PB99-102451

REPORT FHWA/NY/RR-90/149

Case Studies of Two Non-Overlay Cathodic Protection Systems For Bridge Decks

ORLANDO E. PICOZZI
ALLEN C. FRANK

RESEARCH REPORT 149

ENGINEERING RESEARCH AND DEVELOPMENT BUREAU
NEW YORK STATE DEPARTMENT OF TRANSPORTATION
Mario M. Cuomo, Governor/Franklin E. White, Commissioner

REPRODUCED BY: NTIS
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

STATE OF NEW YORK

Mario M. Cuomo, Governor

DEPARTMENT OF TRANSPORTATION

Franklin E. White, Commissioner
Paul W. Taylor, Executive Deputy Commissioner
Michael J. Cuddy, Assistant Commissioner for Engineering and Chief Engineer
James J. Murphy, Deputy Chief Engineer, Technical Services Division
Robert J. Perry, Director of Engineering Research and Development

The Engineering Research and Development Bureau conducts and manages the engineering research program of the New York State Department of Transportation. The Federal Highway Administration provides financial and technical assistance for these research activities, including review and approval of publications.

Contents of research publications are reviewed by the Bureau's Director, Assistant Director, and the appropriate section head. However, these publications primarily reflect the views of their authors, who are responsible for correct use of brand names and for the accuracy, analysis, and inferences drawn from the data.

ENGINEERING RESEARCH PUBLICATIONS

A. D. Emerich and A. H. Benning, Editors
Donna L. Noonan, Graphics and Production
Jayneene A. Harden and Brenda L. Rager, Copy Preparation

CASE STUDIES OF TWO NON-OVERLAY
CATHODIC PROTECTION SYSTEMS FOR BRIDGE DECKS

Orlando E. Picozzi, PE, Civil Engineer II (Materials)
Allen C. Frank, Civil Engineer I (Materials)
Materials Bureau

Final Report on Research Project 181-1
Conducted in Cooperation With
The U.S. Department of Transportation
Federal Highway Administration

Research Report 149
March 1990

ENGINEERING RESEARCH AND DEVELOPMENT BUREAU
New York State Department of Transportation
State Campus, Albany, New York 12232

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
FHWA/NY/RR-90/149

PB99-102451

3. Recipient's Catalog No.

4. Title and Subtitle
CASE STUDIES OF TWO NON-OVERLAY CATHODIC PROTECTION SYSTEMS FOR BRIDGE DECKS

5. Report Date
March 1990

6. Performing Organization Code

7. Author(s)
Orlando E. Picozzi and Allen C. Frank

8. Performing Organization Report No.
Research Report 149

9. Performing Organization Name and Address
Engineering Research and Development Bureau
New York State Department of Transportation
State Campus, Albany, New York 12232

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Offices of Research, Development, and Technology HRD-10
Federal Highway Administration
U.S. Department of Transportation
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
Research Project 181-1

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Study Title:Cathodic Protection for a Reinforced Concrete Bridge Deck.

16. Abstract
Impressed-current cathodic protection systems were installed on two steel-reinforced concrete bridge decks. Primary anodes for both were composites of platinum-niobium wire and conductive polymer grout, bonded into sawed slots in the concrete surface. Secondary anodes were conductive carbon strands and conductive polymer grout bonded into sawed slots. The first installation experienced frequent power-supply malfunctions and significant grout loss. The power supply was replaced, and after 1½ years of service, 10 percent of the anode matrix was repaired. Surface distress, including concrete delamination and additional grout loss, continued through 3½ years of service. It was then decided to terminate the system, and repair the deck with a conventional high-density concrete overlay. The second installation was four times larger in surface area, and was bid using individual construction items rather than the lump-sum bidding used for the first bridge. Unit cost in this instance was $7.08 per sq ft -- a savings of $2.83 per sq ft. After 2 years, some anode-grout distress and concrete delamination have been experienced, but on a smaller scale. The mechanism of anode-grout distress is examined and differences in construction practices are discussed.

17. Key Words
cathodic protection, bridge decks, corrosion, concrete reinforcement, chlorides, corrosion prevention

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	v + 44	

Form DOT F 1700.7 (8-69)

Preceding page blank

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

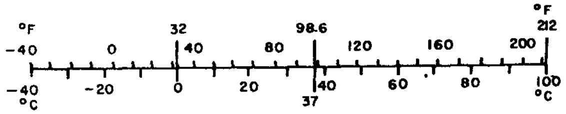
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

---

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

I. INTRODUCTION

Premature deterioration of bridge decks is a major problem facing highway agencies. Its most troublesome form is concrete spalling, resulting from corrosion of steel reinforcement in the presence of chlorides derived from deicing chemicals that have permeated the deck surface. Corrosion products formed on the steel occupy significantly more space than the original metal, and create stress within the concrete that results in bar-level cracks and delaminations. Vibration from passing vehicles and pressure from ice formation in the fractures cause concrete to become dislodged and spall from the deck surface, forming the common pothole. The rate of chloride accumulation at the rebar level and subsequent damage are significantly increased by shallow concrete cover. Also, in severe cases of corrosion damage, loss of steel section can reduce tensile capacity, causing structural problems.

One method of preventing or arresting corrosion of steel reinforcement is to install a cathodic protection (CP) system. Such a system draws on proved technology long used in other industries to protect buried steel, such as natural-gas pipelines. CP systems are simple both in concept and practice, and relatively inexpensive compared to the eventual cost of restoring a bridge deck severely damaged by corrosion.

The New York State Department of Transportation's first CP bridge deck installation -- a slotted anode matrix system using a constant reference potential power source -- was completed in the winter of 1983 on the I 81 northbound bridge over old Rte 26 at Whitney Point in Broome County. This experimental system was built under FHWA Demonstration Project 34 (titled "Cathodic Protection for Reinforced Concrete Bridge Decks"). The design generally followed guide specifications for slotted CP systems published by Jackson (1).

New York's second CP installation was completed in the fall of 1985 on the I 88 eastbound bridge over Schoolhouse Road and the D&H Railroad at Harpursville, also in Broome County. It was constructed as a standard state contract, without experimental funding. Again, the design generally followed Jackson's guide specifications, but was modified based on experience gained at Whitney Point.

This report completes the evaluation of the Whitney Point installation, and compares it with the one at Harpursville. An interim report by Grady (2) described design, installation, and costs of the Whitney Point project, but there has been no corresponding report on the Harpursville bridge.

II. DESIGN, INSTALLATION, AND COSTS

A. Whitney Point Design and Installation

The I 81 bridge is a two-lane, three-span monolithic structure built in 1968. The deck slab was designed with 1-1/2 in. of concrete cover over the top mat of reinforcing steel. The deck slab surface measures about 155 ft long by 37 ft wide, with a skew angle of 29°. Thickness of concrete cover over the top mat of reinforcing steel averaged 1.40 in. and ranged from 0.88 to 2.00 in.

Deck surface preparation consisted of removing spalled and delaminated concrete to a depth several inches below the top reinforcing bar mat, and patching these areas with chloride-laden concrete. A total of 1475 sq ft (26 percent) of the original concrete deck surface was repaired in this manner. Areas of high half-cell potential that were not delaminated were not removed.

Calcium chloride in aqueous solution was introduced as an admixture into the concrete patching material at a rate of 9.4 lb/cu yd. This dosage was selected to match the chloride ion concentration of 6 lb/cu yd measured in the existing concrete at the level of the top mat of reinforcing steel. Aside from using calcium chloride as an admixture and not removing high-potential concrete areas, deck repair followed standard New York procedures for patching reinforced concrete bridge decks using a New York Class D concrete mix. (Class D mix has a nominal 3/8-in. coarse aggregate, cement factor of 725 lb/cu yd, w/c ofo.44, slump range of 2-1/2 to 3-1/2 in., and air content range of 5 to 9 percent.) Concrete cover over the steel was generally thicker along the curb sides of the deck and thinner toward its center. Also, upper bars of the steel reinforcing mat ran from curb to curb. These factors were considered in designing the CP anode matrix.

For the CP design, six separate electrical zones were constructed. Each span was divided into two electrical zones containing about 990 sq ft. In each zone, primary anodes were placed parallel to each curb, bonded in sawed slots 1/2 in. wide by 3/4 in. deep, and offset from each curb by about 14 in. Within these slots, platinized-niobium wires were run to holes in the deck surface, leading to junction boxes on the underside of the structure. The two primary anodes of each zone were electrically connected to each other, providing a redundant power feed from each side of the deck.

Secondary anodes were formed in sawed slots of the same dimensions, cut on nominal 1-ft centers, and perpendicularly intersected the primary anode slots. Two multi-stranded carbon-filament conductors were placed from curb to curb in each secondary anode slot. These carbon-filament conductors, in the form of flat ribbons, were twisted into a rope-like configuration before insertion

Preceding page blank

into the sawed slots. They made electrical connection with the platinum-niobium conductors by simple overlapping contact.

To avoid the possibility of anodes shorting directly to the steel reinforcing bars, all upper steel bars of the top mat (running from curb to curb) were located using pachometers. The secondary anode slots were then laid out several inches away from these steel bars, but parallel to them. Due to this realignment of slot positions, final nominal spacing between the secondary anodes averaged about 9 in. After the slots had been sawed, cleaned, and dried, anode conductor placement was completed and the slots filled with a conductive polymer grout specified to match the FHWA formulation summarized by Jackson (1). Grout components were hand proportioned and mixed, with the resulting mixture squeezed from plastic bags into the slots, encapsulating the conductors and bonding to the slot surfaces. Grout resistivity and compression samples were taken periodically as construction progressed.

In each zone, a zinc-zinc sulphate reference electrode (reference cell) was installed in a sawcut cavity at the upper rebar level. Lead wires were run through the deck to junction boxes on the structure's underside. The cavities were then backfilled with chloride-laden concrete. Three rebar probes were similarly installed in the deck, consisting of short sections of plain steel rebar potted in concrete prisms very heavily dosed with chlorides. The sawcut cavities in this case were backfilled with chloride-free concrete.

All power system and instrument lead wires were dropped below deck and run via plastic conduit to the power supply cabinet mounted on the northeast wingwall. To prevent possible interference, power feed wires and reference cell wires were run in separate conduits. To avoid lightning damage, copper-wire jumpers were welded across each expansion joint of the bridge rail on either side of the deck. The railing was then connected to copper ground rods at each of the four termination points. A contract change order was required for this feature, since it was not included in the original specifications.

The primary contractor on this project was the Gunite Masonry Company of North Belmore, New York. Matcor, Inc. of Doylestown, Pennsylvania, subcontracted to supply the CP system materials, energize the system, and perform and document an engineering evaluation of the CP system.

