SHRP-C/UWP-92-618

Cathodic Protection of Reinforced Concrete Bridge Components

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Strategic Highway Research Program
National Research Council
Washington, DC 1992

SHRP-C/UWP-92-618
Contract C-102B

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December 1992

key words:
anode
bridge
cathodic protection
chloride
corrosion
cp
decks
decks
maintenance
marine
overlay
substructure

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Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

The Authors would like to acknowledge the research team that carried out the original work, Harold Mindlin, Gerald Davis, Ken Han, the late Jack Snyder and the rest of the research team at Battelle, Robert P. Brown of Robert P Brown Associates, Robert Gummow of Corrosion Services Co., David Whiting of CTL and Phil Simon, Consultant.

The input from the SHRP Expert Task Group for the C-102 contracts was also invaluable. None of this would have been possible without enormous cooperation from the State and Provincial Highway Agencies. They responded to requests for time and effort and access to their structures with unfailing helpfulness and support.

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Abstract

This report describes a two-year investigation of cathodic protection (CP) systems installed on interstate highway bridges in North America. The performance of 287 systems, approximately 90 percent of the highway agencies systems, was reviewed through analysis of questionnaire responses and select field investigations. Overall, a majority of the systems were working well but systems in marine or other continuously wetted environments did not perform as well.

Passing a CP current has the beneficial effect of removing chlorides from around the steel bar.

Executive Summary

The SHRP contract C-102B "Cathodic Protection of Reinforced Concrete Structures" was awarded in October 1988. It ran for two years. The investigation started with a questionnaire evaluation of the cathodic protection systems owned by highway agencies in North America, with further information coming from other countries. Information on 287 systems was sent by State and Provincial Highway Agency personnel. An evaluation of these data showed:

- The oldest systems, built in 1973 and 1974 in California, are still working. Systems were built at the rate of one to ten a year until 1983, when Missouri started putting in 40 or more systems a year.

- Approximately 90% of systems were performing properly according to the information and judgement of the highway agency personnel responding to the questionnaire.

- The majority of systems were for decks, with the largest number of anodes of the conductive polymer in slots, followed by the conductive cable system, and flat anodes in conductive asphalt. These are all older systems.

- Some systems had been removed by accident during maintenance.

From the evaluation of those results, a field survey was conducted on 49 systems in 14 states and provinces. The results of that survey showed:

- Approximately 88% of systems were performing properly according to the independent inspection team. While this agrees well with the 90% success rate in the survey, the causes for failure and the systems that had failed were different from those identified in the responses to the questionnaire. Some systems reported as operating properly by the SHA were found to have failed when examined by the survey teams.

- The researchers found several systems that were switched off although the operating agency had thought that they were operating properly. When re-energized they worked properly.

- The majority of anodes were working well, and even those that were damaged were still protecting the majority of steel. The main damage to anodes was conductive paint anodes peeling when exposed to water, and the polymer popping out of slot systems. There was some damage to overlays on titanium mesh and systems, and one case of a damaged anode, with cracked and failed cable.

- There was damage to some of the electrical system, including failed power supplies, broken meters, corroded cable joints and corroded or leaking housings.

- A number embedded half cells had failed.

- A large number of systems was considered to have too high a current density applied. This will lead to a shortening of life of the anode system.

A detailed survey was carried out on six systems. The results of that survey were:

- Chloride moves away from the reinforcing steel with time. This means that current (or voltage) levels can be adjusted regularly to minimize the degradation to the anode system, and extend the life of the system.

- The major causes of degradation of anodes was found to be:

  1. Loss of bond between the concrete and the anode in areas of high current discharge. This was primarily in the presence of high water content, e.g. splash zones on marine pilings, or areas where water ponds on decks. The most susceptible anodes were paints and the polymer slot system.

  2. A build up of deposits under thermal sprayed zinc systems.

From the conclusions in chapter V, the following recommendations are made.

- There must be adequate mechanisms and budgets for regular servicing and maintenance of CP systems by personnel who are properly trained in the field. If not, then systems may fail for trivial reasons, and major expense incurred at a later date.

- Systems should be designed to take into account the differing conditions across the structure. Zones should be designed for probable current demand rather than geometry.

- Conductive carbon based paint coatings should not be used in areas of continuous or regular wetting. However they are inexpensive to apply and repair, and can work successfully if applied with care and adequate surface preparation.

- High circuit resistance leads to inadequate polarization of the steel. When the rebar to anode resistance exceeds 100 ohms, it the cause should be investigated.

- Given the reduction in chlorides in the concrete and the reduction in the depolarized potential after several years of operation, it is likely that current demand will decrease with time.

- Current should at all times be kept to the minimum necessary to protect the steel as damage to anodes (particularly carbon based anodes), and to the anode/concrete interface, is a charge transfer related phenomenon.

- It may be possible to run a zinc anode as a sacrificial anode after a short period of operation as an impressed current anode, as long as the circuit resistance remains low (e.g. in marine environments).

- A high resistance deposit was observed between the zinc and the concrete. This may limit the long term viability of the sacrificial system proposed above.

I

Introduction

The SHRP contract C-102B "Cathodic Protection of Reinforced Concrete Structures" was awarded in September 1988. It ran for two years, and during that time it carried out a questionnaire evaluation of the cathodic protection systems owned by highway agencies in North America, with further information coming from other countries. It was sent information on 287 systems by State and Provincial Highway Agency personnel. After an evaluation of the data, a brief field survey was conducted on 49 systems, and then a detailed investigation was carried out on 6 of those systems.

This report reviews the results of those field investigations. The conclusions from those results are being used in a follow up contract. The SHRP contracts C-102D,E,F and G are now continuing the investigation of cathodic protection of reinforced concrete highway structures.

Cathodic protection (CP) is only one of several rehabilitation methods available to engineers presented with corroding reinforced concrete structures. CP is suitable for reinforced concrete structures containing uncoated plain reinforcing bars. It has been applied to bridge decks suffering salt induced reinforcement corrosion, and in increasingly being applied to substructures.

The Federal Highway Administration has stated that cathodic protection is the only method known to stop corrosion damage regardless of the level of chloride within the structure. However, of the thousands of bridges suffering from corrosion, SHRP has identified 287 cathodic protection systems applied to over 200 bridges in the USA and Canada. This means that CP is very much a minority rehabilitation method compared with overlaying and other repairs.

The FHWA is now investigating the feasibility of applying CP to prestressed, concrete bridges. That work will not be addressed by SHRP.

The aim of the SHRP sponsored research is to evaluate the benefits and pitfalls of cathodic protection, to see how it can be improved. SHRP will develop a field manual to make CP as "user friendly" as possible. This report lays the groundwork for those goals by evaluating the present state-of-the-art, and considering the options for future development which will be more fully developed in the manual.

There are already several texts that give information on cathodic protection of reinforced concrete. This report will not describe the basics of the corrosion process, or of the application of cathodic protection. A bibliography of cathodic protection papers is Volume II of this report. A list of recommended reading on the principles of cathodic protection and corrosion of steel in concrete is given after this section.

The ultimate aim of the SHRP Structures research is to produce a manual of bridge rehabilitation for chloride induced corrosion of reinforced concrete bridge elements. Within that framework the work reported here is part of a series of contracts to produce a manual of cathodic protection, and to develop improvements and recommended state of the art approaches to the application of cathodic protection.

This report provides the basis for that work by surveying the field, with in depth investigations of selected structures. Conclusions are drawn on the performance, limitations and benefits of cathodic protection. The conclusions can be seen as interim to the final reports and manuals of the SHRP Structures research area.

Recommended Reading

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National Association of Corrosion Engineers Corrosion of Metals in Concrete Proceedings of Corrosion 87, Session T-3K (1987).

AASHTO/FHWA/NACE Proceedings of the Conference on Reinforced Concrete Bridge Decks San Antonio Texas, (1985).

II

Questionnaire

Responses

A questionnaire was sent to all major highway agencies in North America. Additional copies were sent to International Coordinators to the SHRP program. The mailing list included the state and provincial agencies of the USA and Canada, toll authorities, and the national highway agencies who have SHRP coordinators. Information was received on 287 cathodic protection (CP) systems installed on bridges throughout the USA and Canada. Information was also received on 14 systems in other countries. For the sake of easy comparison, the overseas systems will not be discussed further in the main text, but are discussed briefly in the Addendum. Responses from toll authorities indicated that they had no CP systems, so the main text will concentrate on the systems installed on bridges owned by state and provincial highway authorities in the USA and Canada.

Replies represent approximately 94% of the systems in the USA and Canada. No replies were received from seven highway agencies, who are believed to account for approximately 20 systems above the 287 identified.

The Population of Cathodic Protection Systems

Table 1 summarizes the responses to the questionnaires.

