CATHODIC PROTECTION OF TRANSMISSION LINE TOWERS

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ABSTRACT

This paper discusses some of the corrosion problems typically experienced by the underground portions of electrical transmission line towers, and examines cathodic protection as a method by which tower footing corrosion can be prevented. A case history of one power company's cathodic protection experiences is also presented.

Keywords: transmission line towers, cathodic protection, galvanized steel.

INTRODUCTION

The corrosion of transmission line tower footings has been recognized as a possible problem since at least as early as 1936, when the Detroit Edison Company began examining the condition of the galvanizing on the underground portions of their steel lattice towers.[1] Furthermore, from as early as 1946 when the California Electric Power Company installed magnesium anodes on a number of their steel towers,[2] and more recently as described in other literature,[3,4] cathodic protection has been used as a means of preventing tower footing corrosion.

Despite these and other published experiences spanning almost 50 years, most power companies still place little emphasis on the importance of tower footing corrosion. In a 1983 survey, only 4 out of 18 Canadian companies involved in power transmission reported that they were aware of any corrosion on their tower footings.[5] To the author's knowledge, in Canada, only SaskPower and Ontario Hydro have

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undertaken extensive programs to cathodically protect tower footings. Hydro Québec[6] and Trans-Alta Utilities have cathodically protected tower footings on a more limited basis, and in British Columbia, cathodic protection has been applied in only one instance where corrosion damage was observed on the footings of some towers which had been knocked over by a snowslide. It is believed that the electrical power companies in Manitoba and the maritime provinces have never used cathodic protection to control tower footing corrosion.

As an illustration of the importance of preserving the integrity of these structures, Ontario Hydro estimates the value of their 45,000 transmission line towers at several billions of dollars,[7] and that furthermore, by the year 2000, 80% of these structures will have exceeded their original design life of 55 years, and will need to be protected against corrosion.

CORROSION THEORY

Corrosion of Galvanized Steel

The majority of transmission line towers are of the steel lattice type, constructed of hot-dip galvanized structural steel members. In earlier installations, the footings of these towers were direct-buried in the soil and anchored to galvanized steel grillages as shown in Figure 1. While the galvanizing normally provides the above-grade portions of the towers with excellent protection from atmospheric corrosion, it is generally less effective in protecting the buried footings, which are exposed to an electrolyte on a continuous basis, and are exposed to more aggressive corrosion mechanisms as well.

The effectiveness of galvanizing as a corrosion prevention measure is twofold. The galvanizing acts as a mechanical barrier, isolating the steel from the electrolyte; however, unlike a dielectric coating, when bare steel becomes exposed as a result of corrosion or mechanical damage to the galvanizing, the remaining zinc coating acts as a sacrificial anode and provides cathodic protection to the steel.

Tests conducted in a variety of soils have shown that zinc experiences an average corrosion rate of 0.3 grams/m^2/day.[8] For a typical galvanized steel tower footing having a zinc coating thickness of 5 mils (3 oz/ft^2), this translates to a life of only 8 years before the galvanizing has been completely consumed. In fact, this life would be considerably less if the galvanic effect between the zinc and exposed bare steel was considered, not to mention the other corrosion mechanisms present on an actual power line installation.

The corrosion rate of zinc is also affected by pH. As shown in Figure 2, zinc experiences a pitting rate in the range of from 1 to 4 mils/year in weakly alkaline solutions, but in acidic or strongly alkaline solutions, the rate is dramatically higher.[9] One case is described in the literature in which grillages installed in acidic soils having a pH of 3 had lost their galvanizing and begun to corrode in less than 2-1/2 years[3].