Appendix A contains diagrams of the Whitney Point CP system. Specifications and construction details were given in Grady's interim report (2).

B. Harpursville Design and Installation

The Harpursville bridge is a two-lane, two-span monolithic structure built in 1974. The deck slab was designed with 2 in. of concrete cover over the top mat of reinforcing steel. The deck slab surface measures about 570 ft long by 41 ft wide without a skew. Concrete cover over the top mat of reinforcing steel averaged 2.8 in. and ranged from 1.13 to 4.25 in.

Deck surface preparation consisted of removing spalled and delaminated areas to a depth several inches below the top reinforcing-bar mat and patching with chloride-laden concrete. Of the original deck surface, 2260 sq ft (9.7 percent) was repaired. Areas of high half-cell potential that were not delaminated were not removed. (Actively corroding steel reinforcement in concrete exhibits a corrosion potential equal to or greater than 0.35 v more negative than a copper-coppersulfate half-cell -- this condition is referred to as a "high half-cell potential.")

Calcium chloride in aqueous solution was introduced as an admixture into the concrete patching material at a rate of 3.1 lb/cu yd. This dosage was selected to match the existing chloride ion concentration of 2 lb/cu yd measured at the level of the top mat. Aside from using calcium chloride as an admixture and not removing high-potential concrete areas, deck repair followed standard New York procedures for patching reinforced-concrete bridge decks using a Class D concrete mix.

Because of the excellent concrete cover thickness, no special design precautions were needed to prevent shorting of the anodes to the reinforcing steel. The anode-matrix design was chosen to give good current distribution, optimize sawcutting production rate, and give reasonable redundancy in anode circuitry.

Twelve independent electrical zones were constructed for this CP design. Span 1, about 90 ft long, was divided into two electrical zones. Span 2, about 480 ft long and continuous over two piers, was divided into 10 equal-sized electrical zones. In each zone, five equally spaced sawcuts were made perpendicular to the centerline (see Appendix B). These would form the primary anode. Secondary anode slots were sawed parallel to the center-line on nominal 1-ft centers, intersecting the primary anode slots.

All anode slots were sawed 1/2 in. wide by 3/4 in. deep, except for the Zone 7 slots which were dimensioned 3/8 in. wide by 1 in. deep. This dimensional variation was used to confirm laboratory test results indicating that deeper, narrower slots had less tendency to experience debonding due to grout shrinkage. (For electrical conductivity purposes, the alternate slot dimension maintained the same cross-sectional area).

Two carbon-filament conductors were placed in each secondary anode slot for its entire length. Each of these was wrapped with a polyester filament, was round in cross-section, and had a diameter less than 3/32 in. A single 0.031-in. diameter platinum-niobium conductor was placed in the primary anode slots to intersect and make contact with the carbon-filament conductors.

Grout components were premeasured and prepackaged at the factory. The material was mechanically mixed and placed in the slots using a cone-shaped implement fabricated by the contractor. Samples from each lot of grout material delivered to the job had first been batched and tested at the Materials Bureau laboratory to assure that all specified requirements were met. Resistivity measurements and compression samples were also taken periodically as construction progressed.

For each zone, two silver-silver chloride reference electrodes were installed in sawcut cavities at the upper rebar level. Lead wires were run through the

Table 1. Whitney Point CP costs.

Description	Quantity	Unit Cost	Totals
Furnish and Install CP System (lump sum)*	1	$55,000	$55,000
Bridge Rail Grounding (lump sum)	1	1,240	1,240
Expose Rebars, sq ft	1,475	8	11,800
Slab Reconstruction with $CACl_2$ Concrete, sq ft	1,475	12	17,700
			$85,740

*Including six reference cells; three rebar probes; 300 lin ft of primary anode (est); 5600 lin ft of secondary anode (est); 700 lin ft of DC conduit (est); 3700 lin ft of connection wire (est); one CP power supply system (six zones): one AC power service; and subcontracted system evaluation, energization, and documentation.

Table 2. Harpursville CP costs.

Description	Quantity	Unit Cost	Totals
Reference Cells	24	$370	$8,880
Rebar Probes	24	260	6,240
Rebar Bonds	1	195	195
Primary Anodes, lin ft	2,488	4.50	11,195
Secondary Anodes, lin ft	21,006	4.10	86,125
DC Conduit, lin ft	1,730	9.20	15,915
Connection Wire, lin ft	36,882	0.40	14,750
CP Power System	1	10,500	10,500
AC Power Service	1	3,800	3,800
Bridge Rail Grounding (lump sum)	1	1,000	1,000
CP System Evaluation, Energization, and Documentation (lump sum)	1	6,000	6,000
Expose Rebars, sq ft	2,260	12.00	27,120
Slab Reconstruction with $CaCl_2$ Concrete, sq ft	2,260	5.00	11,300
			$203,020

deck to junction boxes below deck. These cavities were backfilled with chloride-laden concrete. Two rebar probes were similarly installed in each zone. These consisted of short sections of plain steel rebar potted in concrete prisms heavily dosed with chlorides. The sawcut cavities in this case were backfilled with chloride-free concrete.

All power-system and instrument lead wires were dropped below deck and run through plastic conduit to the power supply cabinet mounted on the west abutment backwall. To prevent possible interference, the power feed wires and reference electrode wires were in separate conduits. Also, to avoid possible lightning damage, copper-wire jumpers were welded across each expansion joint of the bridge rail on either side of the deck. The railing was then connected to copper ground rods at each of the four termination points.

The primary contractor on this project was the Hubble Electric Company, Inc., of New Hartford, New York. Harco Inc. of Hatboro, Pennsylvania, subcontracted to supply the CP system materials, energize the system, and perform and document an engineering evaluation of the CP system.

C. System Costs

Costs related to the Whitney Point system are listed in Table 1. Cost of the CP system, its installation, and bridge-rail grounding was $56,240 or $9.91 per sq ft, based on a bridge-deck surface area of 5,673 sq ft. If costs of preparing the deck surface before installation of the CP system are included, cost of the installation becomes $85,740 or $15.11 per sq ft.

In an effort to reduce the cost per square foot of a slotted CP system, New York's second design was bid as 11 separate construction items. Larger zone sizes and a larger deck surface area helped reduce this cost. Cost of the CP system and the bridge-rail grounding was $164,600 (Table 2) or $7.08 per sq ft, based on a bridge-deck surface area of 23,247 sq ft. Adding the cost of deck surface preparation increased the installation total to $203,020 or $8.73 per sq ft.

III. CONSTRUCTION AND MAINTENANCE PROBLEMS

A. Whitney Point

1. Electrical Problems

Except for installing the power-supply unit, all construction was completed by October 1983. After several delays in delivery, the power supply was installed and the system initially energized in December 1983.

By September 1984, the power-supply unit had malfunctioned. Several zone power-output control cards had burned out and a panel meter had failed. The unit was removed and returned to the manufacturer for repair. During its re-installation in March 1985, the repaired unit caught fire and was again returned. A completely redesigned power-supply was provided by the manufacturer in July 1985, and operated properly without incident for the life of the CP system.

In spring of 1986, protective fuses for three of the power zones blew. (This had also occurred in the spring of 1984). Power was restored by replacing the fuses. Water from melting ice and snow tended to collect along the curb on the east side of the deck. Containing deicing salts, it probably provided a path to ground that overloaded the zone circuitry.

2. Anode-Grout Problems

Anode grout was installed in two phases. After one of the bridge's two lanes was closed to traffic, the anode slots were sawcut and cleaned. After primary and secondary anode conductor wires and strands were placed in the slots, which were then sealed with conductive grout, traffic was switched to the completed lane and the process repeated on the remaining lane.

In the grout placement phase of installation, two problems were experienced relating to proportioning of the grout mixture. In one, a grout resistivity sample indicated a value of about 16 ohm-cm, indicating that insufficient carbon had been added. Typical sample values were around 6 ohm-cm, and the specifications called for a maximum resistivity of 10 ohm-cm. Because it was believed the material represented by this sample would still perform adequately, it was not removed. In the second instance, installed grout did not harden. Apparently, the ingredient that initiates the polymerization reaction had been omitted during mixing.

Figure 1. Typical anode grout distress.

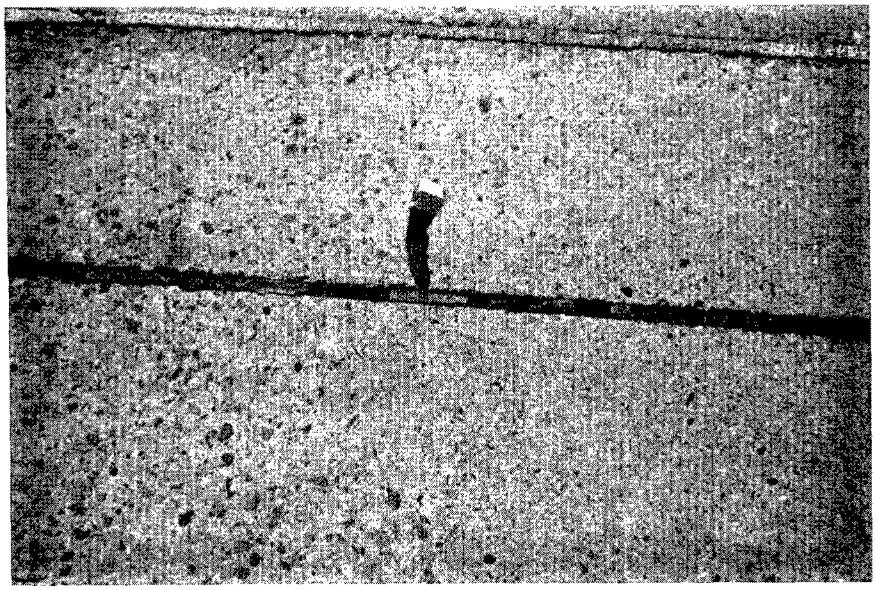
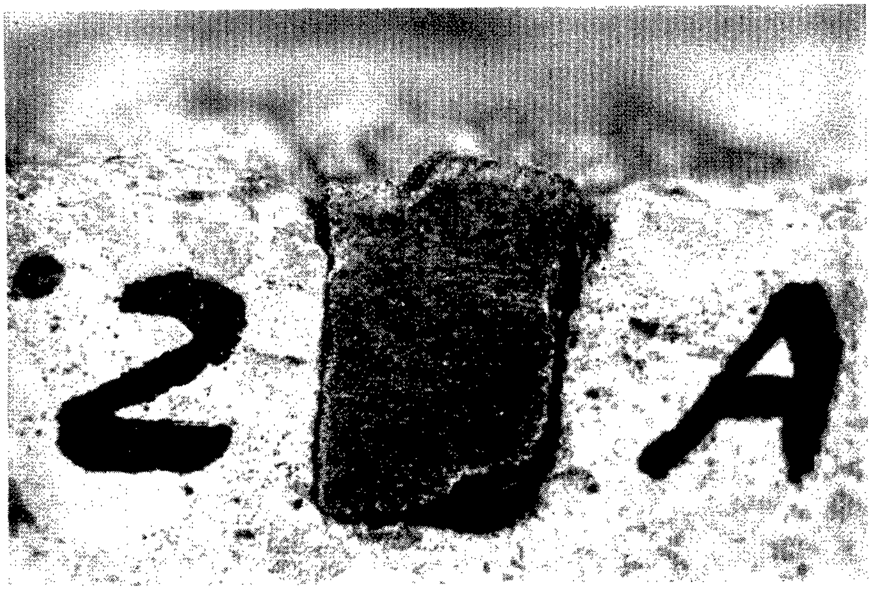


Figure 2. Secondary anode cross-section.