Table 1 - Numbers of Systems to August 1, 1989

Total Number of CP systems recorded	287
Estimated Number missing from survey	<20 (approx. 7%)
Agencies with no systems	11
Agencies with 1-2 systems	25
Agencies with 3-5 systems	6
Agencies 6-20 systems(CA,FL,NJ,OH,PA)	5
Agencies with more than 20 (MO, Ont.)	2

Information requested in the survey included the type and age of the bridge, its environment, the condition survey and concrete repair, the cathodic protection system and how it was commissioned and operated, as well as its present condition. Not all responses were complete, and some were internally inconsistent. Some of these were resolved by the field visits.

Figure 1 shows the number of systems installed per year from the first deck system in 1973 to 1989 when replies to the SHRP questionnaire were received. A few systems were yet to be energized when replies were sent, so the tail off in installations in 1989 was an artifact caused by the cut off date for replies.

The first systems were installed in California, with less than ten per year being installed nationally until 1984. Then Missouri started a large program of installations. This was to deal with a corrosion problem on box girder bridges that were expected to cause major structural problems if allowed to proceed unchecked. Missouri had installed 121 systems at the time of this questionnaire. They were followed by Ontario (44), New Jersey (18), California (17), and Ohio (14). The most innovative agencies, in terms of developing and promoting CP are California, where the initial research and development on cathodic protection for reinforced concrete was conducted, Ontario, which has researched and published many useful results on CP, and Florida, which has concentrated on the sea water substructure corrosion problem.

The Cathodic Protection Anode Systems

The evolution of cathodic protection systems is well described elsewhere, in the references given as further reading in the Introduction (e.g. Berkeley and Pathmanaban). Only a brief review will be given here.

The major anode types (in no particular order) are:

- The expanded titanium mesh has a mixed (or rare) metal oxide coating to prevent chemical attack. The anode is fixed to the concrete surface and overlaid with a cementitious coating.

- New variations of the anode in a ribbon form or a rod, drilled into the member are becoming available, but are not described here as these systems were not surveyed in this work.

- The conductive cable anode is a copper conductor sheathed in conductive plastic, so that current "leaks" out uniformly along the length of the cable. The anode is wound back and forth across the concrete surface and overlaid with a cementitious coating. Although the primary commercial anode for several years, it is no longer available, except on special order.

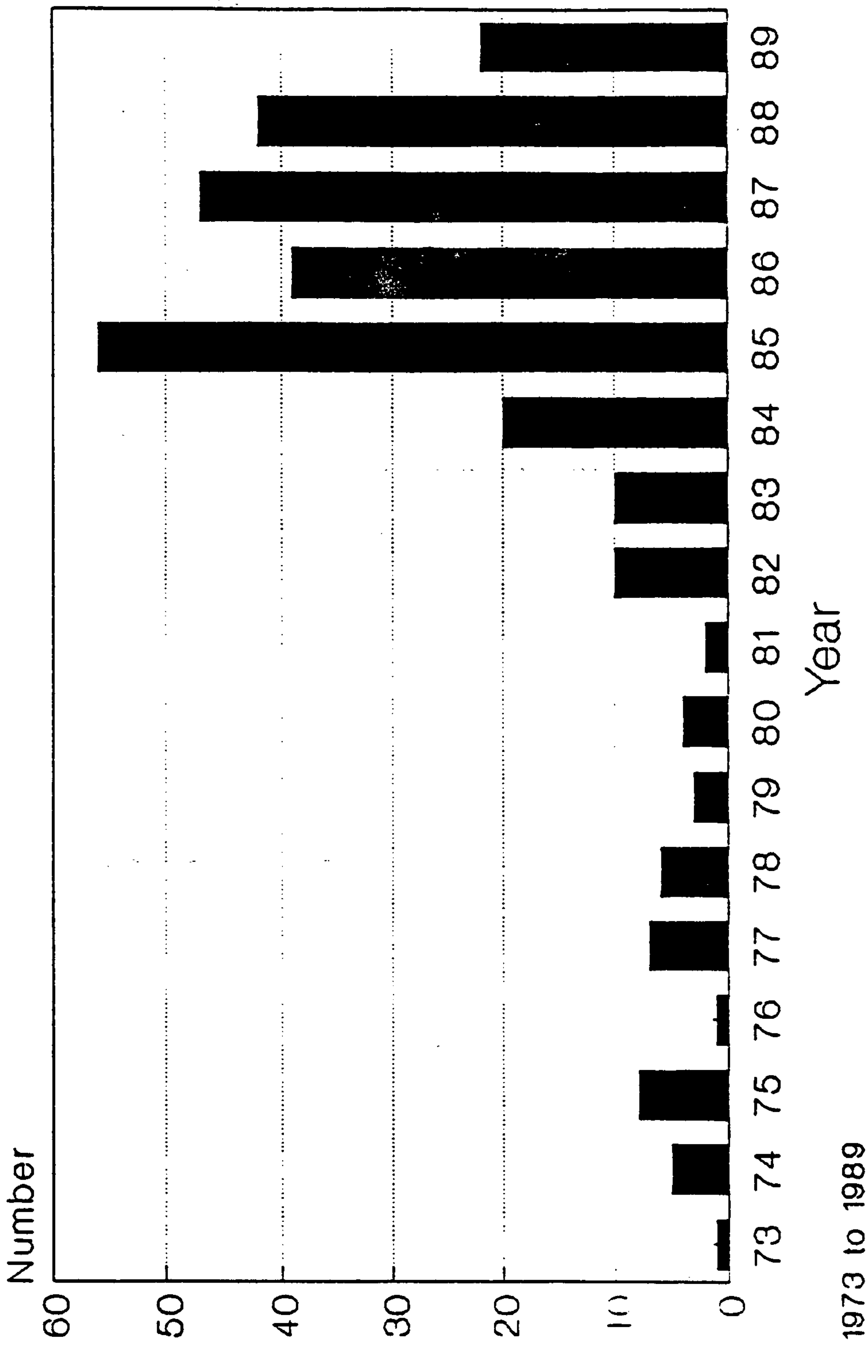


Figure 1 - Number of Cathodic Protection Installations Per Year

- The pancake anode system (usually of silicon iron), fixed to a deck surface, overlaid with a conductive asphalt.
- The slotted system uses a rigid conductive polymer, laid in slots cut on the bridge deck. A variation on this system is to mound the polymer on the deck and apply a cementitious overlay. Primary or additional conductors of carbon fiber and platinized niobium/copper are usually incorporated in the system as well.
- The conductive paint system, usually applied by brush or airless spray to substructure elements.
- The sprayed zinc system, either by arc or flame, can be applied to substructure elements (and has also been applied to decks). This is normally an impressed current system, but experiments to use it as a sacrificial system are underway.

Other experimental anodes include the surface mounted strip (a system of conductive strips fixed to a substructure surface), conductive rubber mats clamped to a surface, and various configurations of zinc metal used as a galvanic anode.

Deck Systems

The statistics derived from the responses to the questionnaire mirror the development of CP for steel in concrete. The early systems were developed by Richard Stratfull at Caltrans, for protecting bridge decks from deicing salt induced corrosion of the reinforcing steel. They were of the conductive asphalt type, usually with a silicon/iron primary anode. Caltrans installed the first system in 1973, with seven more in the next two years. This system was developed further by Ontario Ministry of Transportation. Ontario has installed 30 conductive asphalt systems from 1974 to 1989. Ontario CP practices have been described elsewhere (Schell, Manning and Pianca, 1987). A total of 53 conductive asphalt systems have been installed.

<u>Limitations of Pancake Anode/Conductive Asphalt System</u>

- Increased dead weight
- Increased deck thickness
- Need good air entrainment of the concrete to avoid freeze/thaw damage.

The next development was a system where slots were cut in the deck and a conductive polymer put in with a metallic primary anode wire. A variation on this theme was to put the polymer on the deck and overlay it without cutting slots. These systems were heavily used by Missouri DOT. Missouri dominates the statistics of CP installations between 1985 and 1987 with 89 slotted and mounded systems between 1985 and 1987 with another 17 systems under contract at the time of responding to the questionnaire.

The limitations of the saw slot system
o Need for adequate cover to cut slot
o Expense and difficulty of cutting slots
o Pop out of slot material due to acid attack, poor thermal compatibility and freeze thaw.
o Action of traffic pulling out polymer from slots

The limitations of the mounded polymer systems
o Increased dead weight
o Increased deck thickness
o poor thermal compatibility with concrete

The most recent anode systems for decks are the conductive polymer cable, and the oxide coated titanium mesh (the mesh being the most recent). Both are embedded in cementitious overlays. Most current systems are of this type. With the conductive cable system only available on special order the Ti mesh is the most widely installed on new bridge deck applications. There were 56 conductive cable systems installed and 14 of the coated Ti mesh reported in the survey. Table 2 summarizes the distribution of deck anodes.