There is evidence to suggest that the mechanical protection provided by hot-dip galvanizing is greater than what is afforded by a pure zinc coating alone. When steel is hot-dipped in zinc, a series of zinc-iron alloys form at the interface between the base metal and the zinc surface layer. In tests conducted by Romanoff and others (as reported by the NBS[8]), the pure zinc surface layer was electrolytically stripped to expose the alloy layer, and the alloy layer was found to be as much as 100 mV cathodic to steel. In these tests, the alloy was found to continue to corrode at approximately the same rate as either pure zinc or bare steel, and furthermore, it was found to be ineffective in providing cathodic protection to the bare steel. However, in subsequent tests where the zinc layer was allowed to corrode away naturally, the zinc-iron alloy was often found to experience negligible corrosion rates due to the formation of a passive film, perhaps zinc silicate. Nevertheless, the NBS report concludes that *in any environment in which the protection of steel depends entirely on the sacrificial corrosion of the zinc coating, a galvanized coating could provide only temporary protection at best.*

Corrosion of Tower Footings

In addition to general corrosion, tower footings may experience more severe corrosion as the result of localized corrosion cells existing at individual towers, or long-line corrosion cells existing along the length of the transmission line.

Considering first the case of an individual tower, or even a single tower footing, corrosion may be accelerated by any number of common corrosion mechanisms. Differences in soil conditions (resistivity, pH, soil type, aeration, etc.) between one tower footing and another, or between the upper portion of the tower leg and the grillage, can set up localized anodes and cathodes. A potentially more aggressive corrosion cell is caused by the interconnection of dissimilar metals to the tower footing. Copper counterpoise wires, copper-clad ground rods, and reinforcing steel in concrete are all cathodic with respect to bare steel as well as galvanized steel, and will accelerate the depletion of the galvanizing and the eventual corrosion of the base metal .

Where transmission line towers are electrically connected by either a skywire or counterpoise, the tower footings become susceptible to long-line corrosion cells in the same manner as a pipeline. Again, variations in soil conditions along the transmission line route, and dissimilar metal couples arising from copper grounding grids at substations are both factors which can accelerate the corrosion of tower footings. Furthermore, both man-made stray currents (e.g. DC transit systems, impressed current cathodic protection systems) and geomagnetic stray currents can contribute to corrosion as well. Fortunately, these long-line corrosion problems can often be mitigated by the electrical isolation of the skywire from the towers.

In most newer installations, steel lattice towers, as well as coated-steel pole towers, are installed on reinforced concrete pads. As long as the metallic components of the towers are supported above grade by these pads, they will only be subjected to atmospheric corrosion. However, should the tower leg come into contact with the soil, either because of changes in grade or because of surface flooding, then the tower leg becomes susceptible to all of the same corrosion mechanisms as before, including the additional galvanic influence of the reinforcing steel in the concrete pad (Figure 3).

APPLICATION OF CATHODIC PROTECTION

General

Cathodic protection can be easily applied to tower footings by the installation of packaged sacrificial anodes. Typically, one anode is installed per footing, but the particular type of anode required for a certain application will vary depending upon soil conditions and current requirements.

Normally, a current density of at least 10 mA/m^2 is required to protect a steel tower footing in most soil conditions. A small 1m x 1m grillage of the type shown in Figure 1, connected to a tower leg 2m long, might therefore require a current of approximately 30 mA for protection. In most Canadian soils, this current would be difficult to attain using a zinc anode, because of zinc's relatively low open-circuit potential of -1100 mV. Under most conditions, magnesium anodes are preferred, because the higher open-circuit potential of magnesium (-1750 mV) allows it to produce approximately three times as much current as a comparable zinc anode. In cases where cathodic protection current requirements are low, such as on towers coated with a dielectric material, or where soil resistivities are known to be low (e.g. <1000 Ω-cm), zinc anodes may be preferred, because of their higher current efficiency and longer life.

There may be cases where the cathodic protection current requirements of tower footings are too high to be realistically met using sacrificial anodes. In such instances, impressed current cathodic protection may be used. The primary drawback associated with an impressed current system is the cost of powering and maintaining the impressed current rectifier.

Prioritization of Cathodic Protection of Existing Towers

The most accurate means of determining the extent of corrosion experienced by a tower footing is to excavate and physically examine the footings. Because this is an extremely laborious and costly procedure, structure-to-soil potential measurements are often used to estimate the condition of the galvanizing on the tower footings, which in turn provides a rough indication of the structural integrity of the footings.