The uncured material was carefully removed from the sawed slot, using soft plastic implements to avoid damaging the platinum-niobium conductor. Slot surfaces were then cleaned by wiping with cloths, and new grout was bonded into the slots.

Anode-grout debonding was first observed immediately after exposing the anodes to traffic. Small isolated areas of grout were repaired by the contractor in October 1983. After acceptance of the contract and one winter in service, larger areas of anode-grout distress appeared. By October 1984, about 200 lin ft had debonded or cracked (Fig. 1). Grout distress increased to 600 lin ft by the spring of 1985.

During the winter of 1984-85, the Materials Bureau evaluated several proprietary anode-grout repair materials. Properties of shrinkage, compressive strength, shear-bond strength, freeze-thaw resistance, water absorption, and resistivity were examined. It was determined that the anode-grout mixture is not conductive in the liquid state. As polymerization progresses, the grout mass shrinks. The authors believe that this shrinkage forces carbon particles of the grout mixture into close proximity, making the hardened material conductive.

Several commercially available polymer grouts were tested to determine the effects of this shrinkage characteristic when bonded in a concrete slot 1/2 in. wide by 3/4 in. deep. This showed that a shrinkage crack tended to develop along one vertical face of the slot (Fig. 2). It was further determined that cooling the concrete substrate or narrowing the slot width reduced the tendency for this shrinkage crack to form. Based on this laboratory test program, Harco's "Anode-crete" grout material was selected for the anode repair work, because it exhibited least shrinkage of the grout materials tested.

After selecting the grout repair material, a major effort was made to repair the damaged anode matrix. A crew of seven worked for 10 days replacing damaged anodes. These repairs, in three sessions, began in May and ended in September 1985. Repair work was confined to the secondary-anode slots running perpendicular to the curbs and centerline. Damage was concentrated in or adjacent to the wheelpath areas. Grout repair areas are shown in Appendix C. The greatest damage was found on the southernmost span (Span 1). Primary anodes running parallel and close to the curbs were undamaged.

Repair involved removing defective grout sections by air-chipping, and then hand-tooling the ends of each section of remaining sound grout so that about 1/2 in. of carbon filament conductor was exposed. The slots were cleaned by sand and air blasting. New carbon-filament conductors were then placed in the cleaned slots, overlapping the exposed existing carbon filaments. The slots were then backfilled with grout repair material and sprinkled with silica sand. About 3 cu ft of anode-grout and 1200 ft of carbon anode conductor were required to complete the repair work. By the beginning of October, all anodes were repaired and all zones were energized and fully operational. By the summer of 1986, a survey showed that though repaired anode-grout areas were still well bonded, an additional 150 lin ft of original anode-grout had debonded.

B. Harpursville

1. Electrical Problems

The Harpursville system was initially energized in November 1985. A reference-electrode readout problem caused by faulty wiring of the power supply unit was repaired by Harco personnel. During the system's first winter, the LCD readout meter in the power-supply unit froze. A replacement was installed, and in September 1986 a special heating device was added to protect the meter from cold-temperature damage. In early March 1987, Zone 2 was found to be without power. It was determined that a zone power regulation board malfunctioned. It was repaired by the manufacturer and reinstalled.

2. Anode-Grout Problems

In the spring of 1986, an inspection showed that the CP system had undergone its first winter without sustaining any damage to the anode matrix. An inspection in spring 1987 found that about 1 lin ft of anode-grout had popped out, and additional grout cracking and debonding were also noted. A full survey of the installation in August 1987 showed total grout loss of about 10 lin ft. Total grout distress (losses plus debonded areas still in place) was about 75 lin ft.

IV. FIELD PERFORMANCE

A. Whitney Point

The CP system was energized on December 8, 1983. Its power-supply unit contained feedback circuitry that would adjust output power levels for each zone based on the potential of the zinc-zinc sulphate reference electrodes embedded in the deck. Desired reference electrode potentials for each zone were determined by a National Association of Corrosion Engineers (NACE) certified corrosion specialist provided by the A. V. Smith Engineering Company of Narberth, Pennsylvania, which subcontracted these services to Matcor, Inc., for this project. Resistances were measured at various locations on the deck where exposed steel reinforcing was accessible, to confirm continuity of the reinforcing steel. All measurements proved to be below the 1-ohm-maximum criterion used to substantiate continuity.

E-log I studies on the structure were performed by increasing zone currents incrementally at 3-minute intervals and measuring the corresponding "instant off" reference electrode potential. Reference electrode potential versus the log of external current was plotted on semi-log paper. Theoretically, the breakpoint at which the slope of the curve changes (the end of the Tafel region) is the current level at which polarization is achieved. This technique was used by the corrosion specialist to determine current levels required for polarization of each of the six separate zones on the concrete deck. Based on the results, the system was energized.

Table 3 lists parameters used to energize the CP system. It should be noted that as a feedback system, the power supply was designed to automatically increase or decrease anode current I(Z) to maintain the desired reference electrode potential VREF(Z) determined by the E-log I studies. The system was periodically checked for proper power levels and operation.

In July 1985, after repeated malfunctions, the power supply was replaced with a simpler, more reliable unit not capable of feedback control. The new power system was adjusted to provide 0.75 amps per zone (0.80 mA/sq ft) in a constant-current mode. From that point, another criterion was used to determine whether reinforcing steel was being protected. This entailed interrupting the zone current, immediately measuring "off" potentials, allowing the system to completely depolarize, and then remeasuring the "off" potential values. The potential shift between these two states was then calculated. A shift of 100-mV or more is evidence of full protection. (Corrosion theory states that failure to achieve a full 100-mV depolarization shift does not <u>necessarily</u> mean that cathodic protection is not achieved; however, for the purpose of comparison a depolarization shift of less than the

Table 3. Whitney Point power supply parameters.

Zone, Z	Reference Electrode Potential, volts VREF(Z)	Anode Current, amps I(Z)
1	-0.75	0.18
2	-0.51	0.90
3	-0.11	0.26
4	-0.79	0.53
5	-0.29	0.25
6	-0.60	0.25

Table 4. Whitney Point CP summary.

	% of Span Area Protected				
Date	Span 1	Span 2	Span 3	Criteria	Comments
6/8/83	100.0	100.0	100.0	E log I	Initial energization
4/15/84	--	--	--	E log I	No power unit; about 200 lin ft of grout failure
8/27/85	3.3	97.2	76.0	100-mV shift	Grout repairs completed in Spans 2 & 3; about 600 lin ft of grout repaired by 9/85
8/26/86	57.6	57.5	45.6	100-mV shift	150 lin ft of additional grout failure measured
8/24/87	1.1	0.0	3.7	100-mV shift	Progressive grout failure and surface distress

Table 5. Whitney Point spall and delamination surveys.

		Spalls			Spalls and Delamination			
Date	Area	Span 1	Span 2	Span 3	Span 1	Span 2	Span 3	Totals
1986	Sq Ft	10.5	14.5	0.0	38.0	22.5	5.0	65.5
	Percent	0.5	0.8	0.0	1.8	1.2	0.3	1.2
1987	Sq Ft	12.0	17.0	1.2	70.5	45.5	20.2	136.5
	Percent	0.6	0.9	0.1	3.4	2.5	1.2	2.4

100mV target value has been considered here to indicate an "unprotected condition"). The 100-mV shift was measured with copper-copper sulphate half-cells across the surface of the deck on a 5- by 5-ft matrix.

Electrical system readings and half-cell potential measurements were routinely obtained by Department personnel. Field surveys were also performed to determine the degree of anode-grout distress and the progression of spalls and delaminations on the deck surface. Table 4 summarizes the degree of cathodic protection experienced by the reinforcing steel in the deck at various points in the system's history.

Anode-grout distress was described earlier. A total of 750 lin ft or about 12.5 percent of original grout failed by summer 1986, when it was last measured. As anode deterioration progressed, it was noted that a dark orange to brown discoloration was forming at the grout-concrete interface of the anodes. This is a characteristic stain caused by acid generation, which became pronounced as fewer and fewer anode paths were available to carry the zone current. The stain was noticeably absent from broken and isolated sections of anode-grout not energized.

In 1985, it became apparent that the bridge deck surface was experiencing surface distress in the form of spalling. Spalling and delamination were surveyed in May 1986 and again in May 1987. The pattern of distress was progressive and tended to occur in the travel lanes adjacent to concrete patch areas. Appendix D shows the spall and delamination survey results taken in May 1987. These data are summarized in Table 5.

B. Harpursville

The Harpursville CP system was energized on November 1, 1985 using a constant-current power supply. Although two silver-silver chloride reference electrodes were installed in each zone, they were not used as feedback controls for the power-supply system. These reference electrodes provided a convenient way to monitor system performance without leaving the power-supply area under the bridge.

NACE-certified corrosion specialists provided by Harco, Inc., performed resistance measurements as described earlier. All proved to be below the 1-ohm-maximum criterion used to substantiate continuity.

E-log I evaluations were performed on 4 of the 12 zones to determine typical current requirements for the CP system. On this project, the corrosion specialists used the E-log I determinations as a guide for initial energization of the CP zones, and then fine-tuned the zone current levels based on the 100-mV shift criterion. Table 6 lists the initial power supply parameters at Harpursville.

In August 1987, potential was measured across the entire deck surface using portable copper-copper sulphate half-cells, immediately after power had been turned off. A 5- by 5- ft matrix was used for these measurements. After the deck was allowed to depolarize completely, half-cell potential measurements

Table 6. Harpursville power supply parameters.

