Stray Current Corrosion in Electrified Rail Systems -- Final Report

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EXECUTIVE SUMMARY

Despite a relatively mature technology for its control, corrosion caused by stray current from electrified rapid-transit systems costs the United States approximately $500 million annually. Part of that cost is the result of corrosion of the electrified rapid-transit system itself, and part is the result of corrosion on neighboring infrastructure components, such as buried pipelines and cables. Detailed costs to either the transit systems or the neighboring infrastructure are not available, and, therefore, this limited study was undertaken for the Infrastructure Technology Institute (1) to assess the scope of stray-current corrosion on the electrified-rail systems based upon information in the literature and from interviews with selected transit-system operators, and (2) to determine whether new or additional corrosion monitoring or mitigation techniques are needed. The literature review was conducted through the Infrastructure Technology Institute Library Services Program, the Transportation Library, and the Seeley G. Mudd Library for Science and Engineering, all at Northwestern University. The interviews were conducted with seven rapid-transit operators, which included the following: (l) Chicago Transit Authority, (2) Port Authority Trans-Hudson Corporation, (3) Metro-North Commuter Railroad Metropolitan Transportation Authority, (4) New York City Transit Authority Metropolitan Transportation Authority, (5) San Francisco Bay Area Rapid Transit District, (6) Los Angeles County Metropolitan Transportation Authority, and (7) West Virginia University-Morgantown Personal Rapid Transit System.

The literature review indicated that the technology used today for controlling stray current from electrified rapid-transit systems was developed as far back as the 1920s. Improvements in materials for electrically insulating rails and fastening the running rails, which are used as the return-current path, and stray-current switching instrumentation have been made since that time, but the basic technology is essentially unchanged. The interviews indicated that this was the case for the agencies selected. Corrosion from stray current still occurs on those systems, however, and typically on rail spikes and fixtures to secure the rail to ties, the rail cross-section, steel reinforcements of tunnels, and, in some cases, steel components of the footings in the elevated sections of some systems. Only very limited data could be developed regarding the cost of corrosion to these systems because none of the agencies had a formal cost tracking program in place, in part, because corrosion was not considered to be a significant cost element. Estimates from three agencies have place the annual cost in the range of $10,000 to $200,000, which represents less than approximately 0.5 percent of the annual non-vehicle operating cost. The low cost to the agencies suggests that the major cost of corrosion attributed to stray current annually ($500 million) is being borne by the neighboring infrastructure.

Despite the low cost to the agencies themselves, there was agreement that improvement in corrosion control is needed. The agencies interviewed suggested the following five areas of need to improve stray-current control and reduce corrosion: the development of (1) a stray-current measurement methodology, (2) guidelines for acceptable stray-current control, (3) an in situ spike and pandrol corrosion inspection method, (4) better rail insulation, and (5) a long-term rail monitoring program. To address these suggestions, ideas were developed and recommendations were made to develop (a) a stray-current measurement car to monitor stray current distribution and to assess the effectiveness of remediation measures, and (b) a portable instrument for monitoring rail-spike and pandrol corrosion to accompany maintenance walkers as they inspect the rails, but are unable to see corroded spikes and pandrols under tie plates or in ties. Although cost data are still lacking to evaluate or justify the economic benefit, these developments would benefit both the electrified rapid-transit operators and the neighboring infrastructure components as well.

INTRODUCTION

Every year, the United States spends approximately $10 billion because of corrosion and its detrimental effects(1). The National Association of Corrosion Engineers, Battelle Memorial Institute, and the U.S. Department of Commerce estimate that five percent of this cost, or $500 million, is attributable to stray-current corrosion, mostly due to electrified DC transit systems(1). As a consequence, increased awareness of stray-current corrosion was renewed in the 1950s and 1960s when new, electric-powered transit systems were constructed to alleviate congested highways and to provide efficient mass transportation. Measures taken to control stray-current through proper design utilizing the principles of the early 1900s have become standard practice for newly built transit systems and for new lines added to older transit systems. Design of stray-current-mitigation methods has focused primarily on two aspects; increasing the rail-to-earth resistance and decreasing the negative return path resistance primarily because these are the two parameters for which some degree of control can be exercised after a transit system has been built. However, these two design parameters do not address the need for quantifying the stray-current and corrosion that is still occurring.

Modern design has reduced stray current on newer transit systems, but stray-current leakage and subsequent corrosion is still present on electrified-transit systems, new and old alike. Furthermore, transit agency operators do not know, other than by visual or mechanical inspection, where and how much stray-current corrosion is occurring on their system. In addition, they do not know how significant the problem is and how much of their maintenance and repair costs are the result of stray-current corrosion. Other industries, such as the natural-gas pipeline and the electric-power industry, have recognized that regular monitoring and inspection are an important part of controlling corrosion. Direct and indirect corrosion-monitoring strategies reduce maintenance costs and ultimately the likelihood of corrosion leading to a disastrous situation.

Mitigation of stray-current corrosion on transit systems, however, is commonly performed by reacting to an immediate problem, rather than taking a pro-active viewpoint to the problem. This is largely because the first priority of a transit agency is customer driven; keep the trains running and on-time. Since stray-current corrosion manifests itself over a period of time, it is usually overlooked in the day-to-day management of the transit system. In addition, an education gap can exist, such that maintenance personnel, engineers and management may not fully understand why and where stray-current may be occurring and whether additional maintenance costs are due to stray-current corrosion.

Consequently, there is a need to assess the potential for a significant problem and the costs of stray-current corrosion on electrified rapid-transit systems. This assessment will help to determine where emphasis should be placed. This project has attempted to provide a very limited assessment ofthe problem, and particularly as the stray current causes corrosion on the rapid-transit systems themselves. This report summarizes the results of the project.

OBJECTIVES AND APPROACH

The objectives of this study were (1) to assess the scope of stray-current corrosion on electrifiedrail systems based upon information in the literature and from interviews with selected transitsystem operators, and (2) to determine whether new or additional corrosion monitoring or mitigation techniques are needed. Strong emphasis was placed on discussions with a sample of transit operators to determine the magnitude of the problem and the costs associated with it, to quantify their knowledge and experience with stray-current corrosion, and to determine if operators believe the problem needs further study. The objectives were accomplished in four tasks: Task 1: Literature Review, Task 2: Interview Identification, Task 3: Interviews, and Task 4: Topical Report.

Stray Current Corrosion in Electrified Rail Systems

Literature Review

LITERATURE REVIEW

A literature review was undertaken to determine the state-of-the-art of stray-current corrosion control. A discussion of select literature pertinent to this study is given. In general, the literature search provided many case studies of stray-current analysis and mitigation on various electric transit systems.(2-13) This provided a good overview of the technical methods, past and present, that have been used to control stray current. Also found in the search were articles relating stray-current corrosion from the viewpoint of pipeline, telephone, and electric utility companies. (14-21) Neighboring utility lines are often the recipient of stray-current from electrified-transit systems.

Two articles were reviewed that gave historical background to the problem. (22,23) In addition, three publications that listed statistical information on operating costs and expenses and general descriptions of every rail system in the world were reviewed.(24-26) The statistical information allowed comparison of the stray-current corrosion costs obtained from the transit interviews with total maintenance operating costs. (24-26) No articles in the literature search, however, were found that dealt with or mentioned specific costs due to stray-current corrosion on transit systems.

Special note is given to three, definitive publications on stray-current corrosion. The first is a series of 15 reports issued by the National Bureau of Standards in the early 1920s which represents the first comprehensive attempt to identify the practical aspects of stray-current corrosion and its mitigation. (27) Many of the conclusions that were made then are still valid for modern, electrified-transit systems. In addition, an important idea to come out of the study was the formation of electrolysis committees. These committees, consisting of transit operators, pipeline companies, electric utilities, municipal government and telephone companies, that meet regularly to discuss common problems and possible solutions to stray-current corrosion. These committees have been instrumental in providing an open forum for discussion of problems and have helped iron out many of the differences between the affected parties. Many of these committees are still active today and meet on a regular basis.

The second important publication found in the literature is a series of eight reports issued in 1985 through the National Cooperative Transit Research & Development Program (NCTRP). (1) One aspect of that 5-year study was a comprehensive literature review of 549 publications on stray-current corrosion from 1900 to 1985. Another result of the program was recommendation of a 5-year, $5 million plan to investigate various areas of stray-current corrosion deemed important by participating transit operators, utility companies, and engineering firms. To date, however, that portion of the program has not been implemented, and there are no known plans to do so.

The third publication is an excellent compilation of 35 key articles on stray-current corrosion that was recently published by the National Association of Corrosion Engineers. (28) The articles provide a good overview of important case studies of stray-current control on several old and new transit systems, a discussion of the cooperative approach to the stray-current corrosion problem through local electrolysis committees, and procedures to follow when designing a new system. In addition to these three publications, a corrosion-control manual specific to rapid-transit rail systems, which provides information on problems and solutions to common corrosion problems (including stray-current corrosion) encountered on railway systems, is also noted. (29)

To fully appreciate various aspects of stray current, corrosion, and stray-current corrosion control, a basic understanding of each is needed. Accordingly, a brief description of corrosion and stray currents are presented before the literature review that follows.

Corrosion Mechanism

Corrosion is the spontaneous degradation that a metal undergoes when exposed to an environment, such as air, water, or soil. Corrosion is caused by an electrochemical reaction that takes place between the metal and the environment. There are six forms of corrosion, but only two forms are most often encountered on electrified transit systems, namely, pitting and general corrosion. Corrosion can be localized, taking the form of pits in the surface, or it can be more generalized, forming large areas of metal wastage. In all cases, however, four basic requirements are needed for corrosion:

- An anode, or an anodic region on the same metal with a cathodic region
- A cathode, or a cathodic region on the same metal with an anodic region
- An electrolyte between or in common with the anode and cathode
- A metallic path to connect the anode and cathode for electronic continuity.

If these conditions are met, a cell can be set up in which corrosion can take place.

FIGURE 1 illustrates the conditions needed for a corrosion cell. Steel is immersed in an aerated electrolyte and electrically connected to a voltmeter with which to measure the electrical potential of the steel with respect to a reference electrode. When the steel is immersed in the electrolyte, anodic and cathodic regions develop on the steel surface because of differences in the metallurgical phases of the steel, differences in the steel surface condition (e.g., mill scaled in some regions and none in others), or differences in the electrolyte chemistry. Electrical potentials develop between the anodic and cathodic areas, which can be few or numerous, but only a single potential can be measured with respect to the external reference electrode, and that potential is some mixture of the anodic and cathodic potentials. The electrical potential difference between the anodic and cathodic areas produces currents that circulate. In the electrolyte, the current is ionic, while in the metal components the current is electronic. The flow of electrons in the metal and the flow of ions in the electrolyte constitute the current in the cell. If the anode and the cathode are separated by a wire or a long extent of the metal, such as a rail, and the electrolyte is soil, measurable voltage drops will take place along the rail and in the electrolyte. The current measured is the net current and will depend upon the areas of the anodic and cathodic regions, the types of metal for the anode and cathode, and the potential difference between the anodic and cathodic regions.