The limitations of the conductive cable system
o Increased deadweight
o Durability of cable, especially if damaged
o Increased deck thickness/reduced clearance
o Problems of adhesion of overlays on substructure elements

The limitations of the coated titanium mesh systems
o Increased dead weight
o Increased deck thickness
o Problems with adhesion of overlays on substructure elements

Table 2 - Summary of Deck Anode System Statistics

Conductive Asphalt	53
Slotted and Mounded System	108
Conductive cable System	56
Oxide Coated Titanium Mesh	14

Although there was little information provided in the survey, it is now known that some conductive cable systems have exhibited anode failure. The plastic loses its flexibility, becomes brittle and cracks. Once anode reactions start on the unprotected copper inner conductor, the copper corrodes through and the anode fails. As the conductive cable is a single length there are two connection, one at either end. If there are problems of continuity (e.g. if the cable is not adequately covered by the overlay or if the overlay fails), the cable can be cut and the anode will fail due to lack of continuity in the circuit.

A problem with both the Ti mesh and the conductive cable anode can occur when it is used on substructures. When applied with a sprayed concrete (gunnite or shotcrete) overlay, debonding of the concrete can occur. It is not known what long term effect this has on the performance or durability of the system. However, this phenomenon, observed in CP trials in the UK, has lead the UK Department of Transport to specify conductive paints on substructure CP installations. There is ongoing work to remedy this problem, which will be reported elsewhere.

The expanded titanium mesh with oxide coating is now the main system being applied to deck surfaces. Occasional problems with the concrete overlay suggest that it must be applied with care, but that can be done. Early problems occurred with very thin overlays leading to high resistivity on substructures and to the mesh protruding through the overlay. Currently, thicker overlays are usually applied.

The sprayed zinc system has also been applied to decks, despite its poor wearing characteristics. The sprayed zinc system is described below.

Substructures

The cathodic protection of substructures is much more recent than work on decks. Trials of conductive paints on substructures started in Florida in the 1970s. Coating disbondment occurred in the Florida systems at lower elevations where the moisture content was higher and the coating was exposed to seawater splash. Work continued with Ontario Ministry Of Transportation trials of conductive paints in 1982-1986. Initially these were not very successful. Further Ontario trials found that a series of different coatings applied to concrete lamp posts survived one winter without power, their performance with current applied is being monitored.

Systems installed in Oregon in 1984 to 1985 and Virginia in 1987 are still working well with less than 1% coating loss. Coating disbondment has been noted on footers on a system in Chicago Illinois, where deicing water often ponds. Conductive paints have been used extensively on parking garages in the USA and Canada.

The UK DOT has carried out a four year trial of conductive paint systems on substructures on an elevated motorway, and is currently installing over 220,000 square feet of conductive paint anode systems.

Approximately 20 conductive carbon paint systems have been applied in North America. The total area of substructure protected by CP is 333,600 square feet as reported in this survey, but that excludes a 100,000 sq. ft. installation in Richmond Virginia. Table 3 gives the distribution of substructure anodes.

A problem that has been identified on several structures, is short circuits. For cathodic protection to work, an electronic current must flow from the rectifier, to the anode. It must then convert to an ionic current, and flow through the concrete cover to the rebar, where it is converted back to an electronic current by the cathodic reaction which protects the steel.and flows to the negative terminal of the rectifier. Short circuits through the cover will prevent the protective cathodic reaction from occurring, disabling the system.

The limitations of carbon based paint anodes

- o Requires good surface preparation
- o Cannot be applied to damp surfaces
- o Poor durability in continuously wetted conditions
- o System is likely to require coating after 10-15 years
- o Short circuits to steel chairs and ties protruding from the steel surface can give difficulties in commissioning these systems.

It is likely that short circuits (due to tramp steel) are a problem on many anode systems. They are most commonly observed on paints and other soffit systems where metal in the bottom of the form prior to casting the concrete can cause short circuits. This includes chairs with uncoated feet. There can be considerable cost penalties in removing shorts.

Flame or arc sprayed zinc is another substructure anode of increasing popularity. No problems were identified with this system in the survey.

Table 3 - Summary of Substructure Anode Statistics

Total number of substructure systems	30
Conductive carbon Paints	20
Flame and Arc Sprayed Zinc	7
Other	3

Problems Identified

Of 228 replies to the question "Is the system currently operating as designed?", 205 were said to be working, and 23 were not (10.1%). Three where due to removal of the system (not always deliberately), and one had not yet been commissioned. Of the remaining 18 (no reason was given in one case), nine where due to anode/overlay problems, four were due to power supply or instrumentation problems. One was due to under polarization. This could have been due to lack of power from the rectifier, incorrect setting of the rectifier or high resistance of the anode.

For the different anode systems, three coatings were debonding one conductive cable system had a delaminated overlay, and three polymer slot systems were showing failure. One of the expanded mesh systems also had a debonding overlay and a cast iron anode/conductive asphalt system was showing high resistance after seven years of operation.

Table 4 Causes of Problems

Anodes	6	FL,NY,OH
Overlays	3	AK,SD
Electrical	6	ID,ME,MN,OK...
Underpolarized	1	Alberta/Calgary
Cable connection	1	OH
Short Circuit	1	CT
Not energized	5	CA,MA

Rectifier problems were also identified. In principle these are easily dealt with, as a rectifier can be replaced without disrupting the bridge operation. However it is a costly activity and suggests either poor design, specification or maintenance. All electrical systems have a finite life, and in the case of the older systems in California, rectifier replacement may be expected. Two systems had failed due to power surges. This could be bad luck or bad design. Lightning protection is available for rectifiers (although there is some debate about its effectiveness).

The problems identified here should not be considered to be a definitive overview, but a rapidly compiled global view. Other problems discussed under each anode system will be considered as well as those identified in the questionnaire response.

Costs

A crude analysis of cost is possible by dividing the average system cost of $127,800 by the average system size of 37,065 sq.ft. This indicates an average cost of $3.45 per square foot. This figure is far lower than typical costs of $10-20 sq. ft. quoted in the literature and found by looking at individual costs.

Not all responses included cost, and the items included in the cost were not defined or standardized. Some states, such as Florida, were unable to give costs as they installed their own systems. An analysis of the more recent data from Missouri suggests a cost of approximately $12 sq. ft. for deck systems. This is more comparable with earlier data from the literature. Another major element is what is included in the costs. Some costs were for the cathodic protection system alone, others for the CP system and the overlay. Some included surface preparation, and some included the full job of bridge deck or substructure repair, preparation, CP installation and commissioning.

Survey of Repair and Rehabilitation Methods for Bridges

A survey of repair and rehabilitation options for bridge decks and substructures was carried out as part of another SHRP contact (Chemical and Physical Methods of Rehabilitation, contract C-103). This showed that cathodic protection was considered an experimental repair for bridge decks by 46.4% of the 47 states and 9 provinces who responded, and a standard method of repair by 12.5%. For non-deck applications, it was considered standard by 1 state (1.8%), and experimental by 7 (12.5%).

However, agencies retain a high level of interest in CP, despite its modest level of acceptance, particularly to non-deck elements subject to salt spray and runoff. There is also a perception of CP having an estimated service life of 20 years. This was far higher than for other treatments such as sealers, epoxy injection and concrete patching.

III

Brief Site Visits

Selection and Investigation of Sites

Brief site visits were made to some 49 systems in 14 states and provinces. The investigators took readings and measurements and reviewed the conditions of the systems. Site selection was based on accessibility and getting a broad selection of anode types on decks and substructures, in marine and deicing salt conditions. Investigations were carried out in 14 states, on 30 deck and 19 substructure systems.

System Performance

An anode zone is an electrically continuous area of anode which is separately operated from adjacent zones, with the level of current and voltage set by separate testing. Of the 151 anode zones inspected, 18 (11.9%) had failed by the criteria used by the inspection team.

The 11.9% failure is in reasonable agreement with the overall figure from the questionnaire survey (10.1%). However, these sites were chosen because, according to the questionnaire responses, they were supposed to be operating. Problems were found at the site with several systems thought to be performing correctly by the agency replying to the questionnaire. The percentage failures could therefore be considered to be additive, i.e, 22% failure rather than about 11% in each. The oldest systems investigated were 15 years old, the average age was 7.6 years.

The major problems identified were as follows:

- o Failure of conductive paint anodes under wetting (particularly in the splash zone of marine piles).
- o Pop out of slot systems.
- o Overlay delamination on both decks and substructures, with both the conductive cable and the mesh anode.

The failure of rectifiers, meters, cables, housings, conduits and half cells is often easily remedied without need for traffic control or major expense. It may require better scrutiny of equipment suppliers for design and durability to prevent it recurring or occurring in the first place on new installations. "Permanent" reference electrodes are normally expected to have a life time of up to 5 years in other application where freeze thaw, drying, rewetting and are not a problem as they are on a bridge. A tabulation of problems found is given in Table 5.

Table 5 - Tabulation of problems found

Rust or Spalls in the area		7
System Replaced after accidental removal		3
System found switched off		2
Rectifier Not Working		6
Rectifier Meter Not Working		4
Half Cells Not Working		6
Housings/Conduits failing		2
Cable Damage		2
Anode Damage	Paint	5
	Slot	6
	Cond. Cable	1
	Mesh	1
Overlay damaged		4
Underpolarized		2
High Resistance		8

Current and Voltage Levels

The systems showing high resistance and under polarization may be due to poor design or anode problems. The system resistance (rectifier voltage/current), was generally less than 100 ohms on systems that achieved 100mV decay in 4 hours. Systems with high resistance included substructures that may stay dry for long periods.