Zone	Reference Electrode Potential, volts		Anode Current, amps
Z	V_AREF(Z)	V_BREF(Z)	I(Z)
1	-0.340	-0.438	1.10
2	-0.387	-0.282	1.20
3	-0.341	-0.362	1.20
4	-0.431	-0.440	1.20
5	-0.392	-0.453	1.20
6	-0.421	-0.487	1.20
7	-0.332	-0.384	0.73
8	-0.261	-0.218	0.80
9	-0.235	-0.329	0.80
10	-0.249	-0.311	0.80
11	-0.361	-0.334	0.80
12	-0.341	-0.405	0.80

were repeated, and the 100-mV shift criterion was applied to determine the degree of cathodic protection being experienced, with the following results:

Zones	Percent Protected
1,7	82.6
2,8	80.3
3,9	96.7
4,10	96.2
5,11	99.3
6,12	98.0

In addition to half-cell potential measurements, spalling, delamination, and anode-grout distress were also surveyed on August 25, 1987. A total of 178.2 sq ft of concrete was found to be delaminated. No spalls were found, but 10 lin ft of anode-grout had been lost, and another 65 lin ft of grout exhibited some delamination (i.e., 75 lin ft total distress).

V. DISCUSSION

Steel-reinforced concrete containing chloride levels of about 1.5 or more lb/cu yd, as a result of exposure to deicers or by other means of introduction into the concrete, is prone to corrosion-related deterioration. This takes the form of spalls and delaminations resulting from expansive pressures caused by corrosion products formed at the steel reinforcing. The promise of cathodic protection systems is in completely stopping progression of this corrosion and consequent deterioration. Life of these systems has been estimated to be up to 50 years, and is theoretically limited only by ability of the anodes and power supplies to distribute protective current into the electrolyte.

Slotted CP systems, in addition, seemed to promise minimal repair (removal of spalls and delaminations, but not high-potential concrete) and less traffic disruption, as compared to removal/repair/overlay techniques having life expectancies of 20 to 35 years (using current removal and curing techniques outlined in Section 584 of New York's Standard Specifications).

A. Whitney Point

The slotted-CP system failed to protect the deck from corrosion distress, due to its inability to provide and properly distribute protective current in the electrolyte as a result of breakdown of the anode matrix and/or the power supply. In the first year-and-a-half of the system's life, the power supply was out of service about half the time, and no protection was provided to the reinforcing steel. The major cause of rapid deck deterioration, however, was not the failing power supply, but design and composition of the anode matrix.

The purpose of conductive polymer grout in a slotted CP system is to distribute current through a relatively large surface area (the sawed-slot surface) into the concrete electrolyte. It forms a composite anode (that is, with stranded carbon or platinum-niobium wire conductor elements) and bonds it to the concrete (slot) surface.

Conductor elements within the grout lower total resistance of the anode matrix, allowing current to flow more readily. They also bridge tiny cracks in the grout and reinforce the anode, maintaining continuity. In turn, these encapsulated conductors are shielded by the grout from acids that tend to form at an anode in an electrolyte.

The anode-grout used here proved unsuitable for this task. Laboratory testing and field observations showed that grout shrinkage on setting usually caused it to crack along one vertical face of the sawcut slot. Traffic action, along with differential stresses between the grout and concrete substrate due to temperature changes, caused rapid deterioration of the anode matrix. In design of the system, close anode spacing was selected so that if minor breaks occurred in one anode, current from adjacent functioning anodes would help protect the steel near the broken anode.

In addition, secondary anodes running from curb to curb were redundantly fed with power from each end -- that is, the primary anodes of each zone ran along the two curbs, and were electrically connected so that the secondary anodes were fed from each of their ends. (Because of the deck's skew, some secondary anodes could only be fed from one end). Appendix A shows that one break in a secondary anode does not mean total loss of its ability to distribute protective current to the deck. However, multiple breaks near both ends of many secondary anodes resulted in major impairment of the system's ability to distribute current to the deck surface. This had a cascading effect on the amount of the deck area protected, or rather not protected.

This impairment is dramatically demonstrated by the August 27, 1985 entry in Table 4. Note that 10 percent of the anode-grout was defective at the time of repairs. The table shows that using the 100-mV shift criterion, Span 2 was 97.2-percent protected after completing grout repairs, but Span 1 was only 3.3-percent protected before completion of repairs.

It was shown that when a slotted type CP system fails due to loss of anode-grout, the corrosion process is accelerated, for two reasons. First, additional chloride intrusion is greatly enhanced because new deicing salts need penetrate only a fraction of an inch of concrete to reach the reinforcing steel (from the bottom of the sawed slots), rather than penetrating the original concrete cover of 1 to 2 in. Second, as more anodes cease to provide current paths, those remaining must take more of the current sent to the zone by the power supply. This phenomenon will eventually result in overprotection of some steel with possible generation of hydrogen gas at these overprotected areas. Also, it could cause some of the steel to become anodic if the CP system becomes sufficiently unbalanced. High currents in the remaining anodes will also cause formation of excessive amounts of acids at the concrete-grout interface, further eroding the bond there. (Although the grout resists acid attack well, the concrete is still subject to acid attack.)

Concrete deck distress at Whitney Point, first measured in May 1986, involved 1.2 percent of the deck area. Surveyed a year later, deck distress had doubled (Table 5). All spalls and delaminations detected were found in old concrete adjacent to deck surface areas patched before the system was installed. Since these areas previously seemed "sound" when the deck was surveyed for delaminations in 1983, distress formed either as a result of the rapid deterioration process described earlier, or existed before CP installation as corrosion-induced microcracks, not detectable using standard delamination-survey techniques.

If the distress did precede the CP system, removing only "unsound" concrete for cost savings becomes questionable. Possibly, New York's conservative standard removal criteria for traditional overlay rehabilitation would have eliminated any pre-existing distress areas. This approach includes removal of high half-cell-potential concrete as well as small isolated areas of lower potential concrete between these high-potential areas.

During anode repair operations at Whitney Point, carbon strands in the failed secondary anodes were often found not to be fully encapsulated by the conductive polymer grout (Fig. 2). These strands, supplied by Matcor, Inc., were in the form of flat ribbons that had to be twisted for insertion into the sawed slots before grout application. Bulking of these carbon strands prevented grout material from achieving full contact with the sawed slot bottom for bonding. Other problems included malfunction of panel meters and overloading of zone output circuits (which blew fuses). The meter problem was easily remedied by replacement and was not considered of major importance.

The overload problem, although easily remedied by fuse replacement, was considered more serious. It is suspected that ponding of salty water along the curb as a result of melting ice and snow provided an electrical "short" to ground for several of the zone power-supply circuits. Overloading of zone circuits happened once while the original (feedback) power-supply unit was in operation in spring of 1984. Although designed with overload protection, this phenomenon may have caused some of the problems experienced by this power supply, which eventually had to be replaced. Zone fuses again blew in spring of 1986, this time while the constant-current power supply was in place. Zones were re-energized by replacing the blown fuses, but there was no way to correct the basic problem, because the deck drainage pattern could not be altered.

At Whitney Point, texture of the original unpatched concrete surface was polished, but patched areas exhibited good surface texture. A slotted CP system does nothing to improve condition of the surface texture.

B. Harpursville

Experience at Whitney Point greatly influenced New York's second slotted-CP installation. Goals of better quality construction, reduced cost per square foot, and more maintenance-free system operation were addressed as follows:

1. Selection of a deck with larger area, greater concrete cover depth, minor spalls and delaminations, a low amount of high half-cell-potential concrete, and good surface texture,
2. Separation of various construction activities into 11 grouped operations with separate payment items (rather than a lump-sum bid approach),
3. Requirement of a simpler constant-current power supply,

4. Improved quality assurance through product and material certification, testing, and project sampling, and

5. Prequalification by state laboratory testing of each production lot of anode-grout.

A good working relationship between the contractor, the state project engineering staff, and engineers in the state's Technical Services Division resulted in several construction practices which, based on laboratory tests, would optimize the quality of the anode end-product. These included: 1) use of a mechanical mixing system that was more efficient than hand mixing and resulted in more working time for grout placement, 2) use of a cone-shaped device for more rapid grout placement, and 3) placement of grout only in cool (50 to 65 F) early morning ambient temperatures to retard grout setting time and thereby reduce the possibility of cracking due to shrinkage. The contractor also installed one zone with a narrower slot width (3/8 in. rather than 1/2 in.) at the state's request, since lab tests had shown that narrower anodes were less likely to undergo vertical shrinkage cracking.

Although labor-intensive, grout installation went smoothly, with the material setting in 15 to 20 minutes. Great care had to be taken in placing anode-grout because, once mixed it thickens near the end of its liquid phase. While it is still possible to place it into slots in this condition, the resultant hardened material -- which takes on a porous, punky appearance -- would not be durable and would break out of the slots on exposure to traffic. Placing the anode-grout material at cooler temperatures extended its liquid phase several minutes, but workers complained of a tendency for grout liquid to "run" out of the slots due to the deck's incline. This was considered a minor complication, given that the procedure would lessen the tendency toward shrinkage cracking and eventual anode loss.

The August 1987 survey data (after two winters) showed only 75 lin ft of distressed anode. Of this length, only 10 lin ft of grout had actually been lost. About 0.75 percent of the deck area was delaminated. Because of greater concrete cover at Harpursville than at Whitney Point, the minimal amount of anode-grout loss, and the continuity of cathodic protection, these delaminations appear to have originated as microcracks that could not be detected during the preconstruction delamination survey, using standard delamination-detection techniques.

Carbon strand conductors in the failed grout areas, round in cross-section with polyester wrapping, were found to be well encapsulated by the grout mixture.

VI. SUMMARY AND CONCLUSIONS

1. Anode systems of the type used at Whitney Point and Harpursville are labor-intensive to construct and susceptible to failures due to: 1) the inherent shrinkage properties of the conductive polymer-grout material, and 2) construction operations required -- such as proportioning, mixing, and placement. Mechanical mixing, rapid placement devices, cool placement temperatures, and narrower slots tend to diminish shrinkage-related cracking in the polymer grout studied. When the grout mixture begins to thicken toward the end of its liquid phase, it can still be installed in the concrete slots, but hardens to a porous, punky appearance and is not durable.

2. Loss of anode-grout in slotted CP systems allows deicing salts to attack steel reinforcing bars more readily, because the effective concrete thickness protecting the steel has been diminished through formation of the slots. Loss of anode-grout also causes remaining anodes to carry a greater proportion of total zone current. This unbalances current distribution of the CP system and causes more rapid acid formation at the grout-concrete interfaces of the functioning anodes.