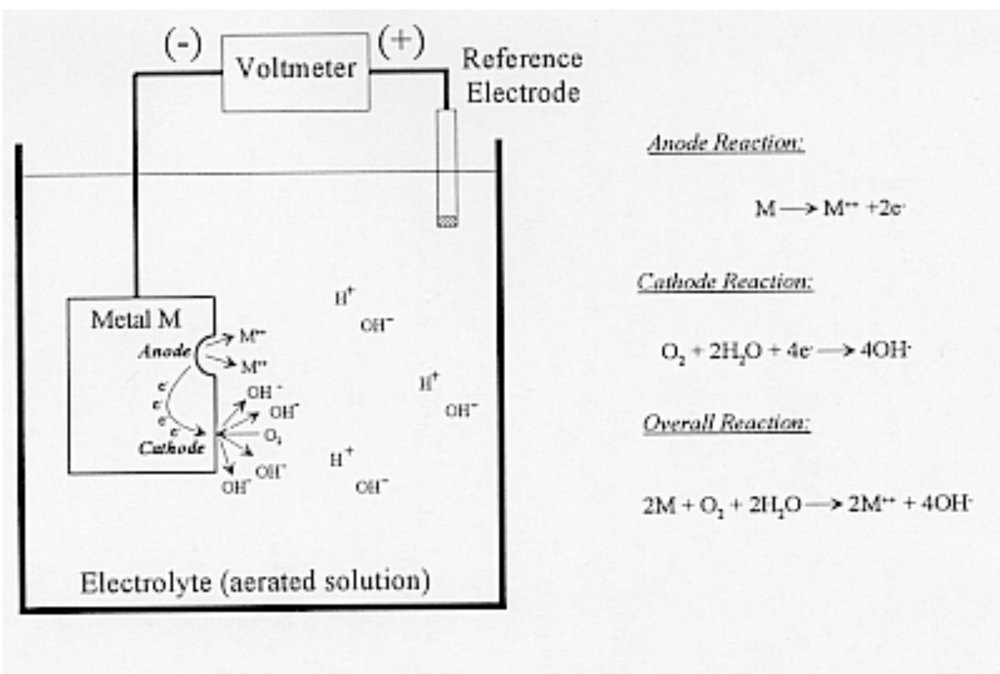


Figure 1. Components of a Corrosion Cell.

At the anode, the metal is oxidized to form ions that go into the electrolyte with the release of electrons. For steel, the reaction is

2 Fe ® 2 Fe++ + 4 e–

where Fe is iron in the steel and Fe++ is the iron ion going into the electrolyte with two electrons e- left on the metal. This is the corrosion reaction. At the cathodes, a reduction reaction will take place to preserve electroneutrality. In an aerated electrolyte, oxygen(O2) in the water will be reduced to form hydroxide ions (OH-) with the consumption of two electrons according to the reaction

$O_2 + H_2O + 4\ e^– ®\ 4\ OH^-$.(1)

In more deaerated and acid environments, the cathodic reaction may involve the reduction of water by the following reaction with the formation of hydrogen gas (H2)

$4\ H_2O+4\ e^– ®\ 4\ OH^-+2\ H_2$

The iron ions formed by the corrosion reaction combine with the negatively charged hydroxide ions to form hydrated ferrous hydroxide, or rust, that is observed visually.

If an external current were to be impressed upon the corroding metal, the reactions will be shifted by an amount depending upon the direction and magnitude of the current. If a net cathodic current is impressed, the corrosion reaction (Equation 1) will be decreased in magnitude and the cathodic potential will become more negative. This is the basis of the corrosion protection method called cathodic protection that is used to protect metallic structures, such as natural-gas pipelines and the reinforcing steel in concrete bridge decks. On the other hand, if the current is anodic, the corrosion reaction will be increased and the cathodic reaction will be decreased, resulting in an undesirable increase in the corrosion rate of the steel.

Stray Currents

As the term suggests, stray currents are those that have deviated from their intended path. They may be DC or AC depending upon the source. They deviate from their intended path primarily because the resistance of the unintended path is lower than that of the intended path, or the parallel combination of the two allows part of the current to take the unintended path. The corrosion current in FIGURE 1 is localized and was generated from the electric potential difference between the anodic and cathodic regions of the steel. However, anodic current that is picked up from an external source, such as an electrified transit system, will also cause metal loss where it leaves the metal. For instance, the current returning to the traction power substation along the rail may stray from its normal or intended path through the running rails and flow partially through the lower resistance of the elevated steel structure back to the substation. Or it is possible that part of the current may also flow into the soil, where it may be picked up by a gas main and discharged back to the soil and then to the rail near the traction power substation. The points where the current leaves the steel structures and goes into the soil or the concrete surrounding the steel are where metal loss occurs. In some cases, underground structures will pick up current at some point remote from the traction power substation and discharge the current to the soil and then to rail near the substation. At the point of discharge, the corroding structure acts as the anode in the corrosion cell shown in Figure 1.

FIGURE 2 illustrates the dramatic effect of stray current corrosion on iron water mains from an electrified rail system. The circled areas are corroded and in some cases, the pipe wall was penetrated by corrosion. This photograph was taken in 1918 before effective stray current control measures were implemented and illustrates why it is important to control stray currents.

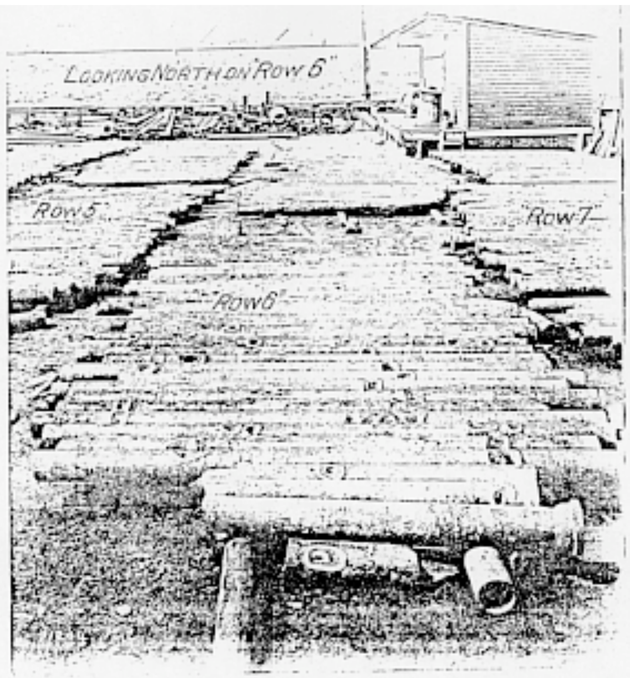


FIGURE 2. Examples of Stray-Current Corrosion (Circled Areas) of Cast-Iron Water Mains 1918 (Photocopy courtesy of Chicago Transit Authority).

While stray current can produce corrosion on nearby structures, corrosion is also very likely to occur on the transit system's properties as well, as the above discussion indicates when stray current leaves the structure or rail. The mitigation of stray current and its corrosion effects have been the subject of study over many years for the electrified transit systems. The following sections provide more detail regarding the historical directions and technology.

Historical Background

The first electrified transit system was developed in 1835 by Thomas Davenport, a blacksmith from Brandon, Vermont. (22) The system was simply an electric railcar that ran on a circular steel track. The electric-powered vehicle contained a small electric motor powered by a battery. However, the battery-powered system was impractical for providing commercial railway service, since the battery needed to be recharged after short periods of time. It was not until the development of the dynamo in the late 1800s, which provided a continuous source of DC power for the railcar, that electrified rail transit systems became commercially viable.

The first commercially successful electric railway line in the United States began operating in 1888 in Richmond, Virginia. (23) Within ten years, thousands of miles of electric railway were operating throughout the United States. Almost immediately, corrosion problems became noticeable by the telephone, water, and gas companies on their underground piping or cable that ran in close proximity to the railway. In addition, the transit agencies began to see corrosion damage on their rails and rail spikes. The corrosion damage, however, was first thought to be caused by the chemical makeup of the soil. It was soon concluded that soil chemistry could not have caused the severe corrosion problems encountered, and after some investigation it was discovered that current leakage off the railcar running rails was the primary cause of the corrosion problem.

Many early studies addressed the practical aspects of the problems and engineering solutions were implemented that mitigated the problem as best as the technology allowed. Most solutions had disastrous effects on the neighboring utilities. A common solution was frequent bonding of the rail return current path to a parallel water main or pipeline, the thinking being that the bond gave a metallic path for the current to follow rather than discharging off of the rail or other part of the transit structure. This exacerbated the problem since the utility line was now a part of the return circuit. Although bonding probably reduced stray-current corrosion on the transit system itself, corrosion would increase on many sections of the bonded utility line because the current was forced onto the utility structure, and when it left that structure to return to the transit system, corrosion could occur.

It was not until 1910, when the United States National Bureau of Standards (NBS) began their 11-year study of stray-current corrosion, that the problem was addressed systematically. (24) In 1921, the National Bureau of Standards recommended the following measures to reduce the occurrence of stray-current leakage on the transit-system side:

1. Provide for adequate track-to-track bonding
2. Minimize the distance between the traction power substations, consistent with system economy
3. Insulate the negative feeders (rails)
4. Utilize a three-wire traction power system.

The first three measures were implemented on many of the transit systems, resulting in decreased amounts of stray-current leakage. The fourth measure, a three-wire system design where the two running rails are neutral and a third and fourth rail are the positive feed and negative return, respectively, was not implemented by the transit companies. This was probably because of the added expense needed to construct a fourth rail to carry the return current back to the traction power station.

It was soon recognized that further mitigative measures were still needed to control stray-current leakage and the subsequent corrosion problems that were still occurring, especially on underground utility structures. Several recommendations were made in the National Bureau of Standards report that were applicable to the underground structures. They were the following:

1. Be selective in locating new construction near tracks
2. Avoid contacting cable with pipes and other structures
3. Use conduits in cable construction
4. Use insulating joints in pipes and cable sheaths
5. Shield structures with an insulating coating
6. Interconnect affected structures and railway return circuits.

These measures, used in conjunction with the recommendations for the railway transit system, represented the best approach to reducing stray-current and corrosion in 1921. The general principles behind these measures remain valid today and form the basis for modern stray-current control design. Special note is given to the sixth measure, however. The installation of interconnections, or drainage bonds, between the underground structures and the return circuit, was recognized as acceptable only as a supplemental or temporary measure, since drainage bonds increase the overall amount and magnitude of stray current because of the lower resistance in the parallel resistance paths of the utility and the return rail. Drainage bonds should not be considered as a substitute to the design of return circuits with high, rail-to-earth resistances.

After the 1920s, construction of electrified-transit systems decreased dramatically, and the problem of stray-current corrosion was relegated to a low level. It was not until the 1950s and 1960s, when construction of new, electrified mass transportation systems increased that stray-current corrosion and its control once again became an important issue.

Transit System Design and Stray Current

The basic traction power system for an electrified rail system is quite simple. **FIGURE 3** shows an elevated, electrified rail system with traction power being supplied to the train from a power substation by a power feed, the third rail. Typically, the substation supplies either 650 or 1000 volts of DC voltage and from 1,000 to 8,000 amperes of current, depending on the size of the train and the number of cars. Traction power substations are usually designed to be about one mile apart to prevent large voltage drops along the traction power feeder, which would reduce the traction power to the train. Since a return feeder, or negative return, is needed, the two running rails are usually used to return the current back to the substation. In Figure 3, the negative current follows a path through the running rails and the elevated structure. Such a design originated in several older transit systems, such as the Chicago Transit Authority transit system and the New York City Transportation Authority.