Galvanized steel typically exhibits an electro-chemical potential in soil of approximately -1100 mV with respect to a saturated Cu|$CuSO_4$ reference electrode. The potential of bare steel, on the other hand, may be in the order of -500 to -600 mV. As a galvanized steel tower footing corrodes, the potential exhibited by the footing gradually shifts in the positive direction, as more and more of the zinc galvanizing is lost and the bare steel becomes exposed.

Various methods of interpreting these potential measurements have been published, a number of which are summarized in Table 1.

A drawback when using potentials to estimate the condition of tower footings is that these measurements actually represent mixed potentials; that is, they are an average of the potentials exhibited by both the galvanized and bare steel portions of the tower leg and grillage, as well as the potentials of counterpoise wires, ground rods, and any other electrically continuous structure in the immediate vicinity of the tower (see Figure 4). As an example of how this mixed potential may not be representative of the tower footing's condition, the literature describes a case where surface potential readings of -900 mV failed to indicate that the grillage was corroding[3]. In this case, the grillage was located in a lower layer of acidic soil and exhibited potentials in the -600 to -700 mV range, whereas the upper portion of the tower leg exhibited a potential of -1000 mV, since it was located in neutral soil having a higher resistivity.

CATHODIC PROTECTION CASE HISTORY

In 1978, SaskPower initiated a program to monitor and control the corrosion of their transmission line tower footings. At the time, SaskPower was responsible for the transmission and distribution of both electrical power and natural gas throughout the Province of Saskatchewan, and so this program arose from a general corrosion awareness from a gas piping point of view, rather than because of any particular corrosion problems being experienced by the tower footings.

Cathodic Protection of Existing Lattice Steel Towers

SaskPower's program involves the regular monitoring of tower footing potentials, and the application of cathodic protection at locations where these potentials are less negative than -600 mV. The potentials measured on approximately 540 galvanized steel tower legs illustrates how these potentials become more electro-positive over time as the galvanizing is consumed (Figure 5).

SaskPower has provided survey data for four transmission lines installed since the 1960's for analysis. Out of more than 900 towers surveyed, approximately 8% were found to exhibit potentials less negative than -600 mV and were subsequently cathodically protected. The majority of towers had potentials in the -800 mV to -850 mV range as shown in Figure 6.

A standard method of cathodically protecting these structures was adopted, and involves the installation of a 17-pound packaged magnesium anode on each tower leg. Each anode is installed approximately 1.5m out from where the tower leg enters the ground, and is permanently connected to the tower leg. A shunt installed in the anode lead allows the current to be monitored without the need to disconnect the anode.

The distribution of potentials recorded for approximately 80 towers which were protected in this manner is plotted in Figure 7. The plot shows an immediate shift in tower potentials from the -400 to -600 mV range, to the -1600 to -1800 mV range after cathodic protection is applied. The most recent survey data indicates that these potentials have become less negative over the last 9 or 10 years, but the towers remain protected and exhibit average potentials in the -1000 to -1200 mV range.

There may be two or more explanations for this apparent decline in potentials. Firstly, the potentials measured during the first year of operation are similar to what would be expected for open-circuit potential measurements on the magnesium anodes. It is therefore suspected that the reference electrode was placed so that it was looking primarily at the anode rather than the tower footing. Secondly, anode current outputs have declined over this period of time from an average of 25 mA to roughly 14 mA, as illustrated in Figures 8 and 9. This may be due to either anode consumption or cathode polarization.

Cathodic Protection of New Coated-Steel Towers

In addition to the program adopted for the existing steel lattice towers, all new 138/230 kV steel H-frame towers are cathodically protected at the time of installation. These structures are constructed using two 400 mm diameter steel poles installed to a depth of between 4.0 and 4.7 m in a crushed rock backfill. The below-grade portions of the poles are coated with 30 mils of polyurethane, and are cathodically protected using a single 32-pound magnesium anode located midway between the two poles at a depth of about 2 m (Figure 10).