The four hour decay criterion is frequently used for assessing adequate polarization of cathodically protected steel in concrete. It is popular because it does not require specialized equipment. The reading is independent of the type or long term stability of the electrode used, and it is easily carried out and understood. However some electrodes display short term instability with age, which makes all criteria measurements erratic.

The logic of the four hour decay criterion is that it shows that the corrosion rate has slowed down. Plots of corrosion rate against polarized potential show that for steel in concrete there is roughly an order of magnitude reduction in corrosion rate with every 100 to 150mV of polarization applied.

Some authors have argued that the figure should be 150mV or more. However, because the polarization decays by 100mV in four hours is usually taken to mean that the total depolarization over a longer period (usually several weeks), shows a far larger decay, usually to a more positive potential than existed before CP was applied.

A thermal sprayed zinc system with a deposit under it was observed. The system was polarizing the steel adequately, but had a high circuit resistance (76 ohms). This result is significant and worthy of further investigation as it is one of the older zinc systems. This is an increasingly popular system, and investigation of the anode may reveal information about the probable lifetime of this system and the failure mechanism.

Figure 2 shows the distribution of current densities found on the systems visited. The investigators considered that most current densities should have been below 0.5 mA/sq. ft. Of a total of 237 readings, only 77 (32%) are at or below 0.5mA/sq. ft., with 44 (18%) over 1mA/sq. ft. If the investigators' view is correct then approximately two thirds of systems are consuming much more current than is necessary to achieve protection.

The main cause of degradation of the system is anode damage, and that is related to the current density, all systems that are operating at too high a level are prone to a shorter anode life than a correctly operated system.

Rust, Spalls and Patches

The observation of rust staining was noted on some structures. This can be due to "tramp" steel corroding, especially if it is in contact with the anode. Although unsightly, this is not a problem, although it can lead to small shallow surface spalls. Problems will arrive if the steel creates a short circuit between anode and rebar (cathode). If this happens then the system will not function properly. Low resistance anodes like arc or flame sprayed zinc will show this problem readily. Other anodes with lower conductivity will hide the problem, which can be more serious.

Another cause of rust is the oxidation of iron containing aggregates. These are unsightly but harmless.

Accelerated anode consumption around patches was noted on some installations. This is discussed further on the Hood Canal, detailed condition survey report in Section IV.

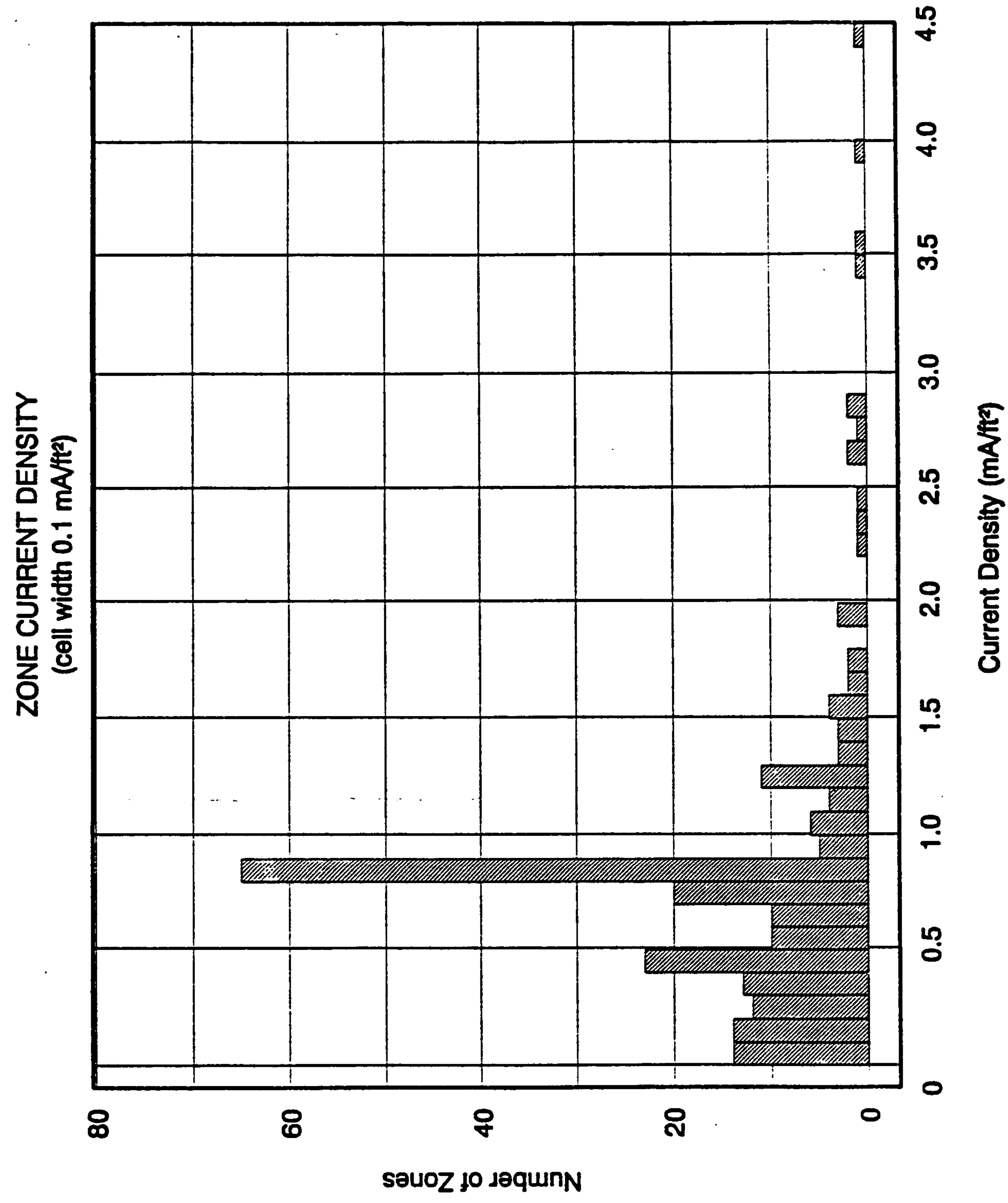


Figure 2 - Population of Current Densities applied to 237 CP Zones.

Half Cell Potential Measurements.

Potential measurements were taken on all systems examined. In some cases this amounted to no more than "on" and "instant off" potentials, and watching for a few minutes to see if the system continued to depolarize. In other cases full 4 hour potential decay curves were plotted. Where systems were found switched off but operable, the system was switched on, and a few measurements were taken after an hour or so.

Interim Conclusions

- Agencies are not always able to maintain systems adequately, and are unaware of failures, including lack of power to the systems. No maintenance has been carried out on some systems, even when problems are minor and easily corrected.

- In some cases, the problem of maintenance expertise occurred when responsibility was passed down to district level. Some districts were able to maintain excellent standards, others were less able. A centralized system often provided more expertise and interest in maintaining the systems.

- Agencies need to have the correct infrastructure to maintain and monitor systems. This will ensure that problems are identified and remedied quickly, and that the correct settings of current and voltage are maintained to that the steel is protected and the system is not overpowered unnecessarily. Staff need adequate training and proper direction on maintenance and trouble shooting.

- o Most systems are performing well, although the level of maintenance is inadequate. Some systems have persistent problems due to poor performance of key components. A badly performing rectifier is more likely to lead to system failure than a damaged anode system.

- o It is not clear whether the failure of permanent, embedded half cells are principally on older systems, or whether there is still poor embedded half cell performance with newer designs. FHWA is presently undertaking research in this area.

- o A circuit resistance (rectifier applied voltage divided by the current) of more than 100 ohms usually shows that the system is no longer polarizing the steel adequately.

- o The two major anode failures were conductive paints in splash and tidal areas on marine substructures, and pop out of slotted systems.

- Other failures were:
  - deterioration of the conductive cable anode,
  - deterioration of overlays on conductive cable and Ti mesh,
  - a case of some debonding and high resistance of a sprayed zinc system.

- It should be noted that carbon based paint and thermal sprayed zinc coating anodes are tolerant of local failure and are easily repaired (although access may be the major cost of repair). This can be an offset against their shorter life.

IV

Detailed Surveys

Selection of Sites

To examine the performance of cathodic protection systems in the field, a detailed site investigation was carried out on six systems. Systems were chosen to represent the different types of anode, environment and age. They were also chosen for their accessibility and the availability of background data on the structure and the system. A list of systems examined is given in Table 6.