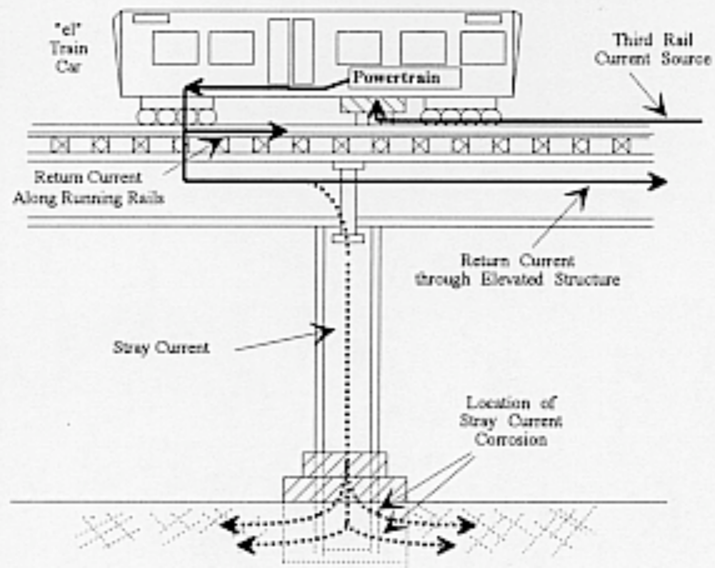


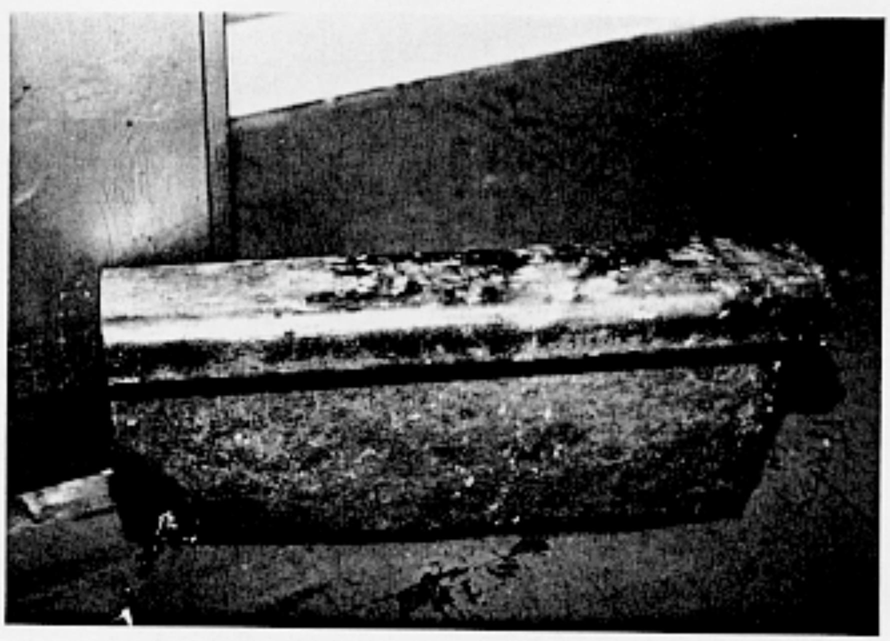
FIGURE 3. Example Path for Stray Current on an Elevated Rapid-Transit System.

An extremely important part of designing a proper traction system is to keep the resistance of the negative current return as low as possible. This is done by providing a metallic, low-resistance path so the current will return to the traction power substation through the intended metallic path. The two running rails are normally used for this purpose. Other designs, such as continuously welding the running rails and crossbonding the two running rails, also decrease the resistance of the negative return path. Unfortunately, other return paths of varying resistance along the transit system exist for the negative current to follow. If these return parallel paths have a sufficiently low resistance, or the equivalent parallel resistance is low, some of the current will return via these alternative paths as well as by the running rails and thereby produce stray currents. Figure 3 shows a low-resistance path that has developed from the running rails and through the elevated structure into the ground. The point where the DC stray current leaks into the ground from the reinforcing steel in the concrete is where stray-current corrosion damage occurs.

The effects of stray-current leakage, or more fundamentally the electrolytic interchange of DC behind cathodic protection, a mitigation method used to control corrosion of metals by reducing the corrosion to negligible levels. On the other hand, DC that flows from a metal to an electrolyte, as shown in Figure 3 by the current flowing from the steel beam to the soil, corrosion occurs at that interface.

The rate at which corrosion occurs depends on the current level and the metal. Generally, one ampere of DC that is flowing from steel to an electrolyte for one year will result in the dissolution of 20 pounds of iron, 75 pounds of lead, 22 pounds of copper, and 6.5 pounds of aluminum. If 5,000 amperes of current flows for one year to power the trains on a transit system, and that 5 percent of this current, or 400 amperes, becomes stray current, the amount of steel metal loss is 5,000 pounds per year. Even if stray currents were reduced to 1 percent of the total current, or 50 amperes for one year, this would still amount to 1,000 pounds of steel metal loss per year. This loss represents the nearly complete consumption of a 100-pound, 39-foot-long steel rail, which weighs about 1,300 pounds.

As a consequence, the effects of stray-current corrosion can be quite dramatic if concentrated in specific areas, such as on the concrete footings of elevated structures, the bottom flanges of rails embedded in the ground, rail tie plates, and rail spikes. **FIGURE 4a** shows the corrosive effect of stray-current on the bottom flange of a rail at grade level on an electrified-transit system. **FIGURE 4b** shows the severe necking from corrosion that occurred on several rail spikes at the point where the spike made contact with the ground. **FIGURE 5** shows a construction site where rehabilitation of a concrete footing on an elevated transit structure is taking place. Part of the deterioration of the footings was attributed to stray-current corrosion.



a. Bottom Rail Flange (Corroded Away).

b. Necking of Rail Spikes.

FIGURE 4. Stray-Current Corrosion Effects on Rails and Rail Spikes ca. 1990.

a. Removal of Concrete Footings.

b. Detail of Stray-Current Corrosion on Footing Anchor Bolts.

FIGURE 5. Rehabilitation on Concrete Footings for an Elevated Electrified Rapid-Transit System.

Stray-Current Control Measures: Present State-of-the-Art

Modern stray-current control follows the same general principles outlined in the NBS report of 1921, but with the advantage of utilizing technological advances that have taken place in areas, such as track bed materials and design, and electronic power circuitry. In general, these control measures can be arranged into two broad categories; (1) modification of the transit system, and (2) modification of neighboring underground structures. Modification of the transit system and neighboring underground structures is accomplished by doing one or more of the following:

1. Decreasing the rail-return circuit resistance
2. Increasing the resistance of the leakage path to earth
3. Increasing the resistance between earth and underground metallic structures
4. Increasing the resistance of the underground metallic structures.

The first two measures are related to modification of the transit system and will be discussed further below. The other two measures are related to modification of the underground structures and will not be discussed, because they are beyond the scope of the project.

Decreasing the Rail-Return Circuit Resistance

Stray-current leakage is a result of the resistance relationship between the rail-to-earth return path and the running-rail return path. A high resistance of the running-rail negative return increases the voltage drop along the rails and, therefore, makes the rail-to-earth return circuit a more favorable path for the return current, thus causing stray-current leakage. The way to decrease the voltage drop through the running rails is to reduce the resistance of the running-rail negative return. Three specific measures used to decrease the resistance of the rail-return circuit are (1) increase the rail size or cross-sectional area, (2) provide adequate rail-to-rail bonding, and (3) decrease the distance between traction power substations. The three measures with methods of implementing them are listed in **TABLE 1.**

TABLE 1. Stray-Current Control Measures.

General Principle	Specific Measure	Other Details
Decrease Resistance of Rail Return Circuit	(a) Increase rail size	Problems with small rails of older systems
	(b) Rail bonding	(1) Continously welded rails (2) Cross-bonding running rails (3) Welded cable bonds on special trackwork (4) Yearly revenue line bond inspection
	(c) Decrease substation distance	Decrease distance to 1 to 2 miles
Increase Resistance of Leakage Path to Earth	(a) Increase rail-to-earth distance	(1) Treated wood ties and well-drained ballast (2) Insulated track fasteners (3) Concrete track ties and clean ballast
	(b) Remove solid-grounding	(1) Remove grounding at substations (2) Use diode grounding
	(c) Storage-yard isolation	Isolate higher revenue line voltages from rail yard
	(d) Revenue line segregation	Isolate revenue line into small sections

Historically, rail size was an issue because electrified-transit systems were often built on existing trolley track used for horse-drawn trolley cars. These running rails were small and did not provide a sufficiently low-resistance return for the current. Today, all transit systems use similar-size running rails ranging from 90 to 120 pounds per yard of rail, which provides a sufficient negative return for the currents needed on modern transit systems. Thus, rail size is not a modern design issue.

The second important measure to decrease the running-rail resistance is to maintain a continuous electrical path for the negative current return. This is accomplished by using continuously welded rails, which is standard practice on newly constructed transit lines, or by using welded cable bonds between discontinuous section of track. The latter method is utilized on older transit systems that have discontinuous track lengths and on special trackwork sections, such as cross-overs and turn-outs. In addition, frequent cross-bonding of the two running rails, every 500 to 1000 feet is good practice, further minimizes resistance, both on continuously welded and welded cable bond running rails. Cross-bonding commonly consists of insulated copper cable that is 100 to 500 MCM (million copper mile). The cross-bonds may also be placed in conduits in locations where they may be exposed to damaging environments, vandalism, or theft.

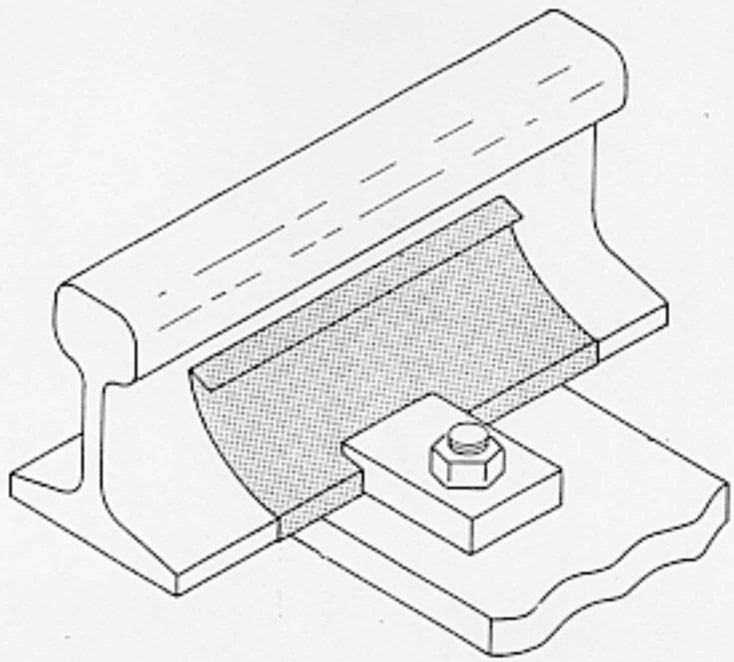
The third measure that can be used to decrease the resistance of the negative return circuit is to decrease the distance between traction power substations. This decreases the length of the positive feeder and the negative return circuit, and thereby reducing the voltage drop and making stray-current paths less favorable. Today, new transit systems are designed with traction power substations spaced one or two miles apart, and most of the older transit systems have upgraded their systems to comply with this design measure, as well. Often, a traction power substation coincides with a passenger station, which can provide added benefit in reducing stray-current, since the current requirements of the trains are the highest there to accelerate the trains, but the running rail return circuit voltage drops are the smallest due to the short length of track.