3. Multi-stranded carbon-filament conductors having round cross-sections and wrapped with polyester were superior to flat ribbon conductors for forming secondary anodes. The round conductors were easier to handle, and their smaller dimensions allowed grout to flow around them easily for encapsulation and bonding to surfaces of the sawed slot.

4. The unexpected amount of concrete delamination on the Harpursville deck cannot be explained by a nonfunctioning CP system or accelerated chloride attack due to grout loss in the anode slots. It is suspected that in the earliest stages of corrosion distress, microcracking forms in the concrete at the steel reinforcing-bar area, undetected by present survey techniques. Depending on the concentration of these microcracks, some concrete areas may develop additional delaminations in spite of an effective CP system.

5. A regulated constant-current DC power supply without feedback circuitry is sufficient to provide power for a CP system.

6. Water from melting ice and snow, mixed with deicing salts, tends to collect along curb lines in the spring. Because the slotted anodes are exposed on the surface of the deck, this may short-circuit them to ground.

7. CP system costs ranged from $15.11 to $8.73 per sq ft on the two installations studied. These included preparing and patching the bridge deck; providing materials, labor, and equipment to install the system; and providing engineering services to evaluate, energize, and document the system. Costs per square foot for the slotted CP systems decreased when:

    1. A larger bridge deck area was instrumented,
    2. Larger zone areas were used,
    3. Individual construction specifications were used rather than lump-sum specifications,and
    4. A constant-current, non-feedback power supply was specified.

    Excluding concrete repair expenses, cost per square foot at Whitney Point and Harpursville were $9.91 and $7.08, respectively.

8. The slotted anode CP systems studied did not improve the surface texture of polished concrete bridge decks.

VII. RECOMMENDATIONS

The Whitney Point CP system was terminated due to progressive failure of the anode system and resulting distress of the concrete deck. The Harpursville CP system is functioning well, though some distress has been observed in the anode system and some concrete deck delamination has been noted. On the basis of the experience discussed in this report, the following recommendations appear appropriate:

1. The Harpursville CP system should be monitored on a regular basis. Zone current levels should be checked quarterly and anode condition should be assessed annually. A delamination study and half-cell surveys should be performed biennially to determine effectiveness of the CP system.

2. Anode damage at Harpursville should be repaired when weather permits. Additional anode damage detected in the monitoring process should be repaired on a continuing basis to assure that the reinforcing steel is adequately protected, and to prevent intrusion of large amounts of chlorides into the concrete through empty anode slots that result from anode distress.

3. No new slotted bridge deck CP system should be installed by the state, based on experience with both the Whitney Point and Harpursville systems. The grout anode system is expensive, labor-intensive, and prone to shorting due to its surface exposure. The grout materials tested have a shrinkage mechanism that tends to cause debond failures upon curing. Loss of anode grout accelerates damage due to unbalanced anode currents and easier salt intrusion into the deck surface.

4. Future CP systems installed on steel-reinforced concrete bridge decks should employ anodes protected by a bonded overlay. This technique would eliminate all the materials compatibility and shorting problems experienced when the slotted-anode technology was used, as well as provide a well-textured riding surface.

5. If high half-cell potential concrete is not to be removed when installing CP systems, further study is needed regarding detectability of delaminations in their initial stages.

For interested readers, the following related documents are available upon request:

1. Harpursville Cathodic Protection Construction Specifications.
2. Conductive Anode Grout Evaluation for Slotted Cathodic Protection Systems.
3. NYSDOT Standard Specifications, Section 584: "Specialized Concrete Overlays for Structural Slabs".

ACKNOWLEDGMENTS

The authors wish to thank H. Scott Strong, Region 9 Project Engineer at Whitney Point; John E. Grady, Engineering Research and Development Bureau principal investigator during Whitney Point construction; Richard Lockwood and Jay Hager, Region 9 Project Engineer and Assistant Project Engineer at Harpursville; Cathy C. Cowan, Materials Bureau principal investigator of grout properties, for assistance with quality assurance at Harpursville and grout repairs at Whitney Point; John A. Burnett, Engineering Research and Development Bureau, who coordinated half-cell potential measurements, spall/delamination surveys, and grout distress surveys at Whitney Point and Harpursville; and Wendall B. Strum, Region 9 Bridge Maintenance Engineer, Albert J. Eucker, Broome County Resident Engineer, and their respective dedicated personnel who completed the field grout repair work at Whitney Point.

REFERENCES

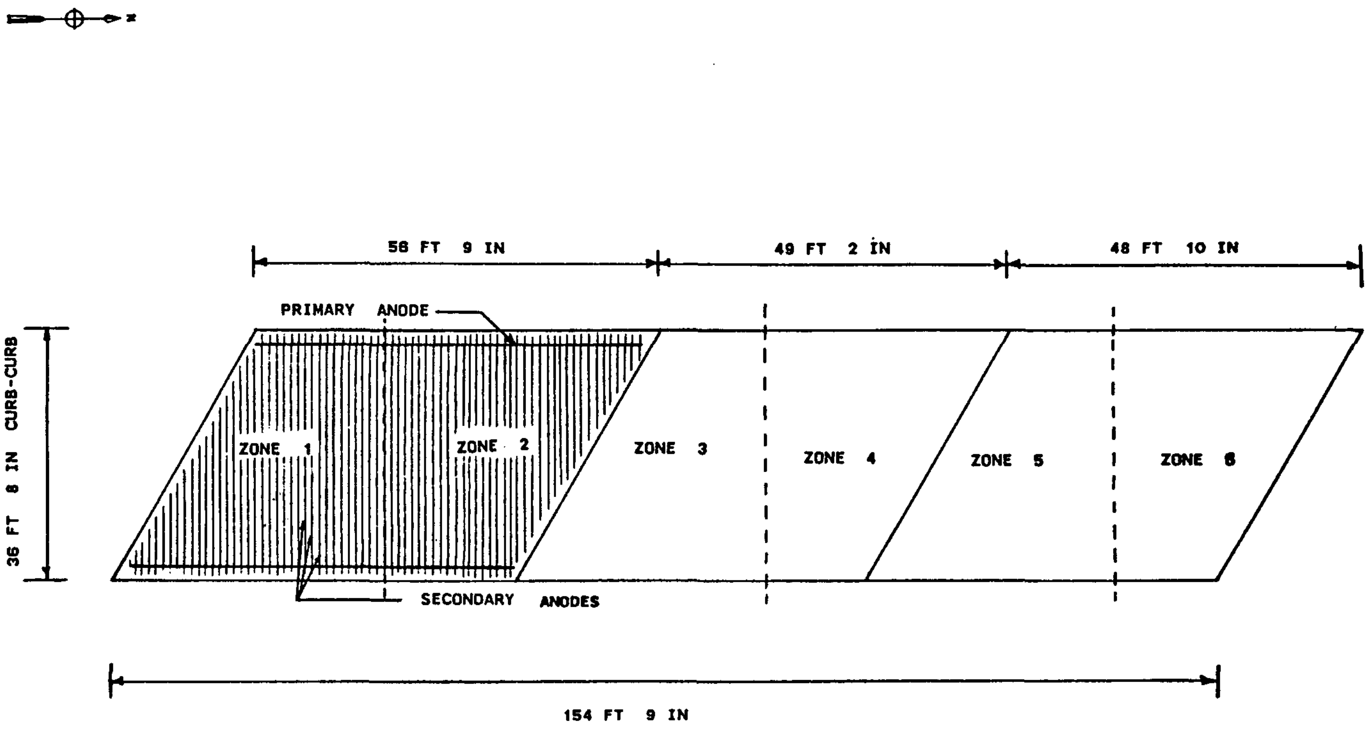
1. Jackson, D.R. Cathodic Protection for Reinforced Concrete Bridge Decks. Report FHWA-DP-34-2, Interim Report on Demonstration Project 34, Federal Highway Administration, U.S. Department of Transportation, October 1982.

2. Grady, J.E. Corrosion and Cathodic Protection of Reinforcing Steel In Concrete Bridge Decks. Research Report 126, Engineering Research and Development Bureau, New York State Department of Transportation, November 1985.

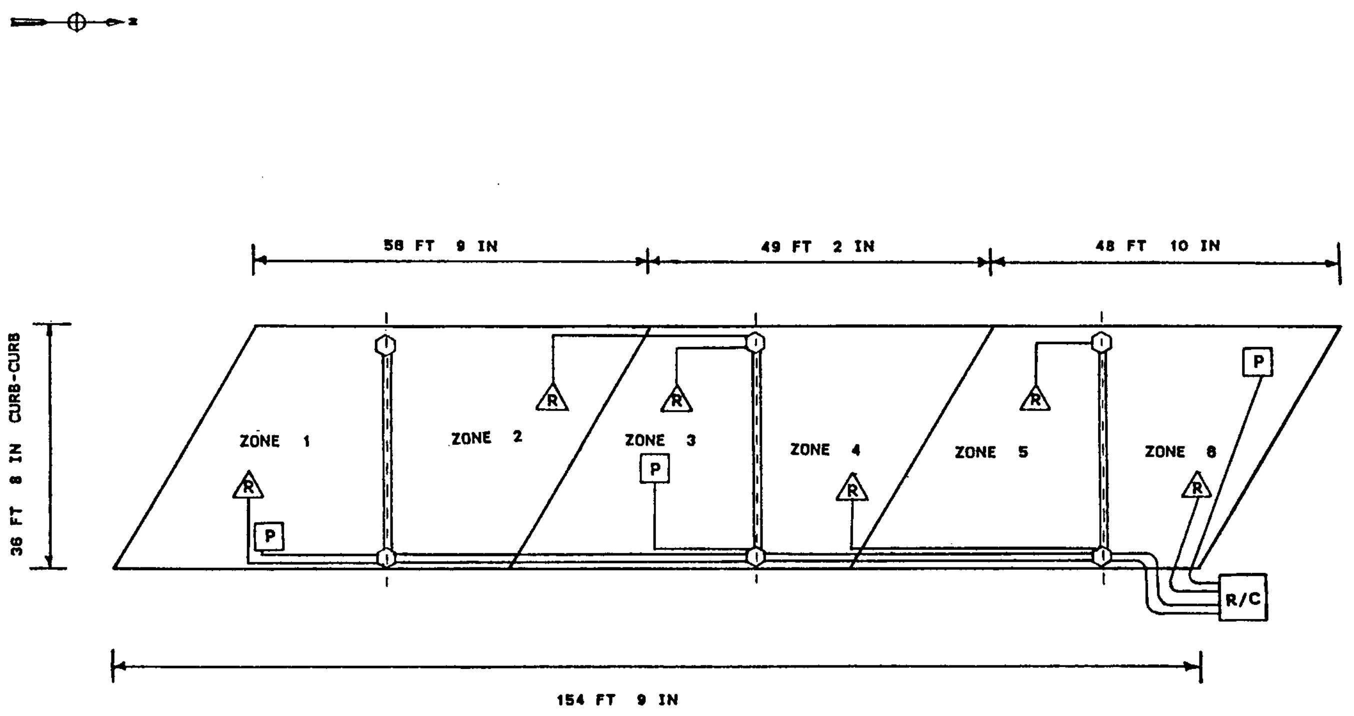
3. Cowan, C.C. Conductive Anode Grout Evaluation for Slotted Cathodic Protection Systems. Materials Bureau, New York State Department of Transportation, September 1986.