Table 6 - Systems Examined in Depth

State/ Prov.	Name	Anode Type & Location	Month/ Yr Inst.	Comments
WA	Hood Canal	Harco Polymer in Slots	6/84	No traffic
WA	Hood Canal	Porter Paint on Bents	8/88	
Alb	H16/Spruce Gr	Cond. Cable, on Deck	8/85	
OR	Yaquina Bay	Porter Paint Coating on beams & soffit	6/89	Active crack Before instl.
FL	Daytona	Paint on Piles	1983	Cracks before Installation.
Ont.	Freemans	Ti Mesh, 2 sources	1988	

Hood Canal Conductive Polymer Slot - Performance of System

This system was the most thoroughly investigated. Examination of the concrete found that it was of indifferent quality, with poor air entrainment (<2% air voids) and some signs of freeze thaw damage. Generally there was no damage or deterioration found around rebar samples taken. There was a change in appearance and concrete failure adjacent to the slot anode, in a zone up to 1/2" wide. This is illustrated in Figure 3.

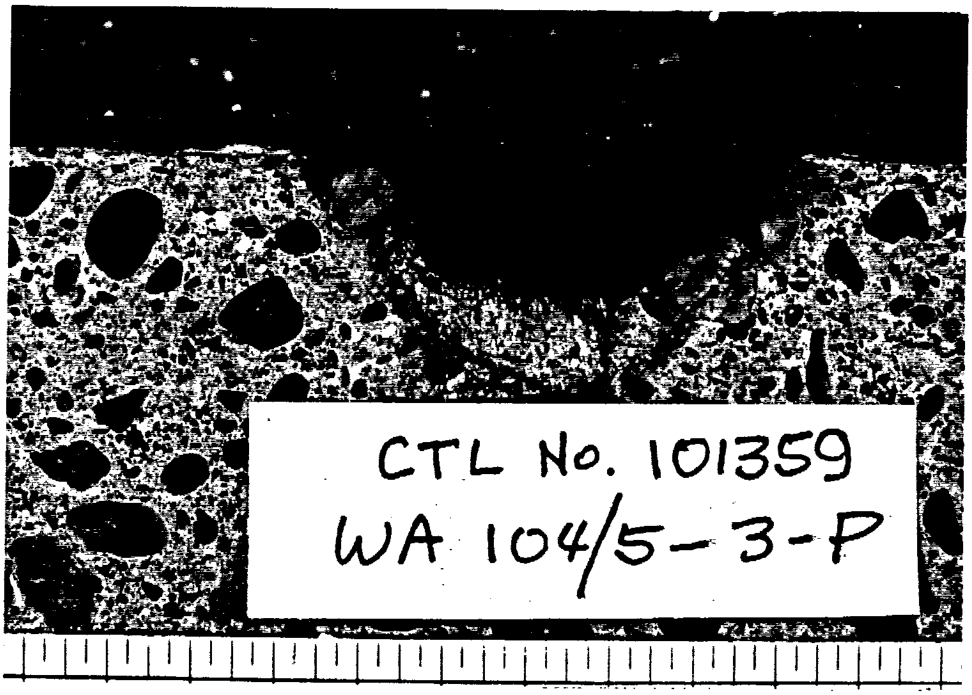


Figure 3 - Deterioration of the concrete around the slot anode from Hood Canal CP System

At Hood Canal the following were recorded on the polymer slot system:

- Chloride Levels
- Concrete condition and makeup
- Potentials
  - Pre CP
  - Instant Off
  - After 3 hours
  - 2 days
  - 7 days
  - 36 days
  - 43 days
  - 72 days
  - 90 Days

- Condition of rectifier and anodes

The following observations were made:

1. The potentials were not distributed in a Gaussian manner at instant off or up to about 36 days. However, dividing the data into subsets for the presence of ponded water or patch repairs did give Gaussian, or normal distributions.

2. After 36 days the potential distribution narrowed to a Gaussian distribution.

3. At 36 days the potential distribution approximates to the pre-CP distribution (which was a skewed Gaussian).

4. For up to 90 days (the limit of data collection), the potentials continue to become less negative, indicating that chlorides have moved away from the rebar, thus changing the environment at the steel/concrete interface. The reduced chloride concentration results in re-passivation of the steel.

5. The damage to the concrete at the anode followed the following pattern, ponded worse than ponded and patched, worse than no ponding, no patch, with no ponding, no patch showing little or no damage. This is consistent with damage being a function of current density or total charge passed. Damage was not extensive in areas where sea water did not pond.

Figures 4-7 show the distribution of potentials for combinations of patched, unpatched, ponded and unponded areas of the slotted system. Ponded areas were those where puddles of standing water formed on a regular basis. The Figures show that the areas without patches or ponded water (Fig 4), had extraordinarily high (negative) potentials, which rapidly fall to be comparable with the others by 36 days (Table 7).

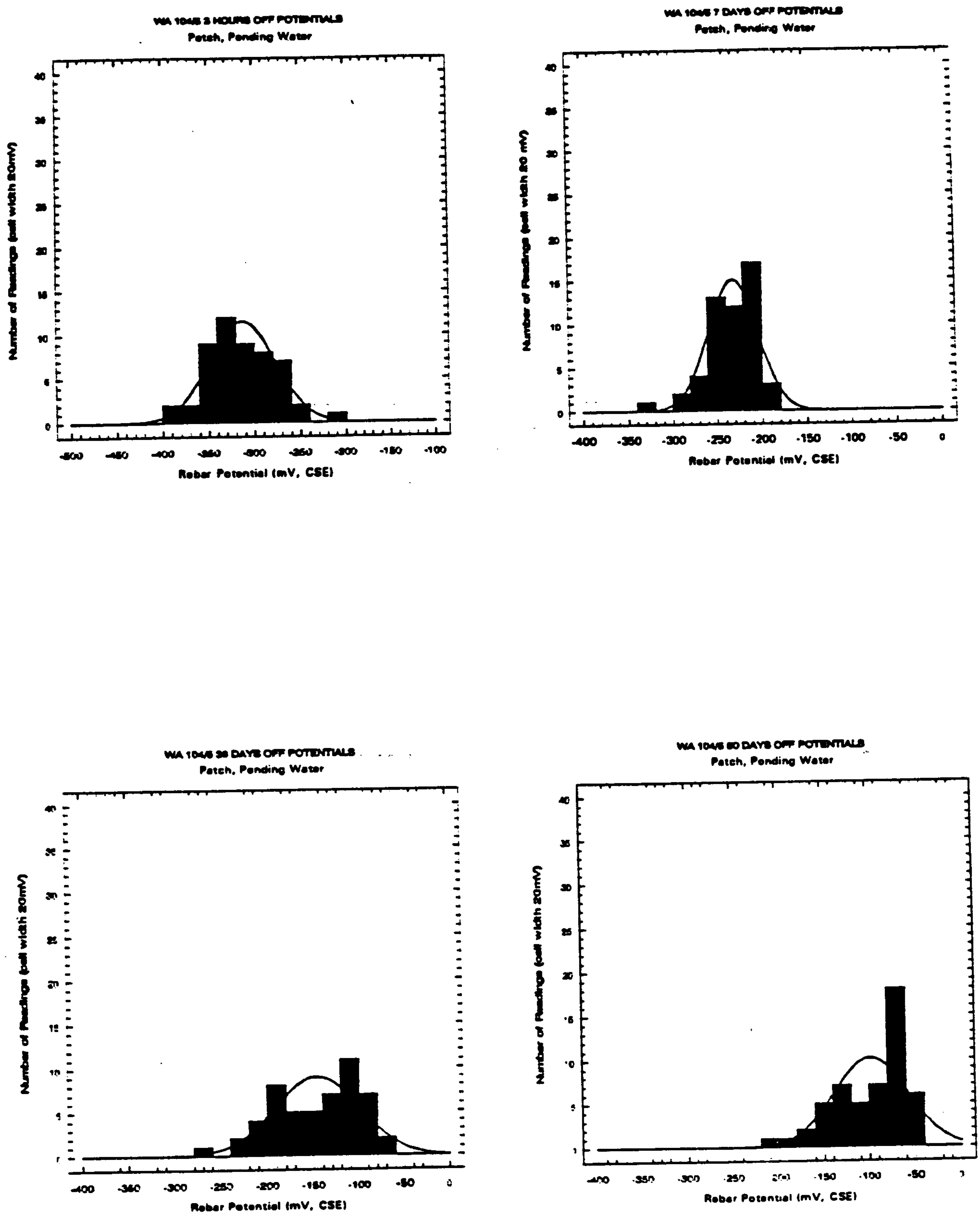


Fig. 4 - Potential distribution against time for Patched and Ponded areas of Washington State Hood Canal Bridge