Since these towers are relatively new, having only been installed in the last five years, only one set of cathodic protection data has been collected to date. Figure 11 gives the potentials measured on over 600 steel pole towers, and plots them against anode current. Once again, these potentials have been measured with the protective current applied, but because these structures are well-coated, and the reference electrodes have been placed close to the poles and remote from the anodes, IR drop errors are expected to be small.

The data shows that 85% of the towers are cathodically protected to SaskPower's criterion of -850 mV. On average, the towers which are adequately protected receive 24 mA of current, whereas those which are under-protected receive only 12 mA of current.

Based on an average current output of 22 mA, the anodes installed on the steel pole towers are expected to last approximately 40 years. At an estimated installed cost of $\$500^{\underline{00}}$ per anode ($\$150^{\underline{00}}$ materials, $\$350^{\underline{00}}$ labour), and assuming an annual interest rate of 8%, the equivalent annual cost[11] of cathodically protecting a tower is approximately $\$40^{\underline{00}}$ per year.

RECOMMENDATIONS

The following recommendations for the effective implementation and monitoring of cathodic protection systems for transmission line towers are based primarily on what has been learned from the review of the SaskPower experience:

1) A more uniform level of protection could be achieved for all towers by measuring the soil resistivity at each tower where anodes are to be installed. Either the Wenner Four-Pin Method or a single probe resistivity device could be used to quickly and easily obtain the approximate soil resistivity at anode depth, thereby allowing a quick calculation of the most suitable anode for use at each tower.

2) In order to eliminate IR drop errors when measuring the potentials of protected footings (such as those measured during the first year of the lattice tower program), the anodes on a tower should all be simultaneously disconnected to facilitate a true polarized potential measurement. This 'off' potential can be compared to the tower's static potential to determine if it meets the NACE -100 mV shift criterion, rather than relying only on the present -850 mV criterion.

3) In order to permit the simultaneous interruption of anode current recommended above, the anodes at each tower should be connected to a common header cable rather than individually to each tower leg. The header cable should then be bonded to a lead wire from the tower inside a test station. This also ensures that there is no exposed wiring or connections which could otherwise suffer mechanical damage on the outside of the tower leg.

SUMMARY

Although the corrosion of direct-buried transmission line tower footings is generally not perceived to be a major problem, the majority of these structures have reached an age at which it is doubtful that their original galvanized coatings are of much benefit in preventing below-grade corrosion. Cathodic protection is a cost-effective means of extending the life of the tower footings, and considering the immense value of these structures, it should be an essential element of any tower rehabilitation program.

ACKNOWLEDGMENTS

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TABLE 1 - GUIDELINES FOR ESTIMATING CORROSION ACTIVITY ON GALVANIZED STEEL TOWER FOOTINGS

Source	Potential Range (mV to Cu|$CuSO_4$)	Interpretation
Ogorodnikov[10]	-0.85 to -1.2 -0.6 to -0.8 ≥ -0.62	Zinc coating acts as cathodic protection. No corrosion. Zinc oxide is acting as a protective coating. Galvanizing does not protect the steel, and corrosion progresses.
Ogorodnikov[10]	-1.0 to -1.75 -0.8 to -1.0 -0.6 to -0.8 -0.4 to -0.6 -0.2 to -0.4	Galvanizing acting as cathodic protection. Tower protected. Galvanizing is acting as protective coating. Tower protected. New tower partly protected, or ungalvanized tower not protected. Galvanized tower not protected, or ungalvanized tower being corroded. Tower being corroded.
CEA[5]	< -1.1 -0.8 to -1.1 > -0.8	Tower leg is a cathode if dc current flows from tower to skywire. Corrosion can be occurring. Zinc galvanizing has either corroded away or ennobled, and tower leg is an anode if dc current flows from skywire to tower.
Duquette[6]	-0.85 to -1.75 -0.7 to -0.84 -0.5 to -0.69 -0.3 to -0.49 -0.1 to -0.39	Galvanizing acts as cathodic protection. Galvanizing acts as protective layer. Tower without galvanizing. Corroded tower without galvanizing. Highly corroded tower.