APPENDIX A

WHITNEY POINT CP SYSTEM



WHITNEY POINT C.P. PROJECT LAYOUT
ZONE CP LAYOUT



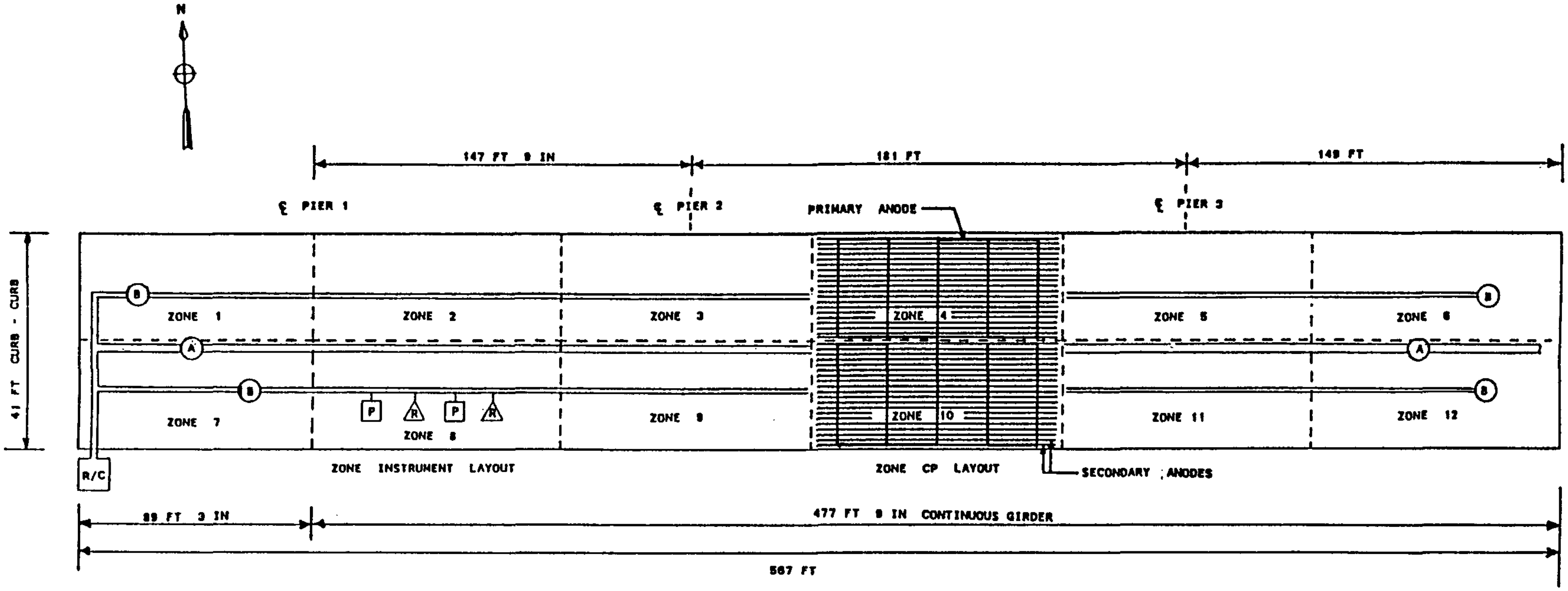
	LEGEND
- - - -	ZONE BOUNDARY
——	CONDUIT
△R	REFERENCE CELLS
P	REBAR PROBES
R/C	RECTIFIER/CONTROLLER UNIT
⬡	JUNCTION BOX

WHITNEY POINT C.P. PROJECT LAYOUT

APPENDIX B

HARPURSVILLE CP SYSTEM

Preceding page blank

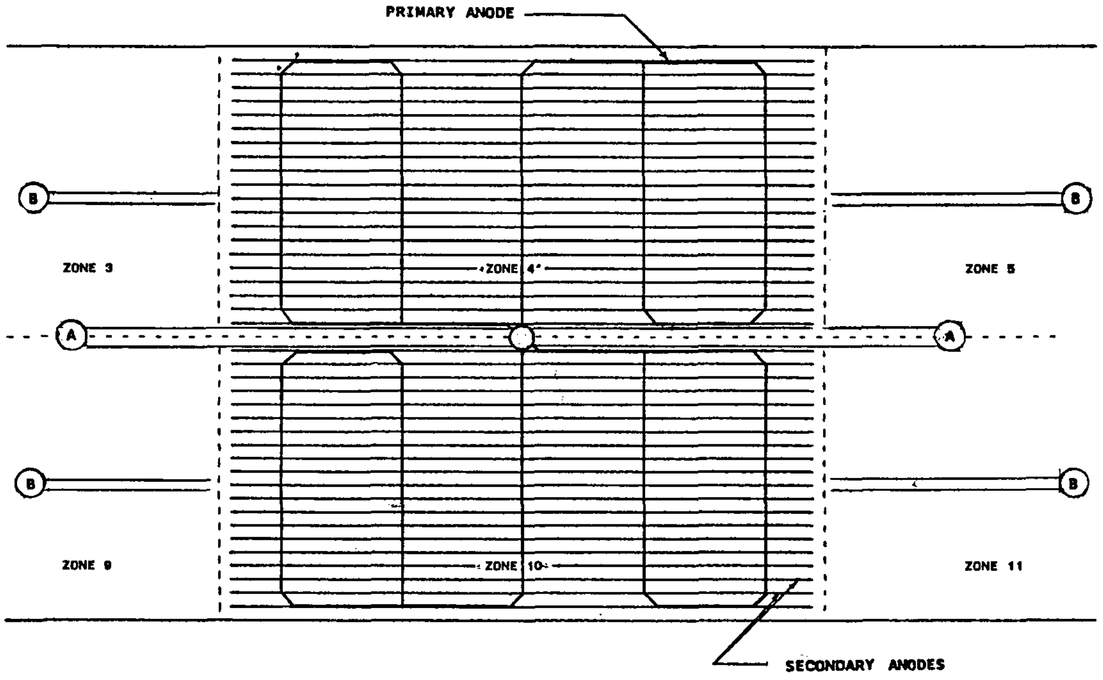


LEGEND

- - - -	ZONE BOUNDARY
-Ⓐ-	CONDUIT FOR ANODE SYSTEM
-Ⓑ-	CONDUIT FOR INSTRUMENTS
△R	REFERENCE CELLS
☐P	REBAR PROBES
R/C	RECTIFIER/CONTROLLER UNIT

HARPURSVILLE C.P. PROJECT LAYOUT

Although shown only in Zone 8 on this diagram, two reference cells and two rebar probes were installed in each zone.



TYPICAL ZONE CP LAYOUT

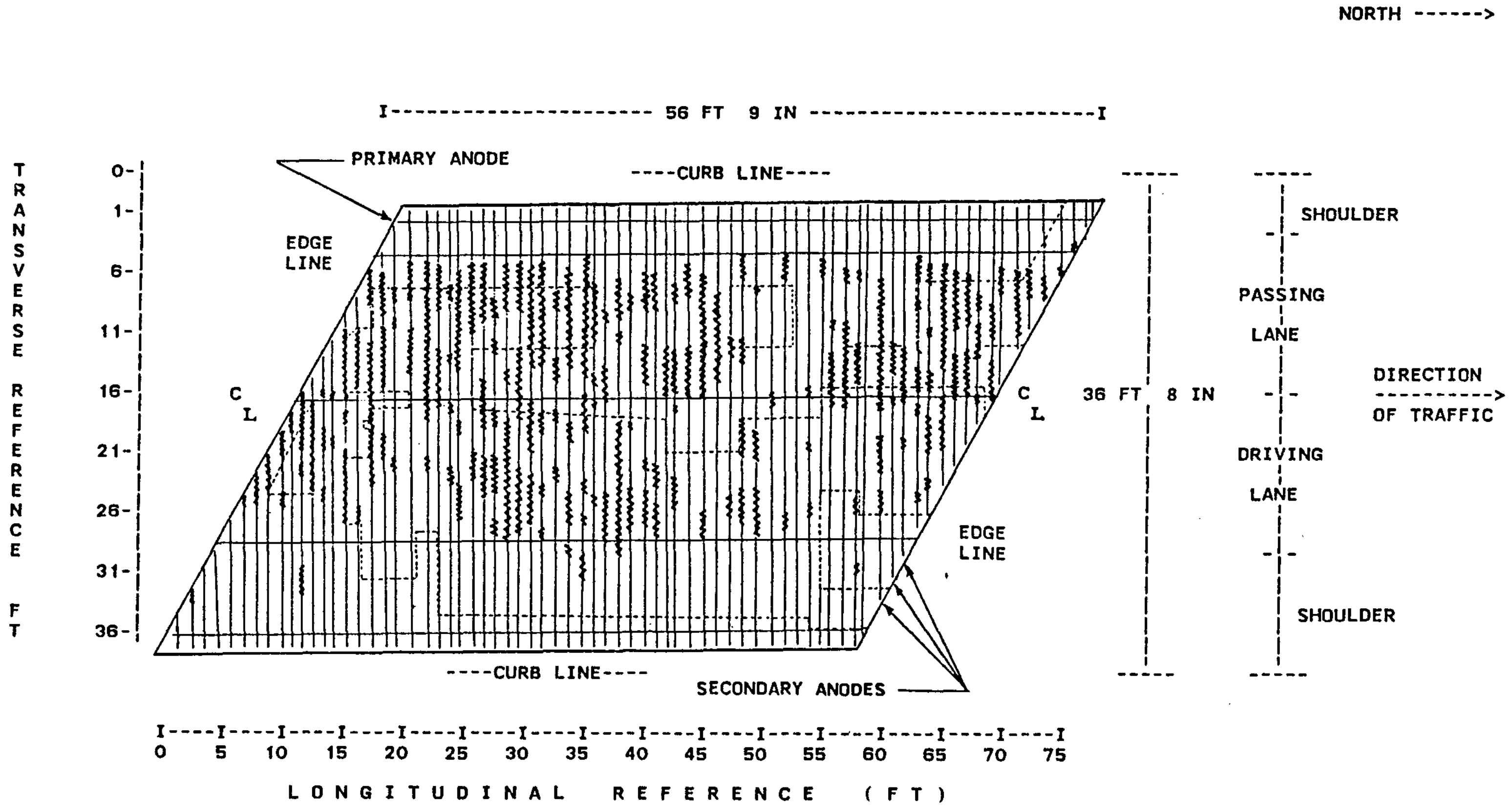
LEGEND

- - - ZONE BOUNDARY
Ⓐ CONDUIT (ANODE WIRES)
Ⓑ CONDUIT (INSTRUMENT WIRES)