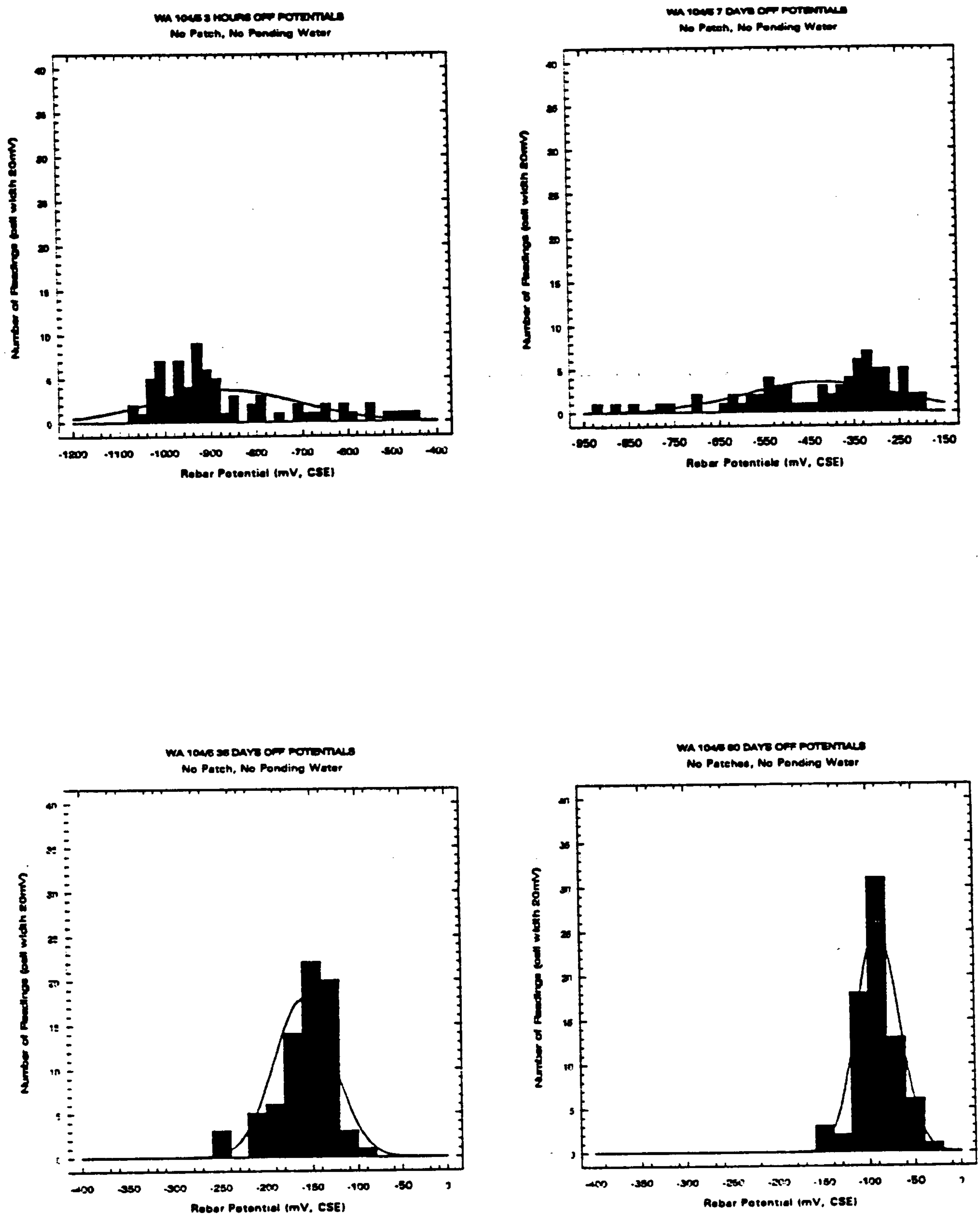


Fig. 5 - Potential distribution against time for Unpatched and Unponded areas of Washington State Hood Canal Bridge

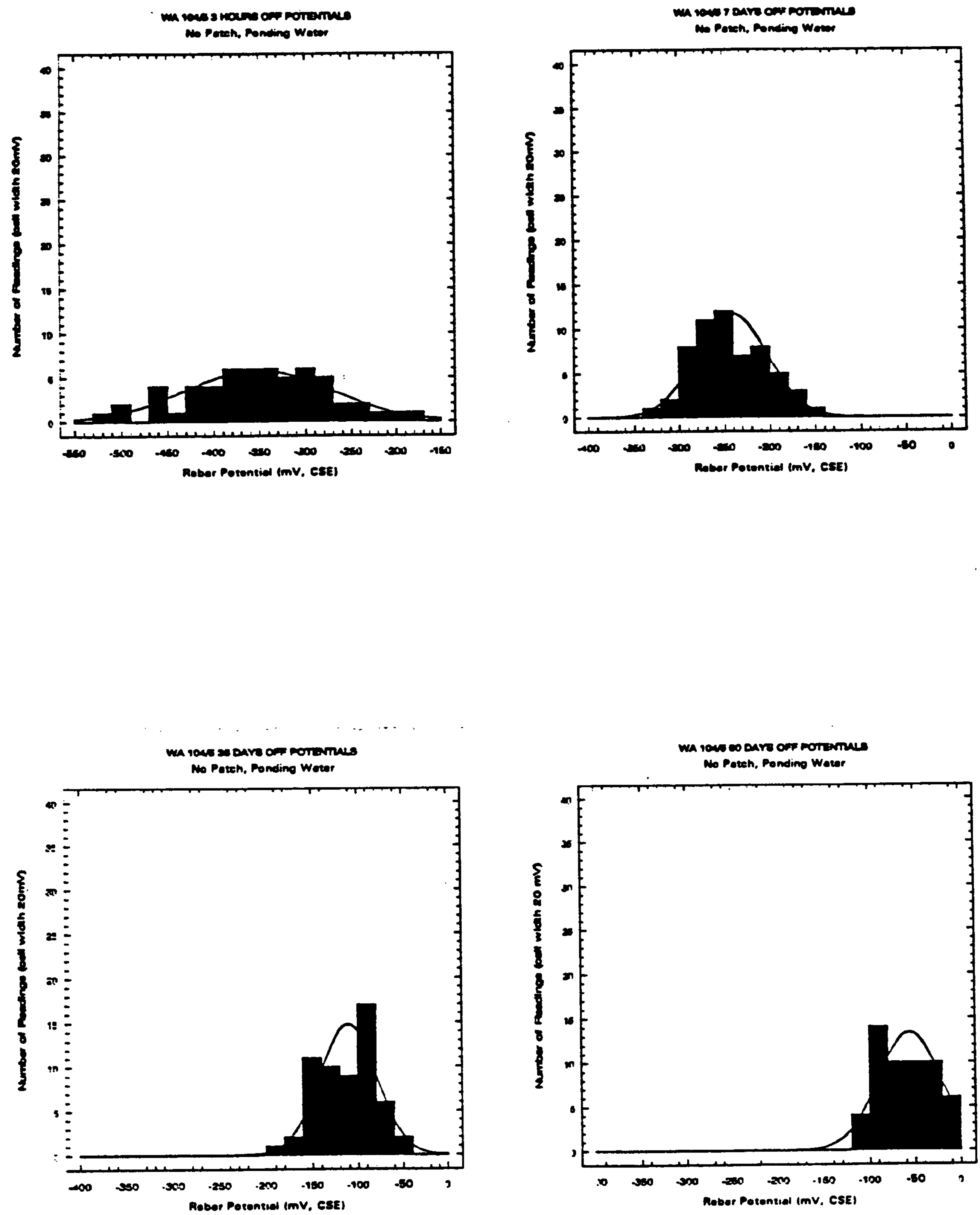


Fig. 6 - Potential distribution against time for Unpatched and Ponded areas of Washington State Hood Canal Bridge

