas to assure adequate cathodic protection current distribution to that region of the facility. We took the somewhat unusual step of placing all of these distributed anodes in the center of facility roadways. This is probably the most protected location for the anodes when considering future construction activity in the facility. See Figure 5, Vertical drilling equipment used during construction.

Utilizing simple mathematical manipulations to the CRT results, a range of current demand from 110 to 500 Amps was obtained. Based on the tank bottom bare area calculations alone, a current demand minimum of 228 amperes was estimated. Based upon experience and an indication of higher current demand by the CRTs, we established a minimum initial design target of 400 amperes for the entire facility.

Each anode was configured so that it was located below the underground plant piping and at sufficient depth to reach up underneath the center of each tank. The last three of the T/R-ground bed installations were designed to provide adequate current distribution to the process piping areas of the facility. A total of eleven T/R-ground bed installations with individual distributed anode groundbeds were designed to provide a total system rated current output of 440 amperes. This required installing 88 vertical anodes and approximately 10 km (6.21 miles) of positive and negative header cables.⁽¹⁰⁾ Even utilizing slightly oversized DC header cables on this project, voltage drops in the header cables range from three percent to sixteen percent of the total driving voltage required to achieve rated current output for the T/R units. Calculated output voltages required range from 15.6 to 20 volts. We did not oversize the rectifiers on driving voltage because it makes it too difficult to make a fine enough adjustment in rectifier current output. However, there is a real benefit in standardization. Therefore, for each particular ground bed installation the next higher commercially available driving voltage was selected for each T/R. A combination of 30, 40 and 50 ampere rated T/Rs were installed. For this project, each T/R was provided with two (2) positive and three (3) negative output circuits. Two negative outputs were connected to tank bottoms or to underground steel pipe. The third negative output was connected directly to the copper grid. Each output circuit contains a 50 ampere/50 millivolt shunt. We located each T/R unit in a non-explosion proof area, therefore all specified T/Rs were post mount, air cooled units with galvanized steel case. See Figure 6, typical tap adjusted T/R used for construction.

Due to the very uniform soil resistivity environment and the relatively uniform anode spacing, all of the rectifier output voltages calculated at close to the same values. This is not usually the case. Therefore, it is extremely important to perform individual rectifier and ground bed calculations when designing cathodic protection for another facility. Please keep in mind that the Puerto Salgar Station is a relatively simple layout from a cathodic protection standpoint. Other facilities could be much more complex.

COMPUTERIZED RECORD KEEPING

It is extremely important that each T/R unit be read at regular intervals with a written record maintained of the readings. We recommended that each unit should be read at monthly intervals. Voltage, amperage, date and the reader's initials are to be recorded on appropriate fill out forms. These data are very useful for trend analysis when there are problems with either a T/R unit or with a ground bed. Another useful bit of information is ground bed resistance. This is not simply voltage divided by amperage. Back EMF must be taken into account to obtain a meaningful number. The back EMF is the sum of the cathodic polarization on the plant underground structures and the anodic polarization on the ground bed. Back EMF is obtained by placing a voltmeter directly across the rectifier output terminals and measuring the instant off potential across those terminals. This number will only change a little bit from year to year. Therefore, it is acceptable to obtain the back EMF value from the previous survey and subtract that value from the rectifier output voltage to obtain the actual DC driving voltage. This driving voltage is then divided by the output amperage to obtain the true ground bed resistance. The amperage value should be obtained by placing a digital voltmeter (DVM) across the output shunt to obtain a precise calculation of the current output. Dividing driving voltage by current output yields the correct circuit resistance. Panel mounted ammeter readings are less precise, but are usually adequate for trend forecasting.

ADDITIONAL RECOMMENDATIONS

Designing a cathodic protection system is only part of the battle. It is extremely important that the cathodic protection system be correctly installed in full accordance with the plans and specifications, utilizing the best available workmanship. **THERE IS NO SUBSTITUTE FOR ADEQUATE CONSTRUCTION INSPECTION.** This means full time inspection of all construction operations during the installation. If the plant owner does not have adequate man power to properly supervise the installation of the cathodic protection system, adequate funds should be budgeted to permit full time third-party inspection and commissioning of the system. Plant owners will gain full benefit from the installed cathodic protection system if the system is carefully commissioned and adjusted to provide adequate protection throughout the facility without overprotecting some areas.

As a part of the installation inspection work and subsequent commissioning of the system, it is extremely important that as-built drawings be generated during conclusion of the project. These records are invaluable during any future construction work within the facility. Cathodic protection header cables are highly susceptible to construction damage during future additions to the facility.

In addition, annual surveys are absolutely essential. Usually, the output of most of the T/R units will be decreased slightly during the first annual survey, due to polarization of underground structures within the facility. Occasionally, it is necessary to increase the output of one or more T/R units in order to assure complete protection in other areas of the facility. This can only be determined by a comprehensive annual survey which repeats potential measurements throughout the facility, as taken during the commissioning survey.

CONCLUSIONS

Successful application of an impressed current cathodic protection system to the Puerto Salgar station was accomplished through the following steps:

- Comprehensive corrosion control survey, including a through review of facility records.
- Careful design of CP facilities taking full account of large bare tank bottoms and a massive bare copper electrical grounding grid.
- Installation of the CP system in full conformance with the plans and specifications.