Increasing the Resistance of the Leakage Path to Earth

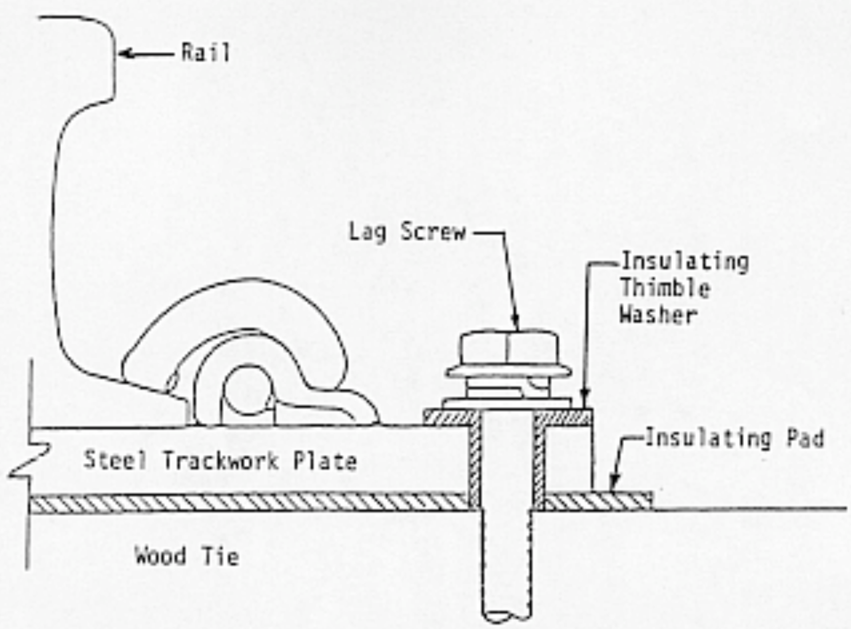
Increasing the leakage-path resistance to earth is a very effective measure in reducing stray-current leakage. By increasing this resistance, the stray-current path is less favorable than the running-rail return path, resulting in less stray current. Table 1 1ists also four specific measures used to increase the leakage-path resistance, which are (1) increasing the rail-to-earth resistance, (2) maintaining an ungrounded or diode-grounded negative return circuit, (3) isolating the yard track and (4) segregating sections of the mainline track.

Advances in the materials used to insulate rails from the earth have made the design of high rail-to-earth resistance easier, resulting in more effective stray-current reduction. Traditionally, rails were installed on wood ties treated with creosote to increase the resistance of the wood and to prevent degradation. The wood ties were installed on stone ballast that was well-drained and, in principle, kept clean by periodic maintenance. Although this design worked well, regular maintenance of the track was often not performed. Stray-current leakage would occur, especially at the rail spikes that were driven into the wood ties and which provided a conductive path to ground for stray current. Problems were also seen on the bottoms of rail flanges at grade level.

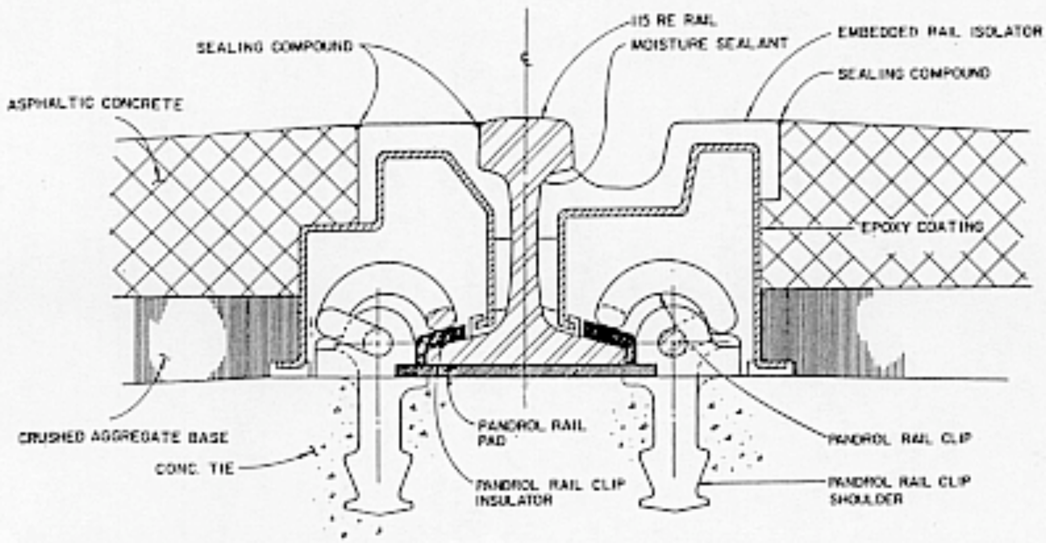
Today, state-of-the-art track design utilizes insulated track fasteners on concrete ties or concrete inverts. Improvements have also been made to the older, wood tie/stone ballast design by adopting insulated track fasteners that are placed on the wooden ties and provide increased resistance to earth. Figures 6a to 6d show four types of fastener designs being used on transit systems. The first design in **FIGURE 6a** uses a polymeric pad placed over the exposed section of the rail in contact with the anchor bolt. The second design in **FIGURE 6b** uses a rubber pad and a polyethylene pad under the rail to provide isolation. Further isolation is achieved by placing the fastener bolts into an epoxy insert in the concrete pad. The third design in **FIGURE 6c** is similar to the second, with a change in the type of fastening for the rail. The clip fastener holds the rail and is designed for easy replacement. The fourth design in **FIGURE 6d** is for an embedded rail at ground level that uses pandrol rail clips on concrete ties, but with insulating pads under the clip and under the rail, with the rail enclosed by an isolator. The insulated fasteners are in the range of 1 million ohms. Although these types of fastener designs have proven successful in reducing stray-current levels, their long-term electrical and mechanical characteristics are not known, especially when subjected to road deicing salts, freeze-thaw conditions, and periodic train movement. Degradation of the insulating fasteners eventually could cause electric shorts and an increase in stray current. However, periodic track maintenance must be performed to ensure against the chance of conductive paths forming from the rail to the ground and circumventing the function of the isolating pads.



a. Simple Polymeric Pad Insulation.



c. Direct Fixation Fastener on a Wood Tie.



d. Embedded Rail Insulation.

FIGURE 6. Four Types of Insulated Rail Fasteners (Continued).

A second recommended practice to increase the resistance of leakage paths to earth is to use an ungrounded, or diode-grounded traction power system. In general, transit power systems can be designed to be either solidly grounded, diode-grounded, or ungrounded. Each type of system has advantages and disadvantages.

Solidly grounded systems were historically used on older transit systems, and used the "tie everything together and let the current flow" philosophy of the late 1800s. (28) Solid-ground systems are not used today on modern transit systems mainly because they cause more problems than they solve. The major characteristics of a solidly grounded system are direct metallic connection of the AC rectifier negative buses to the earthing mats at the substations and the absence of insulation on the running rails. Such a design allows stray current to flow totally unrestricted between the rectifier negative bus and any available underground metallic path.

Consequently, stray-current corrosion occurs frequently on the transit rails, rail fasteners. tunnels. bridges and other transit structures. The only advantage of a solidly grounded system is that the negative return voltage is at the same voltage as the earth ground, which eliminates the hazard of having electric potentials develop between station platforms and the earth ground. Electric potentials can vary from zero to 150 volts and can represent a hazard for passengers.

Ungrounded systems represent the other extreme of traction power system design. An ungrounded system has no direct metallic connection between earth and the rectifier bus at the substations. Rail fastener insulation is also important so that high, rail-to-earth resistances are maintained. In theory, stray currents from an ungrounded system should be low as long as rail shorts are not allowed to develop along the line. Practically, however, because of the thousands of fasteners in parallel on the system, an earth ground does exist. In addition, special trackwork is often difficult to isolate completely, and represents areas where grounding can occur. The one disadvantage of an ungrounded system is that sufficiently high electric potentials can develop between platforms and earth ground. Fortunately, improvements in high speed breakers, overvoltage protection equipment, and platform insulation procedures have considerably reduced the risk of hazardous electric potential being present.

Diode-grounded systems represent a compromise between a solidly grounded and ungrounded system. They are often used to eliminate the problems of stray-current corrosion from a solidly grounded system, but also to keep electric potentials to a safe level. Diode-grounded systems contain a direct metallic connection of the rectifier bus to the earthing mats at substations, but through a diode circuit. The diode circuit allows current to flow from the earthing mat to the negative bus when a certain threshold voltage is reached. The threshold can be as low as 10 volts or as high as 50 volts depending on the conditions at the substation. In this way, electric potentials are dissipated and not allowed to build up to unsafe levels. Diode-grounded systems also follow the recommendations given above, such as maintaining a high, rail-to-earth resistance. Stray-current corrosion can still occur on diode-grounded systems, especially on the rails and rail fasteners where low rail-to-earth resistances are seen. In addition, because of the diode-ground circuit path, the return rails periodically discharge current when a threshold voltage is exceeded. It has been observed that a rail designed for 35 years life on a diode-grounded transit system had to be replace in seven years due to stray-current corrosion and rail cracks. (28)

Two other recommended measures that will increase the leakage path resistance are isolating the track in storage or maintenance yards, and in cases where stray-current activity is concentrated in certain areas, by isolating sections of the main line or revenue track. Isolation of track results in smaller overall track sections which increases the rail-to-earth resistance in these areas. Electrical isolation of storage yard track from the mainline track prevents the higher running rail voltages from being imposed on the storage yard track which are normally at lower voltages. This has the effect of reducing stray currents in storage yard areas. Also, if stray-current activity is isolated onto specific areas of the mainline, installing isolation gaps into the transit system positive and negative supply will isolate this area and make it easier to control. Such a strategy is often used on natural-gas pipelines to isolate areas that are not being protected properly so that effective cathodic protection levels can be applied.

Stray-Current Corrosion Monitoring

Transit agencies utilize stray-current monitoring to determine whether stray-current control measures, such as those discussed in the previous section, are being implemented correctly on their system. Monitoring can be as simple as visually observing the condition of welded cable bonds and crossbonding to ensure that a low-resistance, negative return path is maintained, or as detailed as a stray-current survey performed by an engineering consultant on a specific area of the transit system to determine the level of stray-current activity and the extent of corrosion damage.

Engineering surveys on stray-current activity are generally done to determine the rail-to-earth resistances and the corrosion potential of transit structures, such as station platforms. (28) Rail-to-earth resistances are measured by impressing a low-voltage DC source between the track and ground and measuring the change in potential. The rail-to-earth resistance is calculated from the rail-to-earth potential per ampere of test current. The test procedure allows possible leakage paths to be located on the negative return system. The corrosion potential of transit structures, such as station platforms, retaining walls and subway tunnels are measured to determine whether steel reinforcement or structural steel beams are corroding because of stray current. Structural assessment is then made as to whether repair or rehabilitation is needed. Other measurements made are rail-to-earth voltages, drainage currents, voltages from specific steel structures to the negative bus, and the total current from the traction power substation. These measurements allow assessment of the present stray-current activity and corrosion damage in the area being surveyed.

In general, stray-current control design for a newly constructed transit system is followed by a stray-current monitoring survey in the pre-revenue stage after the system is built to correct any errors in the design or construction of the system. (28) However, stray-current corrosion monitoring is not commonly performed on transit systems on a regular basis, except by visual inspection. Surveys are normally performed only when a recurring corrosion problem is observed at a specific location and they usually indicate that significant damage has already occurred.

Corrosion and Maintenance Costs

The literature provided very limited information associated with the cost of stray-current corrosion. The study by NACE International, Battelle, and the Department of Commerce found that the cost of stray-current corrosion was approximately 5 percent of the $10 billion total cost of corrosion in the United States in 1990, or about $500 million.(l) Most ofthat amount is attributable to electrified transit agencies. The figure of $500 million includes the cost to the transit agency itself (self corrosion), as well as to the neighboring utilities, thus making it impossible to separate the two cost areas. The IIT Research Institute study (l) concluded that stray-current corrosion cost data were lacking at individual agencies, a situation that prevented cost effectiveness to be considered in making stray-current control decisions.

To obtain some idea of the relative cost of stray-current corrosion to transit agencies, information from the American Public Transit Association (24) and Jane's Urban Transport Systems (26) was collected and analyzed. **TABLE 2** gives general information regarding the systems of 26 transit agencies in the United States in 1992-93. **TABLE 3** gives the annualized total operating costs and the non-vehicle costs in 1990 dollars. Included in the non-vehicle costs are the costs of corrosion from stray current. Typically, the non-vehicle costs are approximately 20 percent of the total operating expenses, and average about $195,500 per mile of total track per year. These numbers are the highest estimate for the cost of stray-current corrosion, and more likely the cost is much less. probably less than half of the total non-vehicle cost.