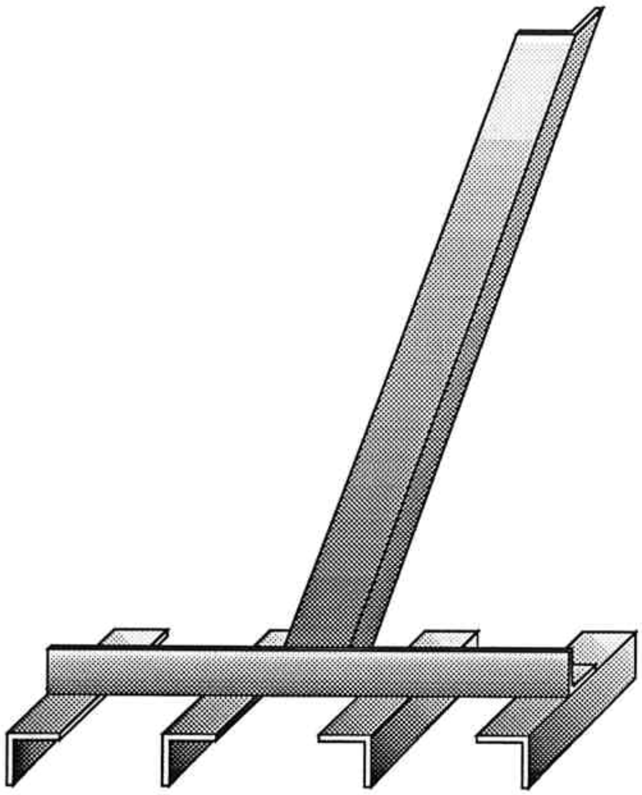

Figure 1 - Typical Galvanized Steel Grillage

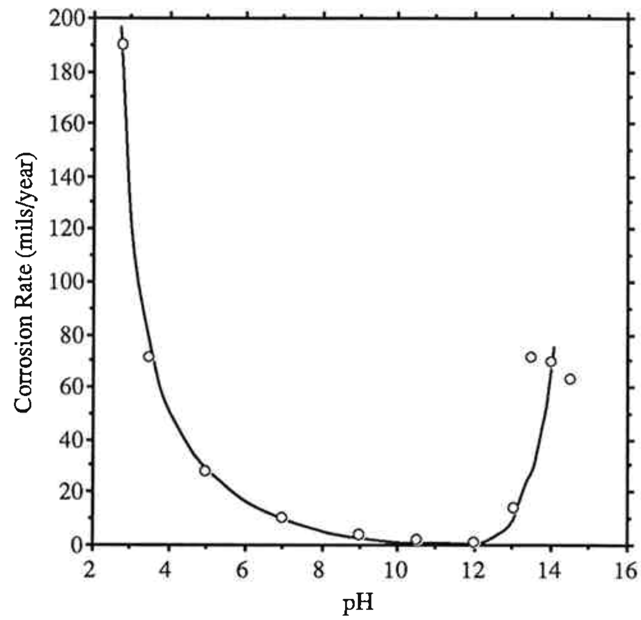

Figure 2 - Effect of pH on Corrosion Rate of Zinc[9]