HARPURSVILLE C.P. PROJECT LAYOUT

APPENDIX C

WHITNEY POINT ANODE GROUT REPAIRS

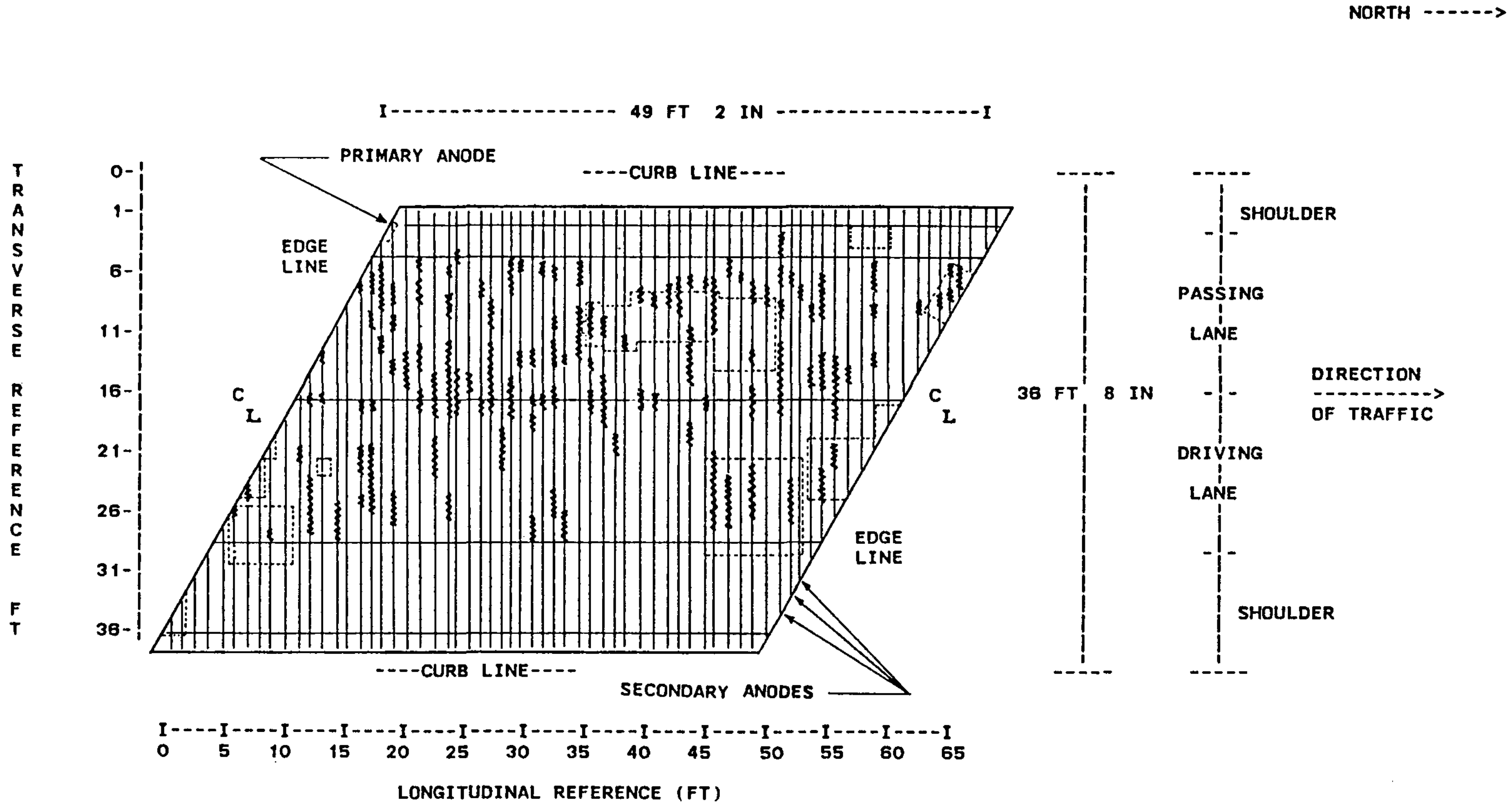


LEGEND

~~~~ GROUT DISTRESS

---- CONCRETE PATCH

ANODE GROUT DISTRESS SURVEY
MAY, 1986
SPAN NO. 1 (ER&DB)
~~~~

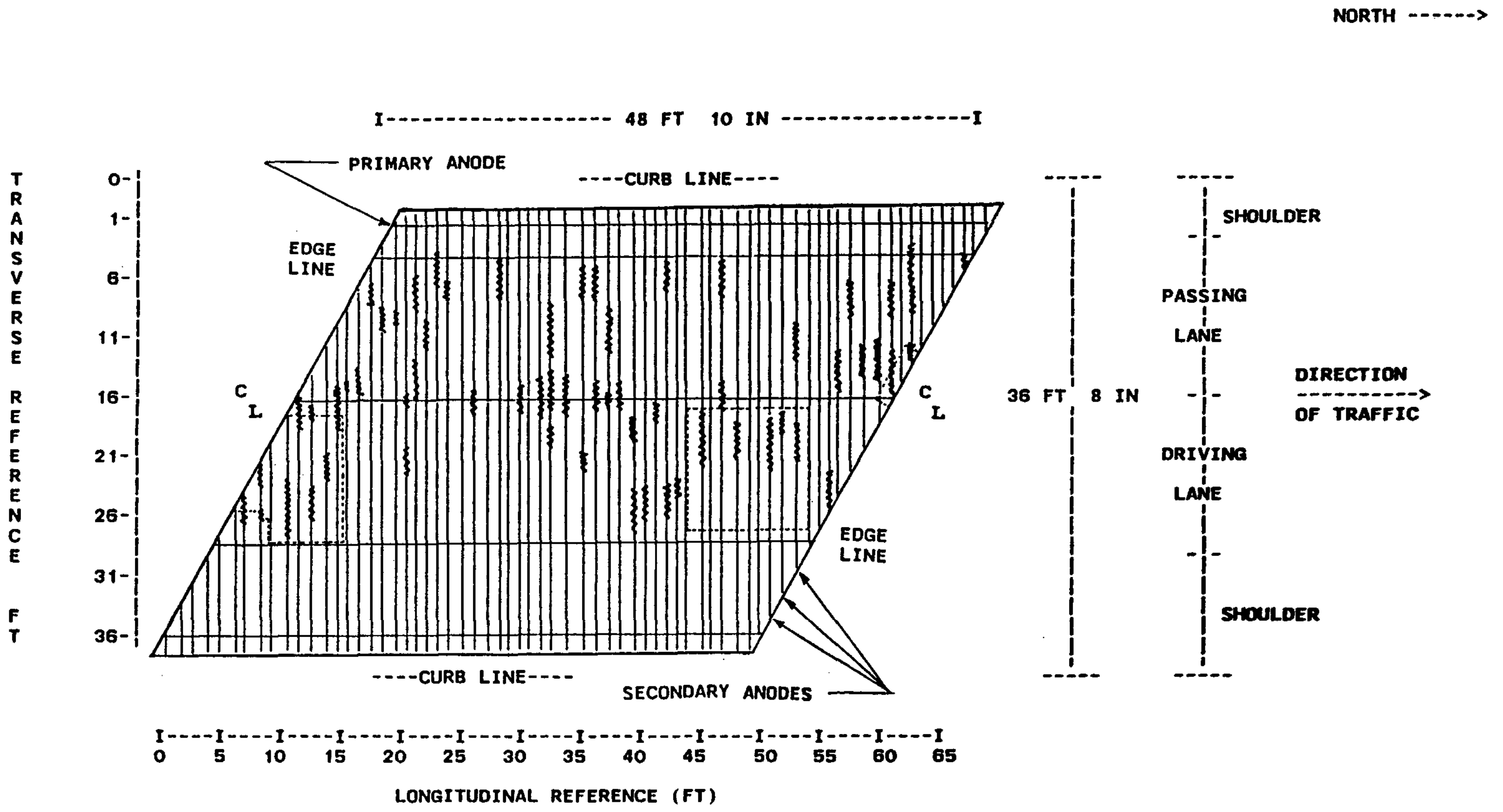


LEGEND

〰 GROUT DISTRESS

---- CONCRETE PATCH

ANODE GROUT DISTRESS SURVEY
MAY, 1986
SPAN NO. 2 (ER&DB)