TABLE 2. 1993 Statistics on Electrified Rail Systems

City and Transit Agency	Mode	Age	Total Track, miles	Power Mode	Millions of Passengers Journeys	Millions of Car-Miles	Lines	Stations	Track details
Atlanta **(MARTA)**	Heavy	15	87	700 dc 3rd rail	67	16	2	29	Continously welded on concrete sleepers Elastomer springing under track to reduce vibration
Baltimore **(MD MTA)** **Boston**	Heavy Light Heavy	11 2 NR	95 115 108	700 dc 3rd rail 750dc ovrhd 600 dc 3rd rail/ cat	13 NR 95	NR NR 19	1 1 3	12 24 53	Continous welded rail Rail on ballast, wooden sleepers on steel
(MBTA)	Light	NR	78	600 dc catenary	65	6	1	85	and concrete sleepers with resilient pads New track continous-welded
Buffalo **(NFTA)**	Light	9	14	650 dc ovrhd	7	NR	1	22	Surface tracks in city center, underground elsewhere
Chicago **(CTA)**	Heavy	100	213	600dc 3rd rail	147	55	6	143	Flat-bottomed rail, timber sleepers on ballast, sleepers on concrete with resilient pads; timber sleepers on iron/steel elevated

Cleveland **(RTA)**	Heavy Light	39 74	41 28	600dc ovrhd 600dc ovrhd	9 4	2 1	1 2	18 29	Continously welded rail sleepers on ballast
Detroit (DTC)	Light (planned)	0	15	600 dc	NA	NA	2	NR	NR
Jacksonville (JTA)	People mover	5	6	NR	0.08	0.025	1	3	NR
Lindenwold **(PATCO)**	Heavy	59 25 re-built	38	685dc 3rd rail	11	4	1	14	continuous welded rail; sleepers encased in concrete (tunnerl), timber sleepers on ballast (surface), concrete deck (viaduct)
Los Angeles (LA RTD)	Heavy Light	1 4	NR 58	NR 750dc ovrhd	NR 7.5	NR NR	NR 1	NR 22	NR NR
Miami **(Metro-Dade)**	Heavy People mover	10 8	53 4	700dc 3rd rail NR	14 NR	5 0.4	1 1	21 9	Direct fixation fasteners with resilient pads
Newark (NJ Transit)	Heavy Light	NR 59	68 8	25 & 12 kV ac 600dc ovrhd	40 3.6	20 0.6	6 1	NR 11	NA
New Orleans (RTA)	Tram-way	159	16	600dc ovrhd	8.2	0.55	2	10	
New York **(NYCTA)** **(Metro)** **(Metro-North)**	Heavy Heavy Heavy	106 NR NR	714 29 69 82	625dc 3rd rail 600dc 3rd rail 11 kV ac 600dc	1028 6 NR	326 NR NR	25 1 8	469 22 116	Sleepers on ballast or concrete with resilient pads Rail on timber sleepers in rock and/or cinder ballast

(PATH)	Heavy	86	36	3rd rail 650dc 3rd rail	56	NR	4	13	Conventional sleepers on ballast, some on concrete trackbed with resilient pads
Philadelphia (SEPTA)	Heavy Light Trolley bus Commuter	NR NR NR NR	76 172 43 658	625dc 3rd rail 600dc 600dc 11 kV ac	68 5 10 24	16 5 1.4 12	3 3 5 13	62 60 NA 181	NR NR NR NR
Pittsburg Port **Authority**	Light	NR	62	650dc overhead	10	2	7	13	Std ballast track at grade, ballasted and open deck bridges, direct fixation subway
Portland **Tri-Met**	Light	8	29	750dc overhead	7.4	1.4	1	30	Continuously welded rail on timber sleepers in ballast
Sacramento	Light	7	56	750dc overhead	7	1	1	28	NR
San Diego	Light	13	41	600dc overhead	11	2.4	2	30	NR
San Fransisco **(BART)**	Light Heavy	12 (re-built) 22	24 73	600dc overhead 1 kV dc 3rd rail	40 70	4 34	5 4	NA 34	10 km city-center tunnel w/high platform stations Concrete sleepers on resilient pads
San Jose	Light	7	20	750dc overhead	7	0.54	1	33	Historic 2 km tram shuttle in city center
Seattle	Mono-rail Tram-way	32 NR	2 4	* *	* *	* *	* *	* *	NR NR
Wash, DC (WMATA)	Heavy	18	152	750dc 3rd rail	144	34	4	67	NR

NR= Not reported

TABLE 3. 1990 Total and Nonvehicle Expenses on Electrified Rail Systems

City (Transit) (Agency)	Mode	Total Expense	Total Expense per mile	Non-vehicle Expenses	Non-vehicle Expenses, %	Non-vehicle expenses per mile
Atlanta (MARTA)	Heavy	$58.296.161	$670.071	$15.375.940	26	$176.735
Baltimore (MD MTA)	Heavy Light	$31.047.751 NR	$326.818 NR	$9.540.025 NR	31 NR	$100.421 NR
Boston (MBTA)	Heavy Light	$201.254.447 $20.718.231	$1.863.467 $265.618	$49.530.025 $3.648.562	25 18	$458.613 $46.776
Buffalo (NFTA)	Light	$11.379.270	$812.805	$3.315.389	29	$236.814
Chicago (CTA)	Heavy	$263.542.528	$1.237.289	$57.548.267	22	$270.180
Cleveland (RTA)	Heavy Light	$19.679.624 $11.018.524	$479.991 $393.519	$6.475.559 $3.502.165	33 32	$157.940 $125.077
Detroit (DTC)	Light (planned)	NA	NA	NA	NA	NA
Jacksonville (JTA)	People Mover	$243.131	$40.522	$58.440	27	$9.740
Lindenwold (PATCO)	Heavy	$20.133.051	$529.817	$4.189.996	21	$110.263
Los Angeles (LA RTD)	Heavy Light	NR NR	NR NR	NR NR	NR NR	NR NR
Miami (Metro-Dade)	Heavy People Mover	$38.161.835 $6.327.990	$720.035 $1.581.998	$3.079.990 $558.238	8 9	$58.113 $139.560
Newark (NJ Transit)	Heavy Light	NA $3.666.279	NA $458.285	NA $305.659	NA 8	NA $38.207
New Orleans (RTA)	Tramway	$3.405.553	$212.847	$75.957	2	$4.747

New York (NYCTA) (Metro) (Metro-North) (PATH)	Heavy Heavy Heavy Heavy	$2.426.450.070 * * $119.686.000	$3.486.279 * * $3.324.611	$609.328.300 * * $25.993.000	25 * * 22	$875.472 * * $722.028
Philadelphia (SEPTA)	Heavy Light Trolleybus commuter	$128.186.199 $46.592.213 $9.767.412 $126.031.393	$1.686.661 $270.885 $227.149 $191.537	$22.090.555 $6.098.143 $668.074 $22.422.470	17 13 7 18	$290.665 $35.454 $16.002 $34.077
Pittsburgh Port Authority	Light	$23.503.604	$379.090	$9.143.214	39	$147.471
Portland Tri-Met	Light	$7.996.130	$275.729	$1.204.850	15	$41.547
Sacramento	Light	$8.239.178	$147.128	$1.187.229	14	$21.201
San Diego	Light	$9.159.170	$223.394	$1.190.775	13	$29.043
San Fransisco (BART)	Light Heavy	$59.998.800 $157.818.040	$2.499.950 $839.458	$2.020.961 $35.159.682	3 22	$84.207 $187.020
San Jose	Light	$9.944.204	$497.210	$2.018.658	20	$100.933
Seattle	Monorail tramway	$18.962.857 $579.628	$9.481.429 $144.907	$1.824.617 $177.094	10 31	$912.309 $44.274
Wash, DC (WMATA)	Heavy	$228.783.283	$1.505.153	$59.084.168	26	$388.712

NR=Not reported
NA=Not Applicable
***=Not available**

To provide a more accurate estimate to the cost of stray-current corrosion, a limited number of electrified rail transit agencies were selected to be interviewed. The results of those interviews are discussed further below.

Stray Current Corrosion in Electrified Rail Systems

Transit Operator Interviews

- Transit Operator Inteviews
- Chicago Transit Authority (CTA)
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- Port Authority Trans-Hudson Corporation (PATH)
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- Metro-North MTA
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- New York City Transportation Authority (NYCTA)
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- San Fransisco Bay Area Rapid Transit (BART)
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- Los Angeles County Metropolitan Transportation Authority (MTA)
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs
- West Virginia University-Morgantown Personal Rapid Transit (PRT) System
    - System Information
    - Corrosion Issues
    - Corrosion Costs
    - Present and Future Needs

TRANSIT OPERATOR INTERVIEWS

A total of seven transit agencies were selected for interview with regard to stray-current corrosion control, stray-current corrosion costs, and present and future technical needs to control stray current and the corrosion that it may cause. The agencies were selected to include different ages, geographical regions, and operating modes. TABLE 4 lists the transit agencies and the principal personnel involved in the interviews. The transit agencies included the following: (1) Chicago Transit Authority [CTA], (2) Port Authority Trans-Hudson Corporation [PATH], (3) Metro-North Commuter Railroad Metropolitan Transportation Authority [Metro-North MTA], (4) New York City Transit Authority Metropolitan Transportation Authority [NYCTA], (5) San Francisco Bay Area Rapid Transit District [BART], (6) Los Angeles County Metropolitan Transportation Authority [91;MTA], and (7) West Virginia University-Morgantown Personal Rapid Transit [PRT] System.

Before the interviews, a questionnaire was developed to provide a uniform basis for collecting and assessing the information. The questionnaire was mailed to the principal contact prior to the visit to allow time for collection of the corrosion cost and other information requested. The interviews were usually carried out with two of the researchers present and with time allotted for visit to the transit property to observe stray-current control measures and or areas where stray-current corrosion has taken place.

FIGURE 7 shows the questionnaire sent to the interviewees. The questions center around the general background features of the transit system, corrosion that has occurred on their system and what steps have been taken to mitigate it, the cost of corrosion caused by stray current, and the perceived present and future needs of the agency and the industry as a whole with regard to stray-current corrosion and its control.

FIGURE 7. Questionnaire Used for the Interviews of Transit Operators

QUESTIONNAIRE
STRAY CURRENT CORROSION ON ELECTRIFIED TRANSIT SYSTEMS

The following questions are provided as a starting point for a more detailed discussion and information gathering for a study for the Infrastructure Technology Tnstitute of Northwestem University. That study is assessing the scope of stray current corrosion related to electrified rail transit systems. The questions are divided into four areas: General System Information, Corrosion Issues, Corrosion Costs, and Present and Future Needs.

GENERAL SYSTEM INFORMATION

(1) What type(s) of electrified rail systems are under your authority?
(2) By type, how old is the system?
(3) What is the length of system, by type?

(4) What area is serviced by your system and is a route map available?
(5) What is the physical environment of your service area?
(6) What are the most recent annual total train-miles per system?
(7) What was the most recent annual passenger-miles per system?
(8) What types of power and distribution system are used on each part of your rail system?
(9) What is the operational mode of your system?
(10) What is the average spacing of power stations on your system?
(11) What are the design elements of your system to reduce stray current and corrosion?
(12) What other methods are used to reduce stray current from your system?
(13) What is the typical rail-to-earth resistance of your system?
(14) What is your program for track maintenance?