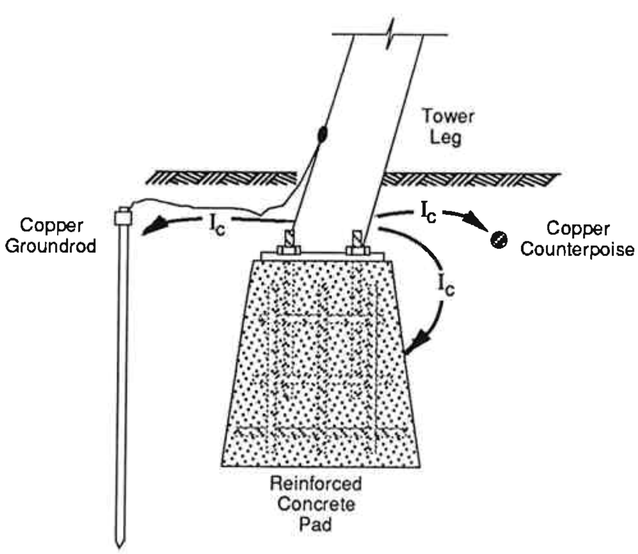

Figure 3 - Possible Corrosion Currents Associated With a Tower Footing

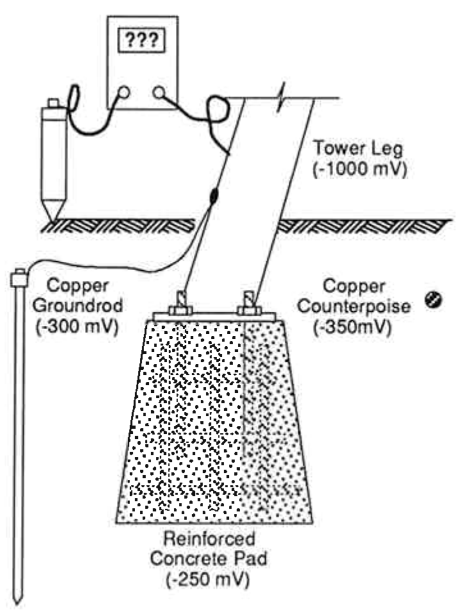

Figure 4 - Measurement of a Mixed Potential

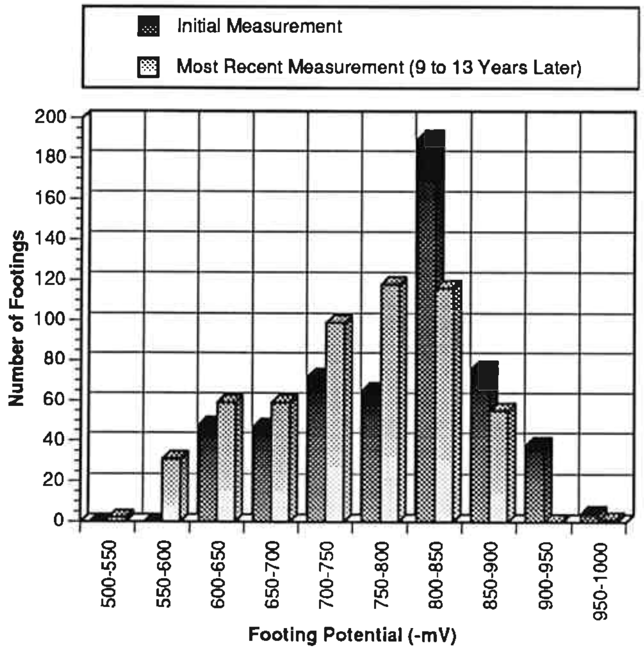

Figure 5 - Change in Potential Distribution Over Time for Unprotected Galvanized Steel Lattice Towers

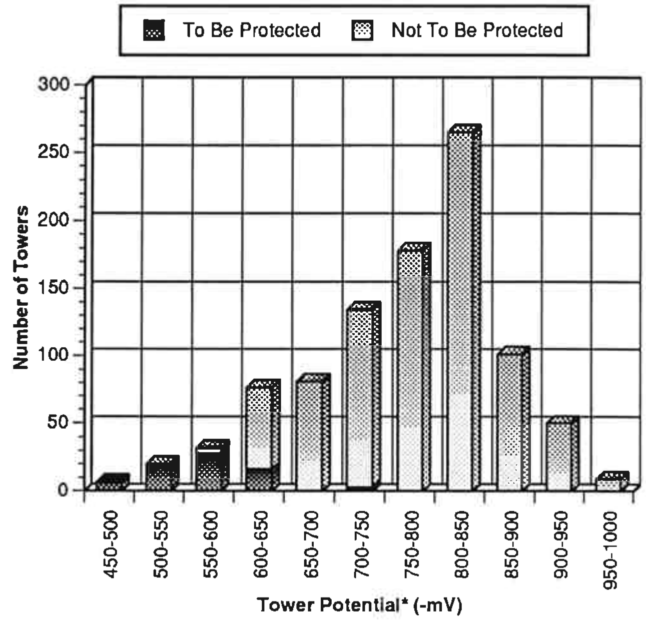

Figure 6 - Initial Potential* Distribution of Galvanized Steel Lattice Towers Showing Potentials of Towers to be Protected