LEGEND

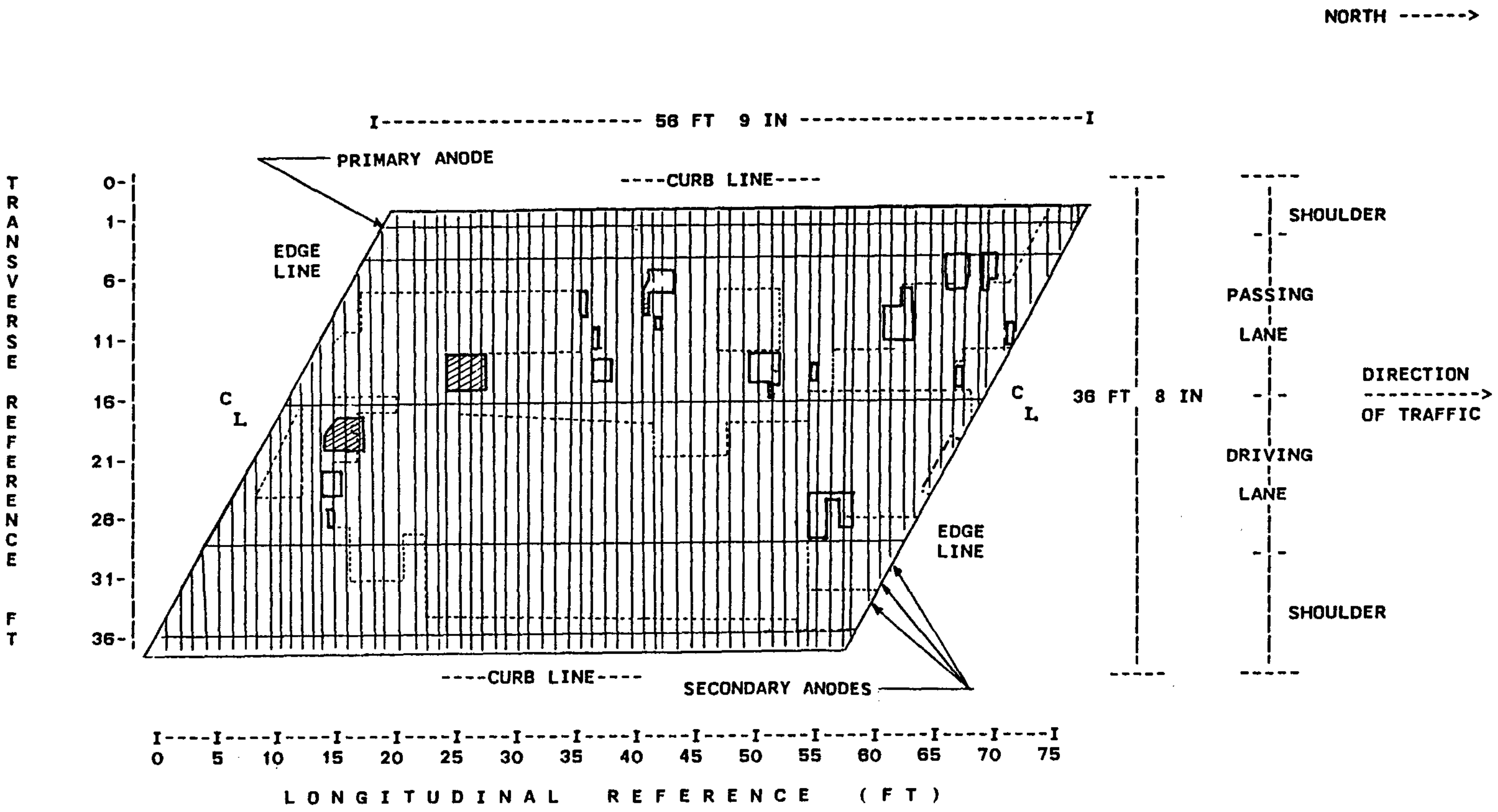
〰 GROUT DISTRESS

---- CONCRETE PATCH

ANODE GROUT DISTRESS SURVEY
MAY, 1986
SPAN NO. 3 (ER&DB)

APPENDIX D

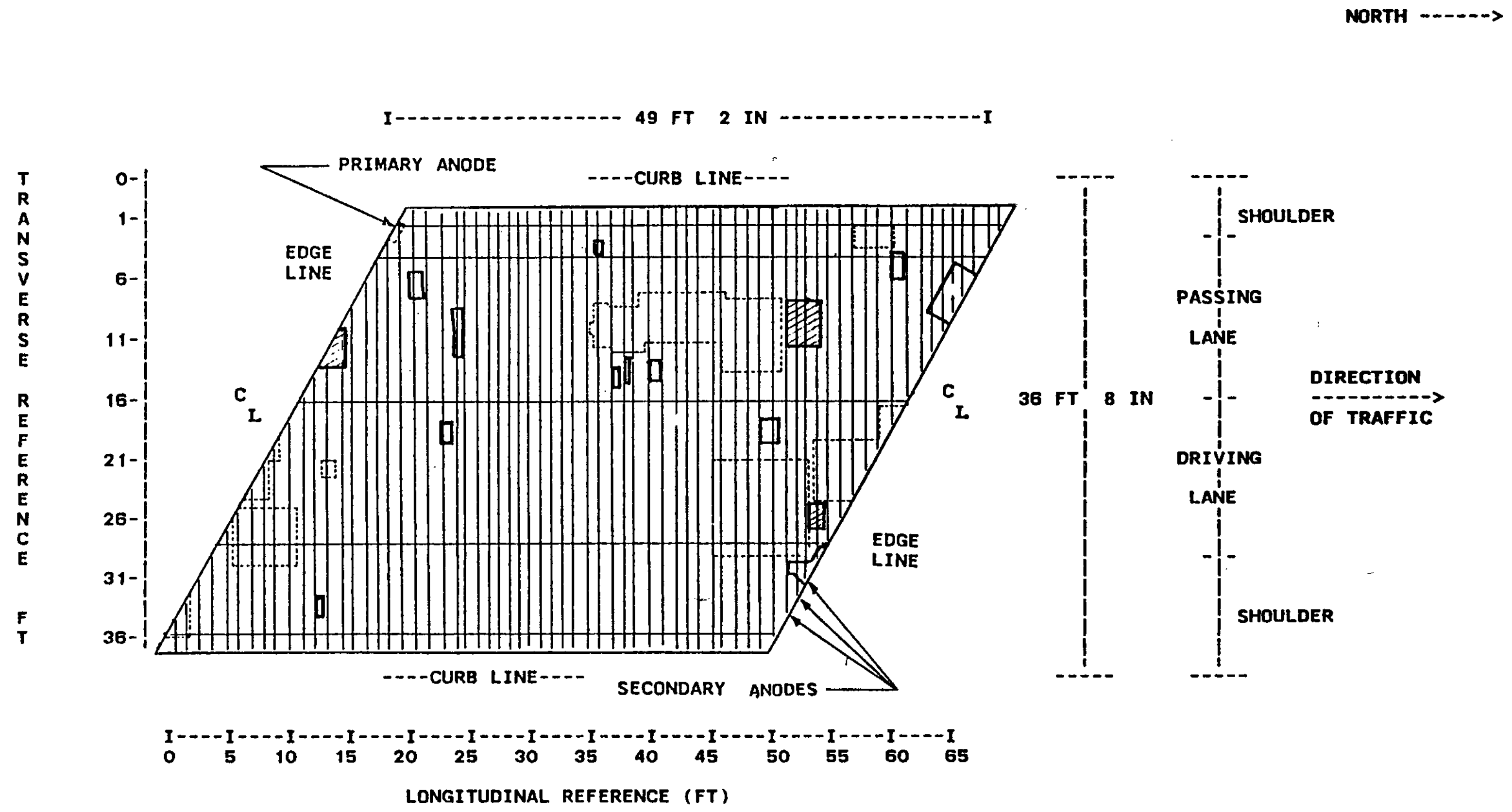
WHITNEY POINT SPALL/DELAMINATION SURVEY



LEGEND

☐ DELAMINATIONS
▨ SPALLS
---- CONCRETE PATCH

SPALL & DELAMINATION SURVEYS
MAY, 1987
SPAN NO. 1 (ER&DB)



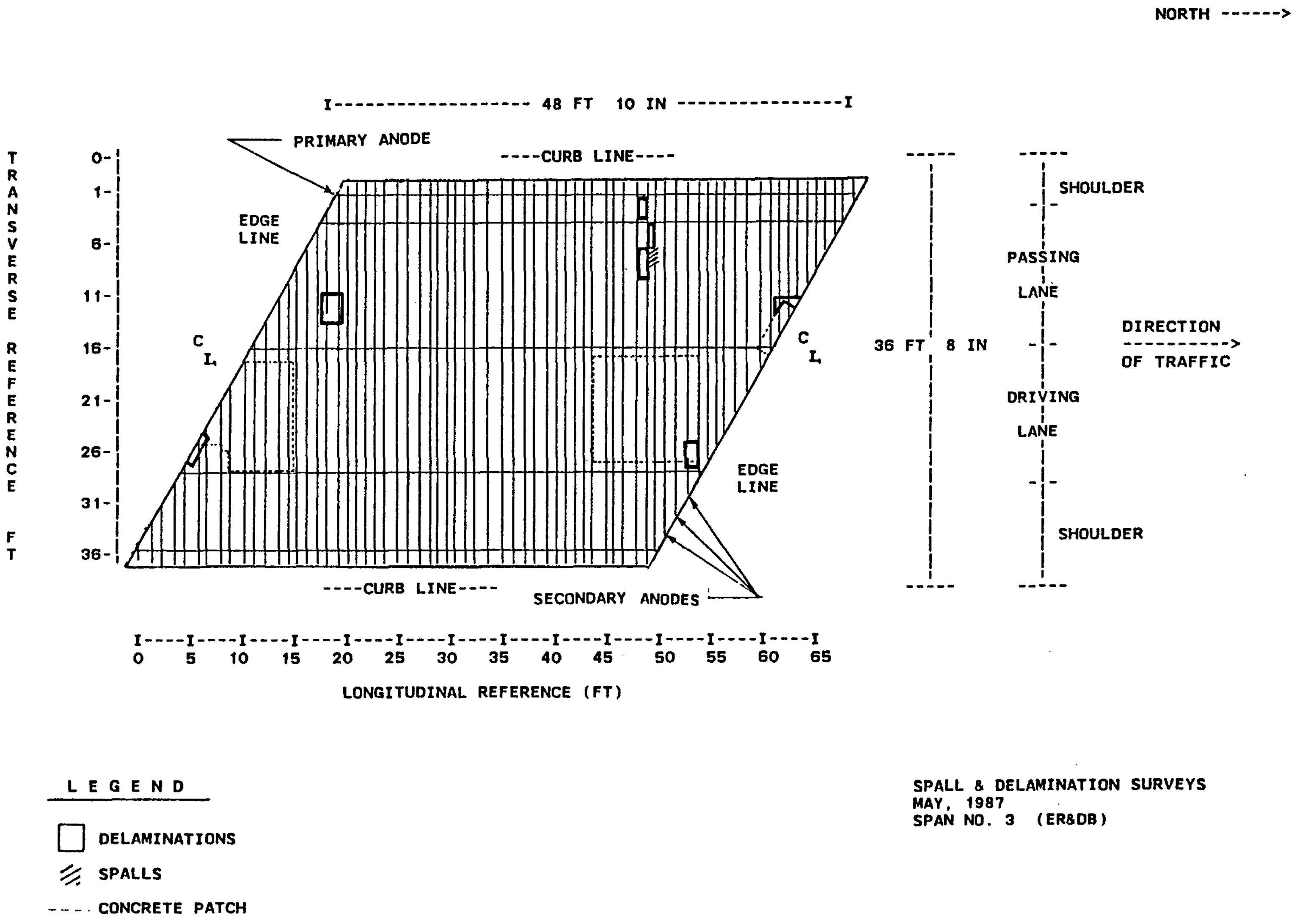
LEGEND

☐ DELAMINATIONS

▨ SPALLS

---- CONCRETE PATCH

SPALL & DELAMINATION SURVEYS
MAY, 1987
SPAN NO. 2 (ER&DB)



SPALL & DELAMINATION SURVEYS
MAY, 1987
SPAN NO. 3 (ER&DB)