CORROSION ISSUES

(1) Have you encountered corrosion-related problems on the electrified structure as a result of electrolysis or other factors?
(2) When was the corrosion problem first noticed?
(3) Where was it found?
(4) How was it found?
(5) How extensive was the corrosion problem?
(6) Have you repaired the areas?
(7) How many repairs are typically made per year?
(8) How long have the repairs been on-going?
(9) Have you set up a maintenance strategy for the repairs?
(10) How have you reduced or mitigated the cause of the corrosion problem?
(11) Is the frequency of corrosion-related problems increasing or decreasing?
(12) Is repair or rehabilitation increasing or decreasing?
(13) What is your esti nate ofthe number of corrosion incidents and their repair to be over the next 5 years?
(14) Can corrosion causd by electrolysis be separated from chloride-induced corrosion?
(15) Are historical corrosion and repair data available for your system?

CORROSION COSTS

(1) What are the latest total operating cost of the rail system?
(2) What part of the total operating cost is for non-vehicle maintenance?
(3) What part of the annual total operating costs can be attributed to corrosion or stray current corrosion?
(4) What is the average total cost per corrosion repair?
(5) What are the relative percentages of the average total cost per corrosion repair for labor, material, and other?
(6) What have been the historical repair costs attributable to corrosion or electrolysis corrosion?
(7) What do you estimate the repair costs due to corrosion to be for the next 5 years?

PRESENT AND FUTURE NEEDS

(1) Are technical or other improvements needed to mitigate electrolysis corrosion?
(2) Do you perceive these needs as specific to problems on your system or are they industry-wide?
(3) ln what areas are present needs being addressed and by whom?
(4) What are the future needs to mitigate electrolysis corrosion?
(5) What are the most critical areas of present and future need?

TABLE 4. Transit System Personnel Interviewed

Transit System	Transit System Location	Principal Interview Attendees	Attendee Title
CTA	Chicago, IL	Mr. Rick Straubel	Testing engineer
PATH	Jersey City, NJ	Mr. Albert Chin Mr. Geroge Figueredo	-Staff Structural Engineer -Supervising Track Engineer
Metro-North MTA	New York , NY	Mr. Micheal Savchak Mr. J. Richard Davis	-Deputy Director, Transportation Engineering -Chief Electrical Engineer, Gibbs & Hill
NYCTA	New York, NY	Mr. Micheal P. Sammons	Director, Power Maintenance
Los Angeles County MTA	Los Angeles, CA	Mr. Edmund R. Richardson Mr. Micheal F. Merrick Mr. John French	-Director, Third Party Coordination -Lead Rail Facilities Coordinator -EMC Team, PSG Corrosion Engineering
BART	Oakland, CA	Mr. John S. Burns Mr. Peter L. Todd Mr. Abdulhaque Sharikh	-Group Manager, Design & Construction -Supervising Electrical/Corrosion Engineer -Senior Electrical Engineer
PRT	San Fransisco, CA	Mr. Robert B. Hendershot Mr. Paul D. Harman	Systems Engineering Manager Systems Engineer-Mechanical

Chicago Transit Authority (CTA)

System Information

The Chicago Transit Authority (CTA) heavy rail, rapid-transit system has served the city of Chicago and its surrounding suburbs since its first train was operated in 1893. The system now consists of seven routes totaling approximately 230 miles of track of which 20 miles are subway, 11 miles are at grade (with street crossings), 84 miles are elevated structure, 32 miles are on elevated embankment, 2 miles are below-grade open-cut, and 51 miles are on expressway median. The system is accessed by 140 stations spaced 1 to 3 miles apart. A recent expansion of the system includes a new line linking Midway Airport with the downtown area.

The 600-volt of direct current used to power the system is converted and rectified from 12,600-volt AC. The traction power is ungrounded. Substations are located at about 2-mile intervals, with crossbonds at 200- to 1,000-foot intervals; on newer routes, the rails are welded. Power to the cars is supplied by a third rail with the running rails providing the negative return. A middle rail is used in some areas to reduce the return resistance. Also, the rails are bonded to the elevated structure to further reduce the resistance of the negative return circuit. Another unique feature of the system is that former streetcar rails were abandoned in-place and are bonded to the elevated structure to further reduce the negative return circuit resistance and provide a return circuit for stray current. Diode drainage and reverse current switch drainage are used also to reduce stray current. The running return rails are anchored to wood ties with conventional spikes and tie plates. In areas at or below grade where ballast is used, 3 ohms per 1,000 feet is the best obtained, with 0.1 ohm per 1,000 feet found in some areas.

Corrosion Issues

The CTA has had a regular spike replacement problem in certain areas of its at-grade line that tend to be wet. Although the spikes should last about 25 years, they last about 6 months. Corrosion occurs in the neck area of the spike where it enters the wooden tie. The corrosion problem is noted by sway in the passenger cars in the area.

The most notable corrosion problem has been with the footings of the elevated portion of the system. Approximately 1,300 columns of the bent areas of the support structure have been affected and are part of an active replacement program. The corrosion problem is noted by movement or sway of the bent when a car passes over it. The sway is the result of corrosion that has taken place on the steel base plate and anchor bolts in the footings of the column of the bents. Although the age of the structure is a contributing factor to the corrosion, stray current is believed to be the most significant factor according to CTA. One indicator of this is the almost simultaneous occurrence of the problem with reduced use of abandoned streetcar rails to reduce the resistance of the negative return circuit.

The CTA uses track inspectors to locate corrosion problems and problem areas on the system. There is no automated inspection devices uses to locate corrosion, but accelerometers are used, in addition to ride gauge, to detect motion of the cars and the structures. There is no formal reporting of corrosion-related fixes, and as a result, there is no way to determine if the corrosion problems of the CTA are increasing; they believe the corrosion problems are about constant.

Corrosion Costs

Because there is no formal reporting of corrosion fixes, there is no cost tracking. As a result, no historical costs due to stray-current corrosion or corrosion in general was available. However, there was cost information on the elevated bent column footing reconstruction program, which was attributable to stray-current corrosion. Estimates of $10,000 to $20,000 per column were given for the footing reconstruction with a total cost of $13 to $26 million. Over a 5-year period, the cost is $2.6 to $5.2 million per year for an average of $3.9 million per year. Over the 100-year life of the system, the annual costs due to stray-current corrosion are approximately $200,000. No other corrosion related costs could be determined without a major records inventory.

Present and Future Needs

For the CTA, an automatic station voltage balancing system, as opposed to the manual method now used, and better tie plate insulation are believed to be needed to mitigate stray current. A method to determine the corrosion status of spikes or pandrels in situ was identified as a critical need.

Port Authority Trans-Hudson Corporation (PATH)

System Information

The Port Authority Trans-Hudson Corporation (PATH) heavy-rail, transit system was started in 1908 and is 86 years old. PATH is a subsidiary of The Port Authority of New York and New Jersey, and took over ownership of the system in 1962 from the Hudson and Manhattan Railroad Company. The PATH system of four lines with 13 traction power substations at passenger stations provides commuter service between lower Manhattan and eastern New Jersey urban communities across the Hudson River and links to other heavy rail or suburban commuter rail lines. Daily ridership is approximately 170,000 persons and 56 million annually. PATH has 22.5 miles of underground track and 12.8 miles of at-grade track.

The PATH system is powered by 650 volt DC rectified AC power that is distributed at each of its 13 substations. The traction power is transmitted to the cars by a third rail and returns by the running rails. The system is ungrounded. Most of the running rails are set on conventional wood sleepers with ballast, but some newer parts of the system use a concrete trackbed (tie in pocket), or a grout slab or wood tie over a high-resilience neoprene pad to damp vibration and insulate the track further from earth. Although some welded rail is in the system, most is discrete rail with bonds for electrical continuity. Diode drainage and reverse current switching are used to control stray current. Stray current pickup on the steel shell of the tunnels is monitored and drained.

Corrosion Issues

PATH does not maintain a separate corrosion inspection program. They have a maintenance program whereby there is a biweekly visual inspection of the system track by maintenance workers, who walk the entire system and check for rail gauge and noticeable corrosion or other problems. Ride quality is also monitored, with sway or rocking an indication of back problems that may be related to corroded pandrels or rail. PATH ultrasonically inspects the rails for damage (e.g., rail cracks and fissures) twice a year with a system developed by United Technologies-Sperry. The method is believed to be able to identify corrosion (loss of section) of the rails. In the past, PATH did have a program of cleaning rail insulators by hand, but now only does this in the tunnels and when considered necessary elsewhere.

PATH believes that corrosion is not a big problem on their system, but that it can impact efficiency of operation. They have found the their worst stray current and corrosion problems are in tunnels when they are wet, such as in the spring. Because of the coastal location, the water in the tunnels will contain some salt in it. As a result, insulators on rail fasteners and rail are corroded and have to be replaced often. Although PATH monitors and drains stray current from the tunnel steel shells, there are no guidelines for what is an acceptable level of stray current and they believe that the stray-current corrosion problems have not been mitigated, but probably are growing. PATH believes that upper management is probably not aware of the corrosion problems, perhaps in part because rail replacement and the like are viewed as maintenance.

Some concern was expressed for stray current influencing corrosion of steel reinforcing bars in concrete structures, such as the World Trade Center where PATH maintains a station. The basis for the concern stems from corrosion seen on some steel components of station fixtures (e.g., station door frames, outside containing walls, and platform roofs and floors). The problem could not be quantified.

Corrosion Costs

PATH could not provide detailed costs associated with their corrosion repairs because they do not track such costs. They did, however, provide a rough estimate of the cost of rail replacement. Approximately 300 tons of 100-pound rail is purchased each year. Of this amount, about one third is for replacement of corroded rail. At $730 per ton of rail, and labor at half of the material cost, rail replacement due to stray-current corrosion is estimated at $110,000 per year. Repairs such as these have been on-going since 1962 for a total approximate cost of $3.7 million. No other corrosion-related costs were provided.

Present and Future Needs

The most critical present and future needs identified by PATH were (1) a guideline for acceptable levels of stray current, and (2) a long-term maintenance program to ensure good negative returns for the power. The so-called Toronto system of rail fasteners with concrete tie-in-pocket rail beds used by PATH is believed to be an expensive, but effective, system for increasing the rail-to-earth resistance and mitigating stray current and its effects. At PATH, like many other of the transit systems visited, the primary concerns are not corrosion, but to "keep the trains running" and "keep the system together."

Metro-North MTA

System Information

Metro-North Commuter Railroad was created in 1983 by the absorption of the passenger service formerly provided by Conrail on the Hudson and Harlem lines of the former New York Central Railroad, and by the former New Haven Railroad lines from Grand Central (New York), which are operated jointly by the MTA and the Connecticut DOT. The age of the Metro-North heavy-rail transit system is not reported, but consists now of eight lines covering 151 miles of electrified rail that provide commuter rail service to suburban commuters of New York City. In 1990, over 100,000 weekday commuters used the system, and 56 million annually.

The Metro-North electrified transit system is powered by two different types of traction power system: 69 miles of the system are powered by a 11,000 volt AC, and 82 miles are powered by a 600 volt DC traction applied to a positive third rail, with the running rails acting as the negative return circuit. Conventional wooden ties and spike fastening of the rails to the ties are common. Diode and reverse current switches at substations are used to control stray current.

Maintenance on the system prior to Metro-North acquisition was reported to have been badly neglected. Metro-North is now in a massive rehabilitation program to restore ridership and electrification, conductor, and passenger station facilities on the system.

Corrosion Issues

Metro-North does not have the ability to identify specific stray-current corrosion problems on their system primarily because of management philosophy and records-keeping practices. No records are kept that will allow them to determine where the problems are and what they are; they are simply trying to "keep the trains running and on time" as their main focus. That is not to say that corrosion problems do not exist on the system. No track maintenance program to keep the track ballast or rail fasteners clean (to increase the rail-to-earth resistance) or to identify corrosion problems were identified.

Corrosion Costs

No costs due to stray-current corrosion were available from Metro-North simply because they have no records to allow such an evaluation to be made. Track and fastener replacement does occur, but no cost could be assigned to it, nor could the portion due to stray-current corrosion be determined.