*Average potential of four footings per tower

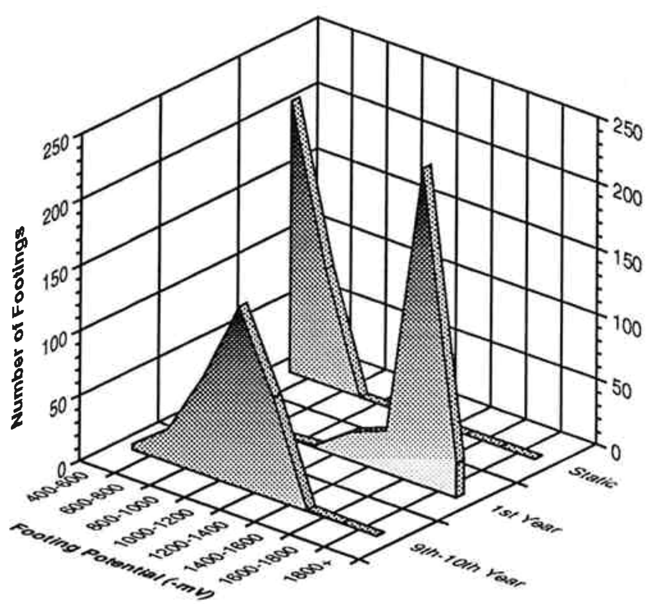

Figure 7 - Change in Potential Distribution Over Time for Protected Galvanized Steel Lattice Towers

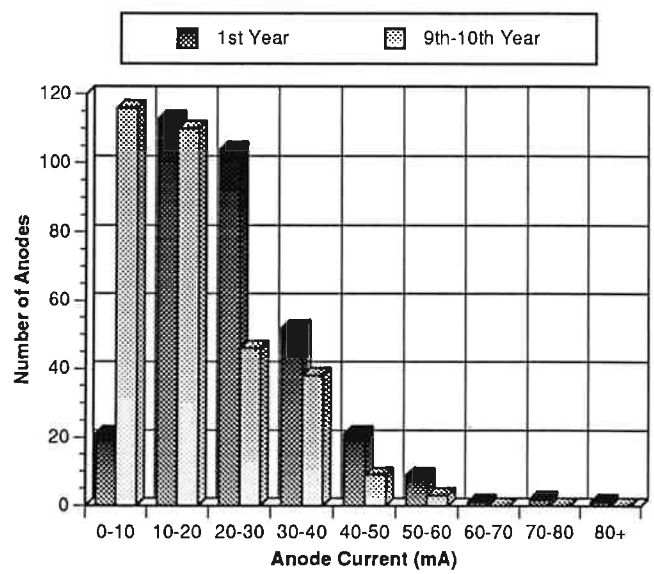

Figure 8 - Change in Anode Currents Over Time for Galvanized Steel Lattice Towers