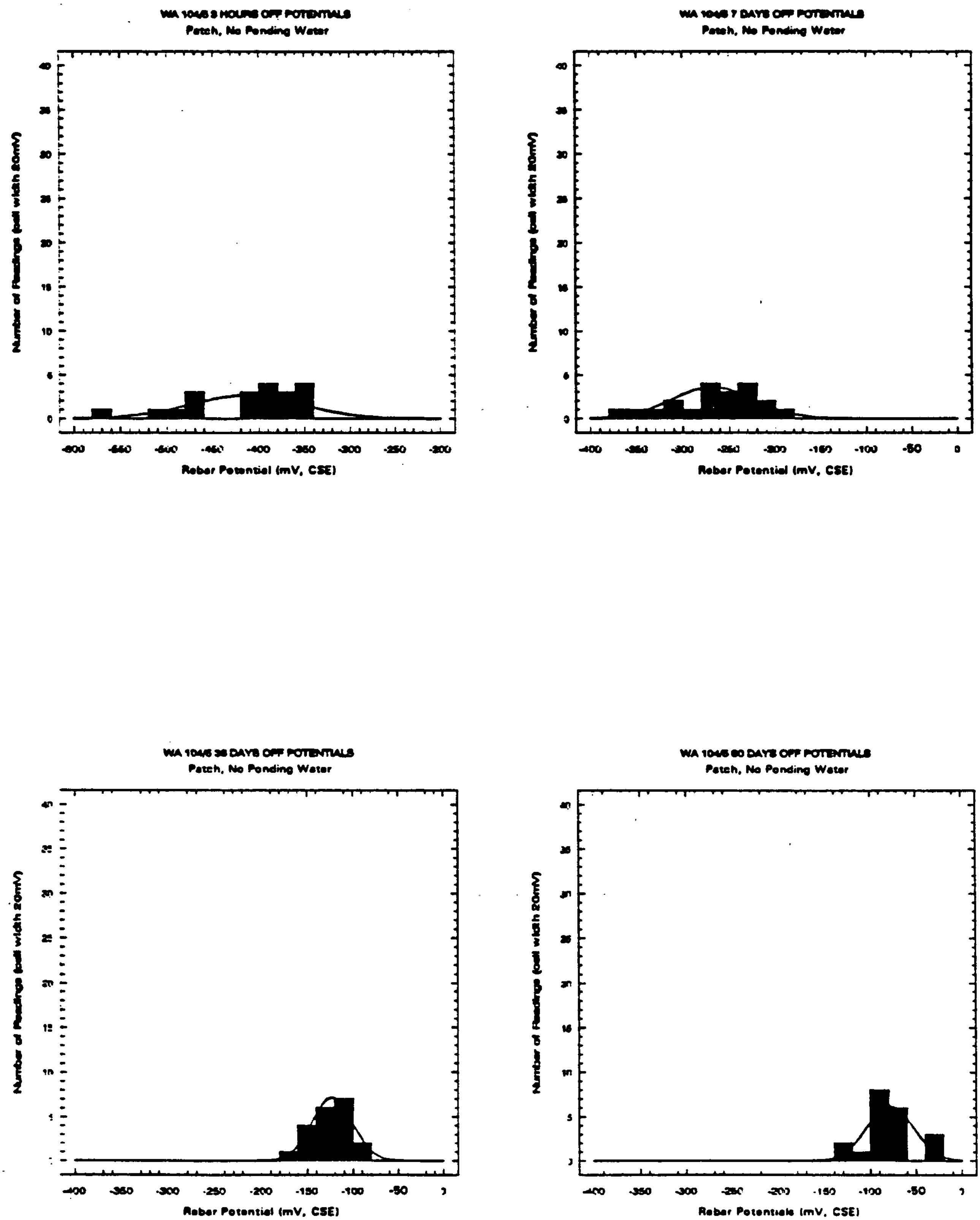


Fig. 7 - Potential distribution against time for Patched and Unponded areas of Washington State Hood Canal Bridge

Table 7, MODE OF POTENTIALS WITH TIME FOR PATCHED & PONDED AREAS (millivolts vs copper/copper sulfate half cell)

Time	Patch Pond	No Patch No Pond	No Patch Pond	Patch No Pond
3 hours	-310	-880	-350	-420
7 days	-240	-430	-240	-260
36 days	-150	-160	-120	-120
90 days	-100	-80	-60	-80

Figure 8 shows a comparison of potentials before CP was applied and after 90 days of depolarization (90 days after switching off the system). This is a comparison of the "natural" potentials before CP was applied and after two years of operation.

Figure 9 is a plot of the average and the median of potential decay with time on a semi-log plot. The fact that it is from 1.5 second off rather than the "instant off" is of no material significance. The data suggest that the average rest or "natural" potential after two years of operation is around 600mV decay, i.e. a drop of about 160mV from the initial rest or "natural" potential.

Discussion of Polymer Slot System Potential Data

The potential data show clearly that for this system, which had been running for six years, the decay found after 3 hours, averaged less than 100mV. This was only a small fraction of the total decay of 456mV found after 90 days. The semi log plot suggests that the ultimate rest or natural potential after full decay would be around -10 to zero mV. However the initial potentials were averaging around -170mV before CP was applied. From this we may deduce that chlorides move away from the rebar and the steel is repassivated with time.

The behaviour of different areas subject to ponding or that had been patched is also interesting. Unpatched, unponded areas were most easily polarised. This is not in line with theory, which suggests that low chloride areas should polarize most easily. The chloride measurements from a patch gave 0.007% Cl^- by weight of cement at 2" and 0.11% at 1.5", against a typical level of 0.2% elsewhere in the deck (about 1lb/cu yd.). It would appear that patches and pond reduce the amount of polarization, but all come down to the same passive potentials after 90 days.

A phenomenon that was observed during the first few minutes of depolarization was the movement of potentials in a negative direction is the less polarized areas, as the system seemed to move towards equilibrium. Some potentials moved up and others down once the constraint of the applied current was removed. Then all potentials moved toward less negative values and converged.

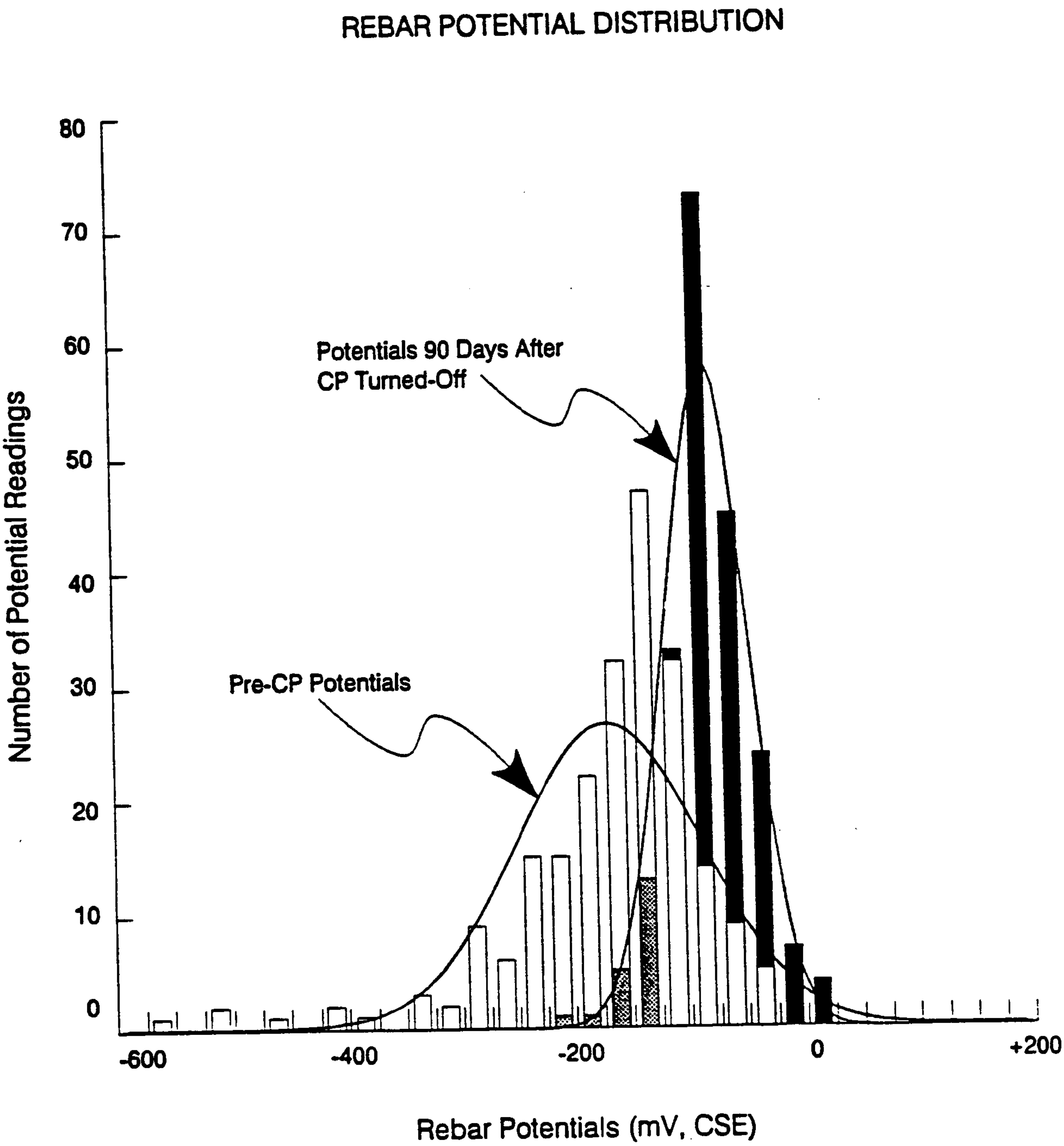


Figure 8 - Potential distributions before Cathodic Protection was applied and after 90 days of depolarization after at least 4 years of operation. Part shaded columns show the separation of the two distributions