Present and Future Needs

No present or future needs could be identified by Metro-North.

New York City Transportation Authority (NYCTA)

System Information

The New York City Transit Authority (NYCTA) heavy rail transit system dates back to 1832 when the first horse-drawn street railway was started. However, the first electric trolley-car line started in 1887, with the first electric-powered elevated train beginning operation in 1901. In 1994, the NYCTA subway system consists of 815 miles of back on 25 routes throughout the four boroughs of New York City. Of the 815 miles of track, 70 miles are elevated, 23 miles are at-grade, and the rest is underground. Each weekday, an average of 3.5 million passengers use 469 stations to reach their destinations. Annually, over 1 billion passengers travel on the system.

The NYCTA vehicles are powered by 650 volts DC from 215 substations that are 0.5 to 0.75 miles apart. The traction power system is isolated with a floating negative return running rails. Stray current control is provided by diode drains and bonding of all tracks in the right-of-way, with cross-bonding every 800 to 1000 feet. While most of the running rails are secured by conventional spikes to wood ties on ballast or concrete, NYCTA has an ongoing program to use insulated clip-type fasteners to secure the rails to the ties, and to replace sections of rail with a welded rail. The rail-to-earth resistance of the track is approximately 1 ohm per 1,000 feet at worst, and approximately 1,000 ohms per 1,000 feet at best. The environment under the rails and ballast varies from bedrock (Manhattan) to heavy clay (Brooklyn). Tunnels that traverse the Hudson River, have steel shells that have stray-current drainage and cathodic protection applied to the outer surface for corrosion control.

NYCTA has several upgrade and maintenance programs on-going. Besides a program to upgrade the running rails (welded rails and new clip-type fasteners), they are upgrading the traction power insulators too. NYCTA also has a daily track walker to inspect the rails for broken, cut, or vandalized bonds between rails and tracks. They once used a washing train to clean the rail ballast to maintain a high rail-to-earth resistance, but it reportedly created more problems than it solved by the residual wash water providing a reduced rail-to-earth resistance. NYCTA, however, is purchasing a vacuum train to clear rail and ballast as an alternative to the wash train. Annually, NYCTA inspects all track with the track inspection "Geometry Train" and will use a new Swedish system to profile tunnels to determine changes or damage over time. NYCTA also maintains an Electrolysis Task Force to provide a central body of information and advice on stray-current control among its own departments and outside utilities.

NYCTA undertook a massive $12.4 billion capital rebuilding program between 1980 and 1990, and is now in a modernization program that will spend $7.9 billion over the five years between 1992 and 1996.~26' In the first 10-year program (1980-1990), priorities were placed on fleet, track power, shop, and yard improvements and expansion. The 5-year program (1992-1996) will focus on station, signals, and other infrastructure upgrading, including automatic fare collection systems.

Corrosion Issues

Relatively few corrosion problems due to stray current could be identified. Among the corrosion issues identified were corrosion of rail spikes and bonds at expansion joints of the elevated structure. Like the CTA in Chicago, the NYCTA elevated structure is part of the negative return circuit, and there is reason to believe that the loss of the expansion joint bonds could lead to corrosion of the steel components of the elevated structure footings. Corrosion of rail spikes is attributed to corruption of the ballast with soil and water wash, which lowers the rail-to-earth resistance, thereby allowing current from the return rails to discharge to the spike and then earth, corroding the spike. No other major corrosion problems were identified. Because of the major modernization program at NYCTA, any database of information that did exist regarding corrosion problems is becoming irrelevant because of changes taking place in the rail upgrades.

Corrosion Costs

No stray-current corrosion costs could be identified. Identification of corrosion problems and corrective action may be carried out in different divisions or departments, making cost detail very difficult to follow without a formal interdepartmental reporting process. NYCTA maintains an Electrolysis Task Force to unify the various departments and divisions in stray-current control, but there is no formal cost reporting to build a database and activities reporting may be limited in scope and detail.

Present and Future Needs

NYCTA indicated that one of the present and future needs was to develop a standards manual that could be used as a guideline for quantitative stray-current control. Another need for the future was to develop a "Stray-Current Train" to do audits on stray current by profiling current (by voltage drop) in the return rails and determining where current is lost.

San Francisco Bay Area Rapid Transit District (BART)

System Information

The BART heavy-rail transit system started operation in 1972. The system serves three counties in the San Francisco Bay area with its four lines, 34 passenger stations, and 73 miles of track. There are plans to extend the system another 30 miles with double track and 10 new passenger stations. In 1994, approximately one third of the system is at grade, one third is elevated, and one third is underground, 3.5 miles of which is the transbay tunnel. Approximately 250,000 passengers use the BART each weekday, and 70 million annually.

The BART transit system is traction powered by a positive third rail at 1,000 volts DC and uses the running rails as the negative return circuit. Traction power is supplied from 41 substations, about 2 to 3 miles apart, that are usually located at passenger stations where the power draw is the highest from accelerating trains. BART uses regenerative breaking to feed back power to auxiliary loads on the slowing train and to nearby trains that are not braking; about 20 percent of the kinetic energy of the braking train is recovered in this way. The third or power rail is a steel and aluminum composite rail mounted on ceramic insulators at 10-foot intervals. The continuously welded, cross-bonded, negative-return rails are mounted on rail fasteners spaced 30 inches longitudinally on concrete slabs on the elevated sections of the system and in tunnels. At grade, the rails are supported on steel reinforced concrete ties spaced 24 inches on rock ballast. The rail fasteners are a steel/elastomer composite that has a lower resistance to earth than the positive ceramic insulators. The ballast and fasteners gives a rail-to-earth resistance of 16 ohms per 1,000 feet of rail at best, and about 1 ohm per 1,000 feet at worst. Because of the coastal area served by the BART system, the ground water environment may be salt water (transbay tube), brackish, or fresh-like. Earthquakes are prevalent also.

The BART system controls stray current by its focus on rail insulation, substation grounding, and service yard isolation. A BART-developed rail fastener elastomer pad placed between the rail fastener and rail provides the needed electrical insulation and reduces water and dirt accumulation; see Figure 6a. BART also uses diode blocking arrays and a shorting switch they developed to allow stray-current pickup at the substation ground, block negative return currents from flowing to earth, and allowing for fault current of the substation, and acceptable rail-to-earth-to structure voltages for passenger safety. On the new extension of the BART system, thyristor based negative-grounding devices are being used at traction substations to provide conduction to return current. Stray current return to the substation should be limited to that occurring during the traction power faults and excessive negative return voltage events, thereby reducing stray current from the present levels. Stray current problems associated with the vehicle service yards are related to the grounding requirements of the service shops. BART is improving the isolation between the shops, Yards. and revenue lines.

BART also uses the United Technologies-Sperry track inspection system to locate cracks, fissures, and damage to rails. Ballast cleaning is an issue to be taken up in the future. The subaqueous transbay tube between Oakland and San Francisco is a vital link in the BART system. It is a twin-bore concrete and steel structure buried in a trench 75 to 135 feet below San Francisco Bay. The tube has a cathodic protection system utilizing impressed-current anodes to prevent corrosion of the steel skin of the tube from saltwater corrosion. The anodes are placed approximately 250 feet apart on both sides of the tube. Permanently mounted reference electrodes are used to monitor the steel potential. Because of the criticality of the tube, visual inspection of the steel structure is carried out periodically.

Corrosion Issues

BART visually found corrosion on the rail bottoms in wet areas, such as tunnel approaches, and on the steel encasement shells in tunnels. Some concrete spelling from rebar corrosion has been noted also. BART is now carrying out an inspection of the transbay tube exterior surface, and its condition is not presently know with regard to corrosion. Corrosion from stray current is expected to increase as the system gets older and mitigation may depend upon federal funding levels.

Corrosion Costs

BART provided the following estimates for yearly costs for 1993 directly attributable to stray current corrosion:

• Rail and track fastener replacement	Up to $10K
• Service yard piping	$1K
• Subway walls and inverts	$1K
	Up to $12K

Costs for projects to improve stray-current corrosion control include:

• Diode replacement with thyristors	$1.7M
• Service yard isolation from main line	$2.8M
• Transbay tube corrosion control	$2.6M
• Rail insulation development and application	$0.3M
	$7.4M

The apparent direct annual costs are about 0.18 percent of the costs to improve the system ($7.4M), and only about 0.04 percent of the $35,159,682 in 1990 non-vehicle costs.

Present and Future Needs

Improvements in the rail-to-resistance of rail fasteners are needed industry wide according to BART. Thyristor grounding systems may also improve the present situation with stray-current control. BART is also looking into the future use of satellite monitoring of train movement for power saving, which could impact stray current.

Los Angeles County Metropolitan Transportation Authority (MTA)

System Information

Light and heavy rail rapid transit systems in the Los Angeles area are relatively new. Some portions of the system are built, while others are under construction or planned. The MTA was created in 1993 by merger of the Southern California Rapid Transit District (RTD) and the Los Angeles County Transportation Commission. The MTA presently operates 21 miles of light rail (Blue Line) and 4 miles of heavy rail (Red Line), in addition to being responsible for constructing and planning the present and future transport needs of the greater Los Angeles region. The light rail system is 3 years old and the heavy rail system is 1 year old; both the light and heavy rail systems have only one line at the present time. The light rail system serves the Los Angeles to Long Beach area and the heavy rail system serves the Los Angeles business area, with extensions planned for both modes. The light rail system has 22 passenger stations and the heavy rail system has 5 passenger stations. Both lines area at grade, except for a short subway section in downtown Los Angeles. Approximately 11.8 million passengers used the light rail system in 1993 and approximately 2 million the heavy rail system.

The light rail system is powered by a 750 volt DC positive overhead catenary wire with the running rails the negative return circuit. The heavy rail transit system is powered by a 750 volt DC positive third rail, also with the running rails providing the negative return. Traction power and passenger stations are usually collocated and at approximately 2-mile intervals on the light rail system and at 0.5- to 2-mile intervals on the heavy rail system. The traction power circuit is ungrounded. Stray current is controlled by using continuously welded rails with cross bonds and concrete ties on rock ballast with insulated rail fasteners. Various types of rail fixation are used, including direct fixation and embedded track; see Figures 6b and 6d. All of the designs for the revenue line use a pandrol clip fastener with insulator or insulating pad. The design rail-to-earth resistance is 500 ohms per 1,000 feet of rail, but some dry areas are much higher than this, while some areas are lower. The shop yards are reasonably well isolated electrically from the revenue lines, but use conventional wood ties with spike rail fasteners. No rail maintenance programs are presently in place because the systems are too new. However, some stray-current testing is carried out, but problems are usually fixed as soon as encountered due to the infrequency of problems requiring immediate attention.

Corrosion Issues

There are no stray-current corrosion problems reportedly on the heavy rail (Red Line). A possible stray-current problem on the light rail (Blue Line) may be occurring from surge currents seen on some neighboring utility structures, however, the problem is under study. No stray-current corrosion problems are anticipated for the near future.

Corrosion Costs

No costs due to corrosion from stray current are known, but an estimated $10,000 cost has been attributed to monitoring of a possible stray current trouble spot at one location on the system.

Present and Future Needs

For the MTA system, a track cleaning program is under consideration for development in the future. MTA believes that "getting rail operations to perform a regular testing and inspection program" is needed in the future to keep the entire system within the design specifications, which they believe is the key to successful control of stray-current corrosion.

West Virginia University-Morgantown Personal Rapid Transit (PRT) System

System Information

The PRT system is an automated guideway transit system which provides personal rapid transit between the two separated campuses of the University of West Virginia and the business district in Morgantown, West Virginia. The system was completed in three phases over the period from 1971 to 1979. The system consists of fleet of 73 AC electrically powered, rubber-tired, passenger vehicles that operate on 8.8 miles of dedicated guideway network either on demand or on a schedule year around, except for about 1 week each trimester when scheduled preventive maintenance is carried out. Approximately 54 percent of the guideway network is elevated and remaining 46 percent is at grade, with about 400 feet in tunnel. There are 5 passenger stations that serve about 2.25 million passengers annually.