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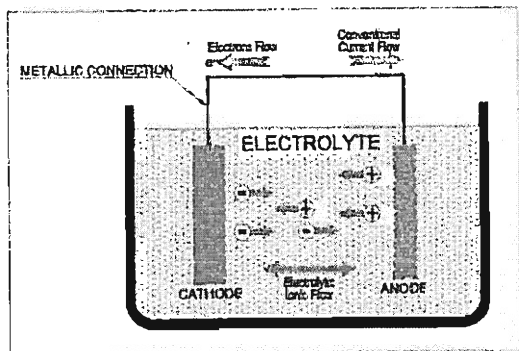


Figure 1 Corrosion Cell

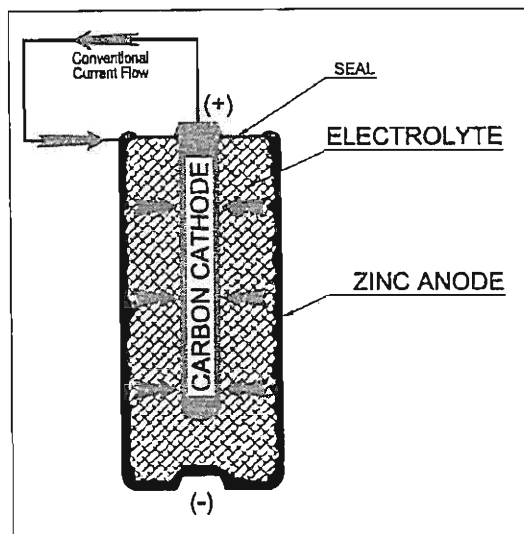


Figure 2 Corrosion cell, the Dry Cell battery

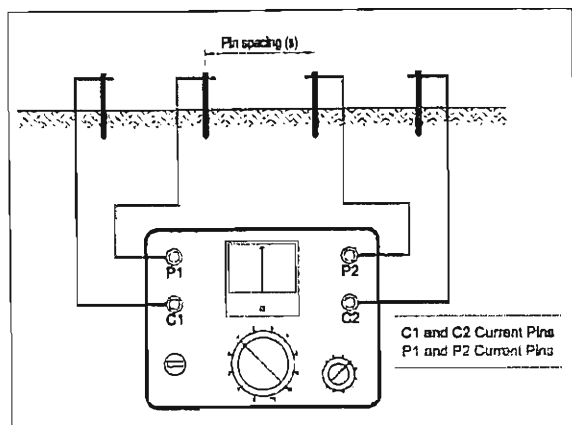


Figure 3
Pin Arrangement for Resistivity Measurement

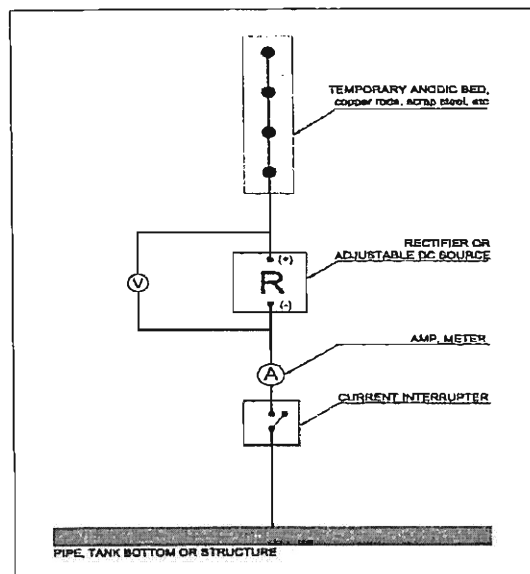


Figure 4
Typical Current Requirement Test Arrangement

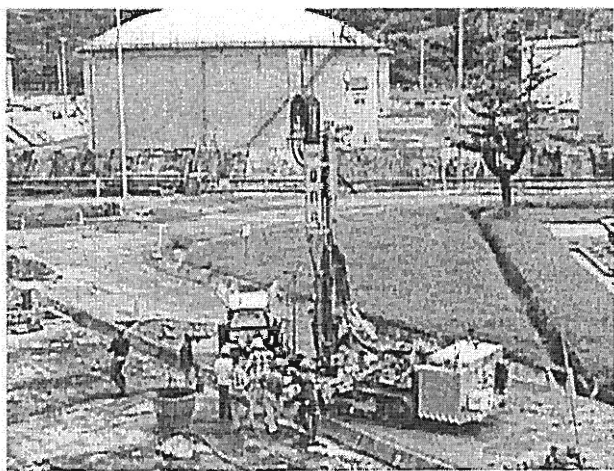


Figure 5
Vertical drilling equipment used during construction

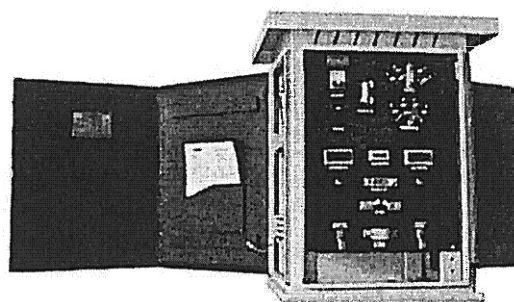


Figure 6
Typical tap adjusted T/R used for construction