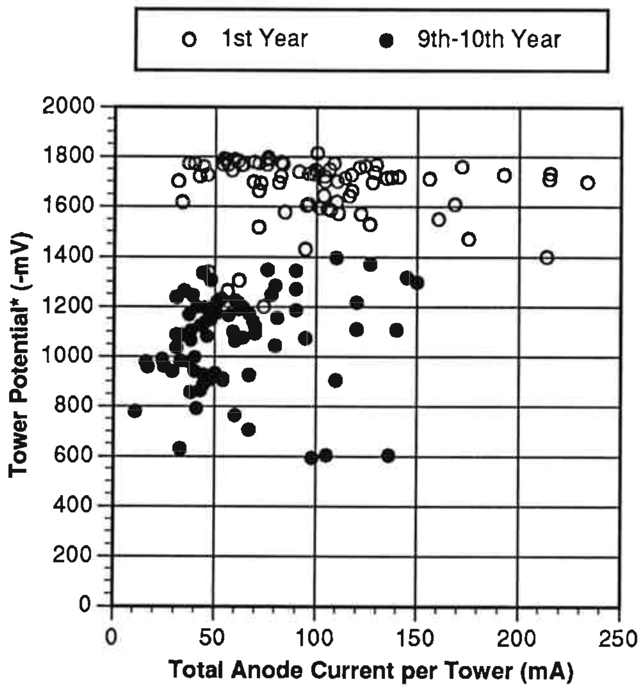

Figure 9 -
Tower Potential* Versus Anode Current for Galvanized Steel Lattice Towers
*Average 'on' potential of all four tower footings

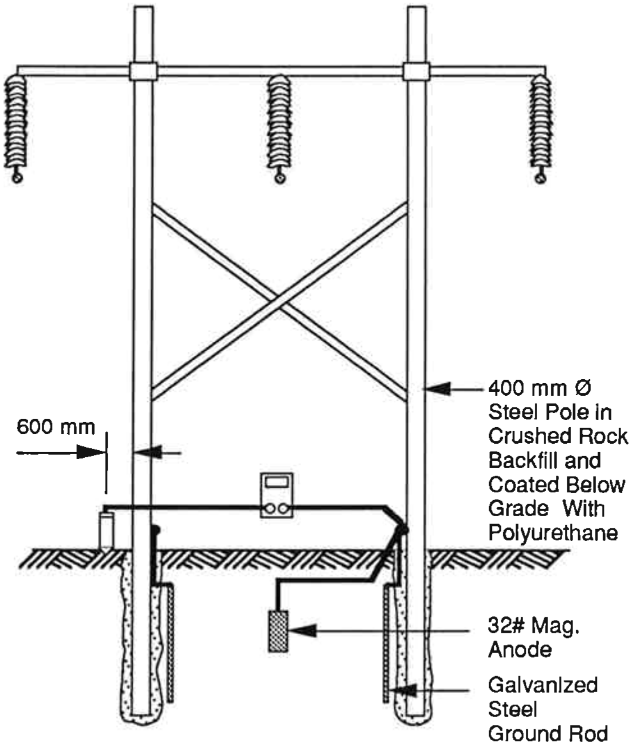

Figure 10 -
Cathodic Protection of Coated-Steel Pole Tower

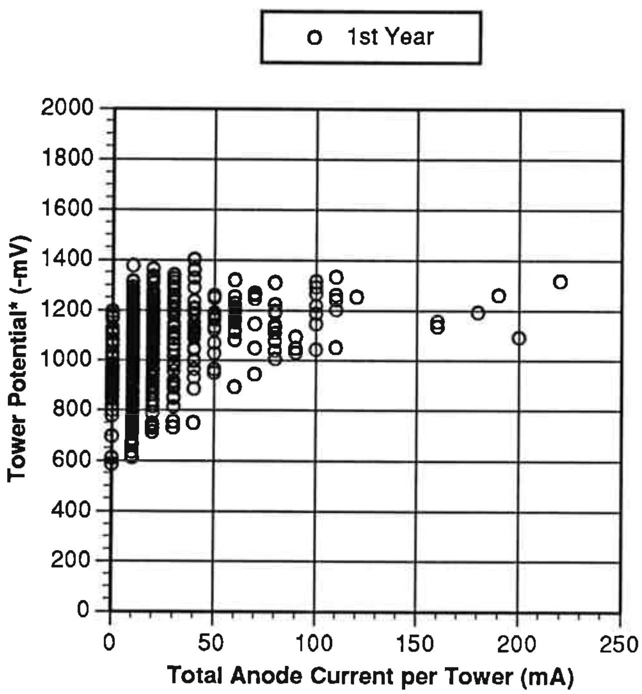

Figure 11 -
Tower Potential* Versus Anode Current for Coated Steel Pole Towers
*Average 'on' potential of both tower legs