The PRT system receives 23 kV, three-phase, AC at its main power substation and distributes it underground or in the elevated guideway substructure to each of the three propulsion substations located along the guideway and to housekeeping substations located at each passenger and maintenance station facility. The propulsion substation converts the 23 kV AC input power to 575 V AC, three-phase, delta power for distribution to the guideway power rails. The housekeeping power substations supply 480/270 V AC for heating, lighting, air conditioning, displays, and uninterruptable power supplies.

Power rails anchored to and running along the guideway distribute the 575 kV AC to the vehicles. Remotely controlled circuit breakers operate the connection of the guideway power rails to the vehicle propulsion system. The power rails, hung from glass-fitted polyester fasteners on the guideway, are aluminum conductor bars with a smooth stainless steel surface and sheltered by a polyvinylchloride (PVC) cover running along both sides of the guideway wayside, except for where the sintered carbon/copper power pickup brushes of the vehicle make contact. The 575 kV is reduced onboard to 355, 120, and 61 V AC, and 26 V DC for propulsion and facilities. The propulsion system is a 70 hp, DC motor, which operates at 2730 rpm with 420 V AC on the armature and 25 V DC (400 A max) on the shunt field.

Operating year around, the PRT is equipped to thermally heat the vehicle guideway running pads, power rails, and propulsion power pickup brushes. The guideway vehicle running pads are heated and maintained in a dry condition by an ethylene glycol and water solution circulating in piping embedded in the guideway base. Resistance wires heat the power rails and power pickup brushes in winter months to keep snow and ice from inhibiting electrical contacts.

The PRT system is shut down three times each year (May, September, and December) for preventive maintenance. During that time, the system guideways are walked for visual inspection purposes, and maintenance is carried on the vehicles, guideway, and control system.

The PRT system has no intentional design considerations for stray current mitigation, since the system is operated with AC, and AC is expected to only produce about 1 to 5 percent of the corrosion produced by an equivalent amount of DC. (31,32)

Corrosion Issues

There are no apparent corrosion problems on the PRT system that can be attributed to stray current. A number of corrosion-related leaks have occurred on the guideway vehicle heating piping, but the cause does not appear to be related to stray current, AC or DC.

Corrosion Costs

No corrosion costs were identifiable.

Present and Future Needs

There were no identifiable present or future needs for this type of rapid transit system cited.

Stray Current Corrosion in Electrified Rail Systems

Discussion

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DISCUSSION

The technology to control stray-current corrosion on rapid-transit systems is sufficiently mature to be effective. Most of the methods identified in the National Bureau of Standards studies in the early 1920s are used today to design and mitigate stray current on rapid-transit systems. Some improvements in electronic switching and rail-fastener design and insulation have been made over the years, but the basic methods developed over 70 years ago are still implemented today. In some of the older systems, however, lack of maintenance and funds have stood in the way of the availability and implementation of these newer methods and materials. The latest developments in rail fastener and insulation and stray-current drainage can be seen in the newer rapid-transit systems, such as the Los Angeles County MTA, and in upgraded sections of older systems, such as on the NYCTA and BART systems. In all cases, however, the rapid-transit systems are complex and stray-current control methods used may differ in detail and effectiveness depending upon the age and maintenance of the line.

Designing for stray-current control is a usual practice for all DC traction-power systems; AC traction-power systems normally do not have the need for such designs. However, maintaining those design parameters is often more difficult. Once the system is designed, the major parameters to affect stray-current control are primarily the rail-to-earth resistance and the running rail return resistance. As a result, all of the agencies have a track maintenance department, a part of whose function it is to locate and replace corroded items. None of the agencies interviewed had a formal corrosion department, although most had at least one person who was very familiar with electrolysis or stray-current corrosion and its control, among other duties. Part of the reason for the low profile of the corrosion specialist is the prevalent notion that stray-current corrosion is not a major problem. Moreover, the problems are fixable, and have sufficient reoccurrence to be viewed as a part of maintenance. In this regard, all of the agencies interviewed typically take a reactive view to corrosion, finding it by track-maintenance walkers, by sway of the rail cars, or, in the case of the CTA, by movement of the elevated structural bents.

Stray-current corrosion on electrified rapid-transit systems is usually associated with thinning of the base rail cross-section, the fastener (clip or spike), steel reinforcement shell of tunnels, and, in some cases, steel components of the footings in the elevated sections of some systems. Corrosion is typically found in areas that are wet, such as at tunnel approaches, where groundwater may bridge the rail insulators and reduce the rail-to-earth resistance.

To what extent the view that corrosion from stray current is not a major problem on rapid-transit systems is not clear from the information developed as a result of the interviews. None of the agencies interviewed had a formal tracking system for such costs, and most indicated that the collection of such data would take a significant effort, in part because actual remediation of stray-current corrosion could be carried out in different departments or divisions of the often large operational agencies. Very limited cost information was able to be developed, and that was for the BART, CTA, and PATH systems. The annual BART system stray-current corrosion costs were reported to be approximately \$12,000; those for the CTA were approximately \$200,000 for the footing-replacement project annualized over the life of the system (100 years); and approximately \$110,000 for the PATH system. While these data offer little opportunity to draw clear conclusions and projections regarding the cost of self-corrosion to rapid-transit agencies, they lead to the notion that the costs may, in deed, be relatively low, amounting to less than 0.5

percent of the respective total non-vehicle costs. The low cost lead further to the conclusion that a very significant portion of the $500 million costs attributable to stray-current corrosion annually in the United States is associated not with the 50 or so electrified rapid-transit agencies, but with the multitude of neighboring infrastructures.

Even though self-corrosion costs may be low, the overall cost of $500 million is not. This latter cost is about half of the $956 million in total non-vehicle costs for all of the rapid-transit agencies listed in TABLE 3. Therefore, remediation of stray current will not likely have as significant an impact on the cost to the rapid-transit agencies as it will have on the neighboring infrastructure. Toward developing ideas for each agency or industry to better control stray-current corrosion, the interviews identified the following needs:

- Stray-current measurement methodology
- Guidelines for acceptable stray-current control
- In situ spike and pandrol corrosion inspection method
- Better rail insulation
- Long-term rail monitoring program.

Other needs or areas of investigation now under consideration by some rapid-transit agencies included satellite monitoring of train movements to reduce power consumption and stray current, and automatic traction-station power balancing to reduce voltage drops in the rails and consequent stray current. If the first item in the list above could be developed, then it may be possible to influence the other items in the list or provide a means of assessing the effectiveness of methods to address those items.

One approach to satisfy the need for a stray-current measurement methodology is to develop a rail car with appropriate equipment on-board, much like the car that is used now to inspect rails for physical damage. The idea for such a stray-current car came about from discussions with the NYCTA during the interviews. The on-board equipment should be able to develop a profile of the current along the rail, from which attenuation characteristics could be used to assess areas of current leakage and to determine attenuation or leakage changes over time that may signal the need for trackwork. Depending upon the technology used and other factors involving the electrical environment, the car also may be able to determine areas of more local current discharge, such as at rail spikes or fasteners. Alternatively, a separate hand-held device could be developed using ultrasonic or electromagnetic ultrasonic testing technology that would allow track maintenance walkers to inspect spikes or pandrols for loss of cross-section from corrosion. The development of a stray-current measurement car, coupled with a strong inspection and maintenance program, directly or indirectly address essentially all of the needs indicated above by providing a quantitative means of assessing stray current flowing from the rail or to ground from rail fasteners, and the effectiveness of track maintenance programs. This would allow the agencies to dedicate its resources to those areas where they are most needed and cost effective.

In this way, stray-current corrosion and its cost could be reduced on a transit agency's own properties and that of its neighbors.

CONCLUSIONS

The following conclusions have been drawn from information in the literature and from the discussions and interviews with a sample of rapid-transit agencies presented above:

• Stray-current corrosion or electrolysis caused by electrified rapid-transit systems has been recognized since the first systems were operated in 1893
• Design considerations developed in the 1920s to mitigate stray-current corrosion are still used today by all rapid-transit agencies with DC powered traction systems
• More recent improvements in insulating materials, rail tie and fastener design and insulation, and stray-current switching have been implemented by new rapid-transit systems, but are slow to reach some older systems without major upgrading programs
• Stray-current corrosion of the running rails, rail fasteners, steel tunnel shells near approaches to tunnels, and on some elevated structure footings is common
• Corrosion is usually found through regular maintenance programs that involve visual inspection of transit rails, fasteners, ties, and tunnels, and by changes in car ride quality
• The cost of stray-current corrosion on rapid-transit operator properties is not tracked, thus making it difficult to quantify
• Based upon very limited data, the cost of stray-current corrosion on rapid-transit operator properties appears to be small, amounting to between $10,000 and $200,000 each year, which is less than 0.5 percent of the annual total non-vehicle costs
• The more significant portion of the annual cost of stray-current corrosion in the United States ($500 million) appears to be borne by the neighboring infrastructure that becomes part of the stray-current path
• The development of (1) a stray-current measurement methodology, (2) guidelines for acceptable stray-current control, (3) an in situ spike and pandrol corrosion inspection method, (4) better rail insulation, and (5) a long-term rail monitoring program may help to reduce stray current and its corrosion effects.

RECOMMENDATIONS

This study has provided an overview of the technical literature regarding the methodologies for control of stray current and the corrosion it can cause on electrified rapid-transit systems. Some of the features of a selected number of rapid-transit agencies have been summarized along with the areas where they have experienced corrosion. However, the study was not able to produce much information on the cost of that corrosion because of the lack of formal reporting and tracking of such costs within the agencies. The data that were generated indicated that the cost to the agencies was probably small, but that most of the industry-wide annual cost ($500 million) attributable to stray-current corrosion was borne by the neighboring infrastructure. The study for NCTRP also found that such corrosion cost data were difficult to obtain, but went on to say that "A cost-effective approach to deal with the effects of stray currents cannot be determined until sufficient economic data are developed on corrosion costs." (1) It is very unlikely that such an effort to develop that data will be forthcoming in the near future. However, it is possible that inroads can be made to reduce stray current and its effects on both the rapid-transit agency properties and the neighboring infrastructure by directing some efforts toward the needs identified by the agencies interviewed.

The five areas of need were the following: the development of (1) a stray-current measurement methodology, (2) guidelines for acceptable stray-current control, (3) an in situ spike and pandrol corrosion inspection method, (4) better rail insulation, and (5) a long-term rail monitoring program. As was mentioned above, the development of a stray-current measurement car and an in situ method to monitor spike or pandrol corrosion could satisfy essentially all of the needs identified when combined with an active inspection and maintenance program. Accordingly, those development are believed to be achievable and are recommended for further consideration.

The development of the stray-current car could begin with discussions with experts in the field, such as Parsons Brinkerhoff, Quade & Douglas, Grumman Corporation, and United Technologies. Those discussions should identify feasibility of the idea, impediments to its development, and applicable technologies. If a concept can be proffered, industry should be contacted for interest and feedback. The development and commercialization of the concept, which could take 3 to 4 years to complete, should proceed with funding from industry and federal agencies because of the breadth of the parties that could benefit from its development.

The separate spike and pandrol inspection method could be developed within the Infrastructure Technology Institute framework. Applicable inspection technologies probably already exist within Northwestern University and BIRL, but those technologies need to be explored in more detail. The device to be developed should be portable and usable by the maintenance walkers that inspect the track and its right-of-way. Such a device could possibly be developed and commercialized in 2 to 3 years.

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