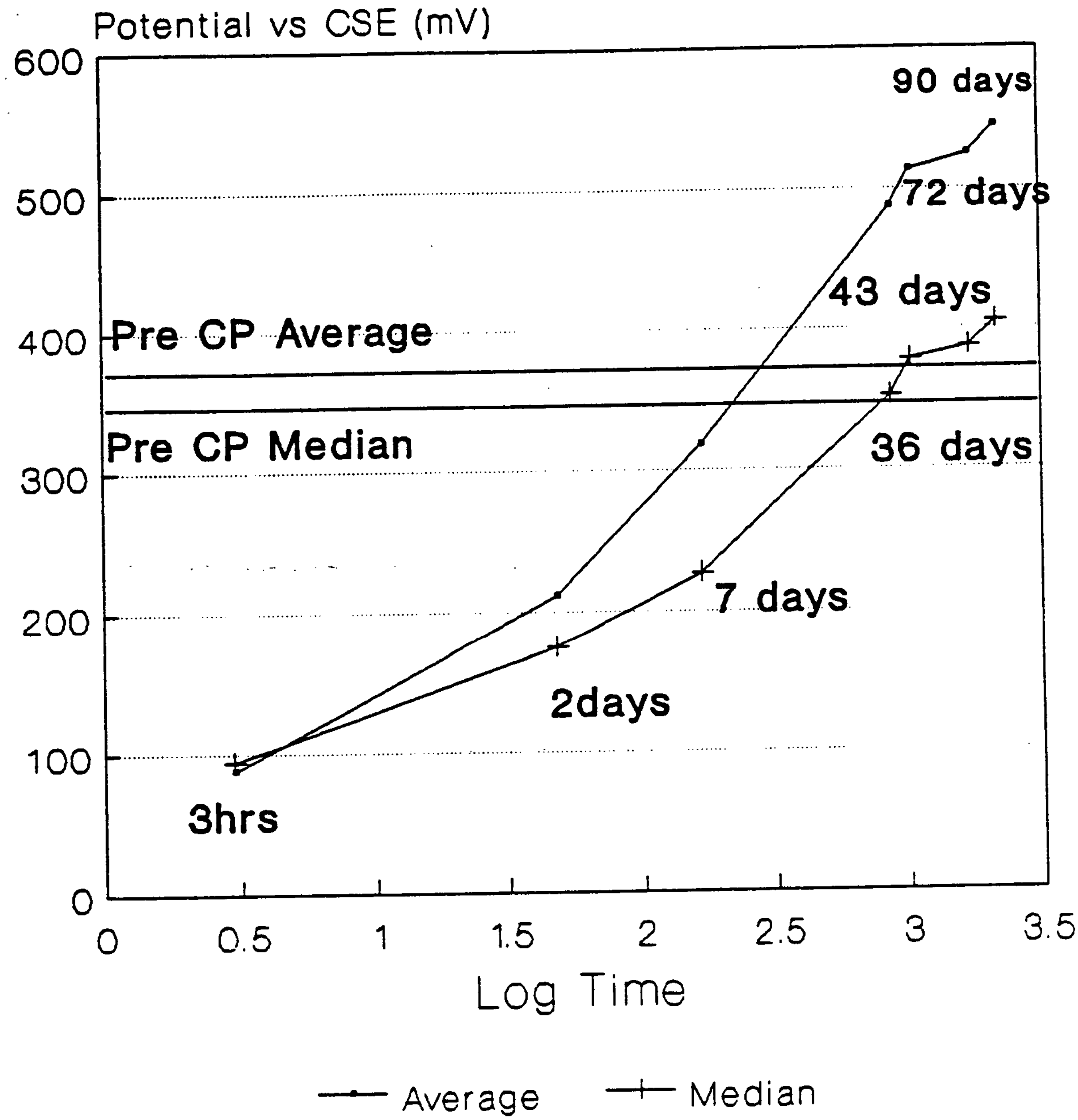


Figure 9 - Potential Decay from 1.5 seconds off, plotted against log time.

This phenomenon is illustrated for the potentials on the conductive coating system on Hood Canal, discussed below.

Hood Canal, Conductive Coating on Columns

The second system investigated on the Hood Canal Bridge, was a series of columns with a conductive coating system applied. The Hood Canal WA conductive paint system was off at time of inspection. It was switched on for testing. A schematic is shown in Figure 10.

Potential measurements were taken on a number of columns. A typical set of data is shown in Figure 11. This illustrates the points made earlier that the potentials can move in the negative direction (Grid location 1.5, 52.5 between 30 and 60 minutes). This is despite an overall decay of 122mV in an hour, 311mV in 7 days and 428mV in 52 days. These decays are well in excess of the 100, 150mV or 200mV shift criteria. Again the convergence of potentials can be seen as they are allowed to decay after switching off the system. One possible cause of this phenomenon is the existence of junction potentials within the cathodic protection circuits. As the current is switched off these potentials are removed and the system responds by producing unexpected potential shifts.

A list of damaged areas was recorded on several columns. These included patches and delaminations particularly at corners, spalls, rust stains and exposed tie wires.

The amount of damaged areas, including patches and delamination was found to be 2.9 sq. ft, 5.25, 5.75 and 8.75 for columns approximately 66 sq. ft. in surface area. Most loss or damage was in small areas that would not affect the polarisation of the steel. Where damage was more extensive, repair is easy with conductive paint type coatings, although the need for surface preparation and a dry surface during application and curing of the paint coating must be emphasized.

A control bent was seen to have 21.18sq. ft. of delaminated area (6.2% of a 341sq. ft. surface area), as well as 65 sq. ft. of patches (19.1%). That is over 40% damage, against a range of 4 to 13% in cathodically protected areas. One would expect little or no damage in a well designed and operated cathodic protection system. However, the use of a conductive paint on bents exposed to water spray, may have lead to some loss of performance. Also, there is a possibility that some of the damage may have been done prior to application of the CP system.

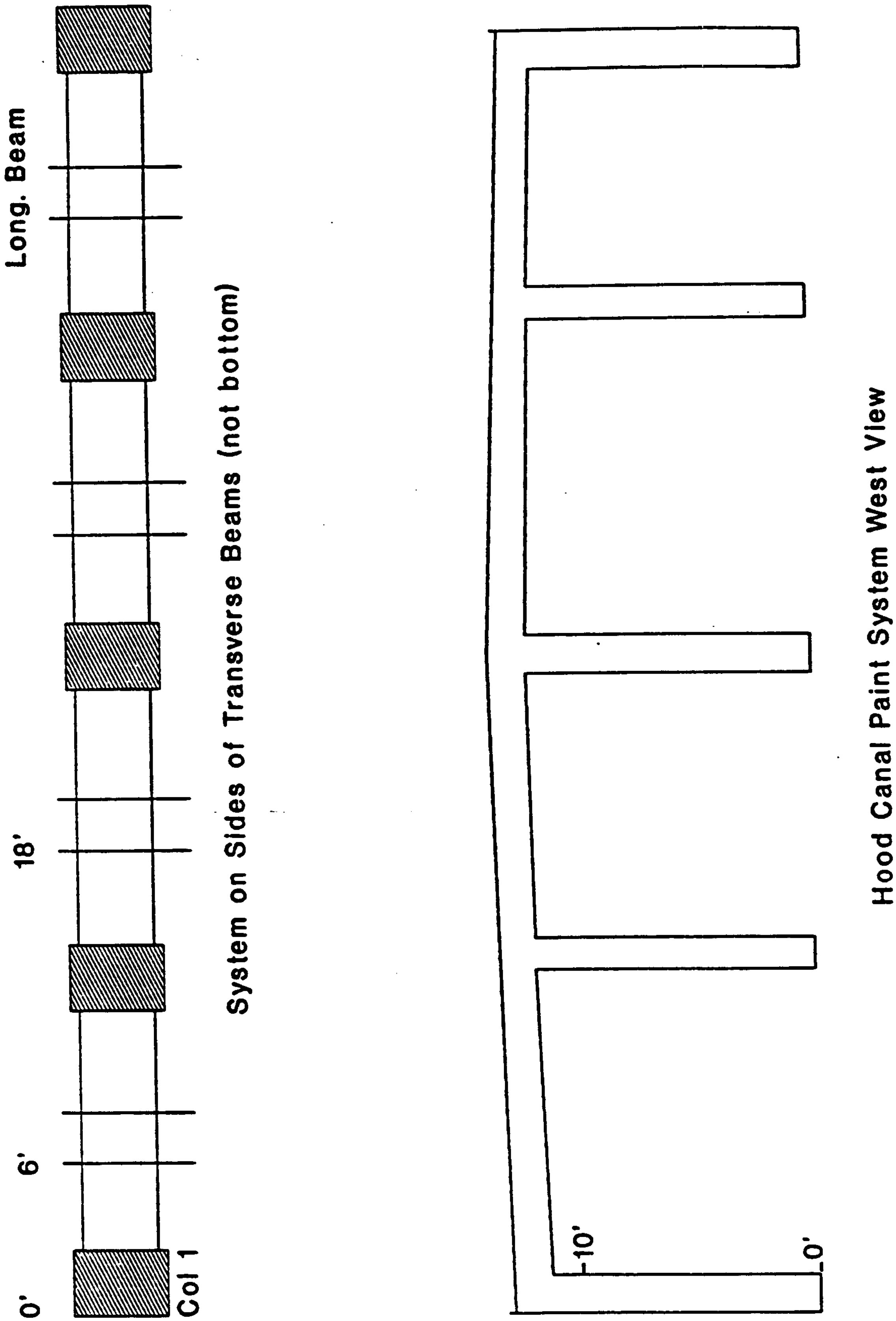
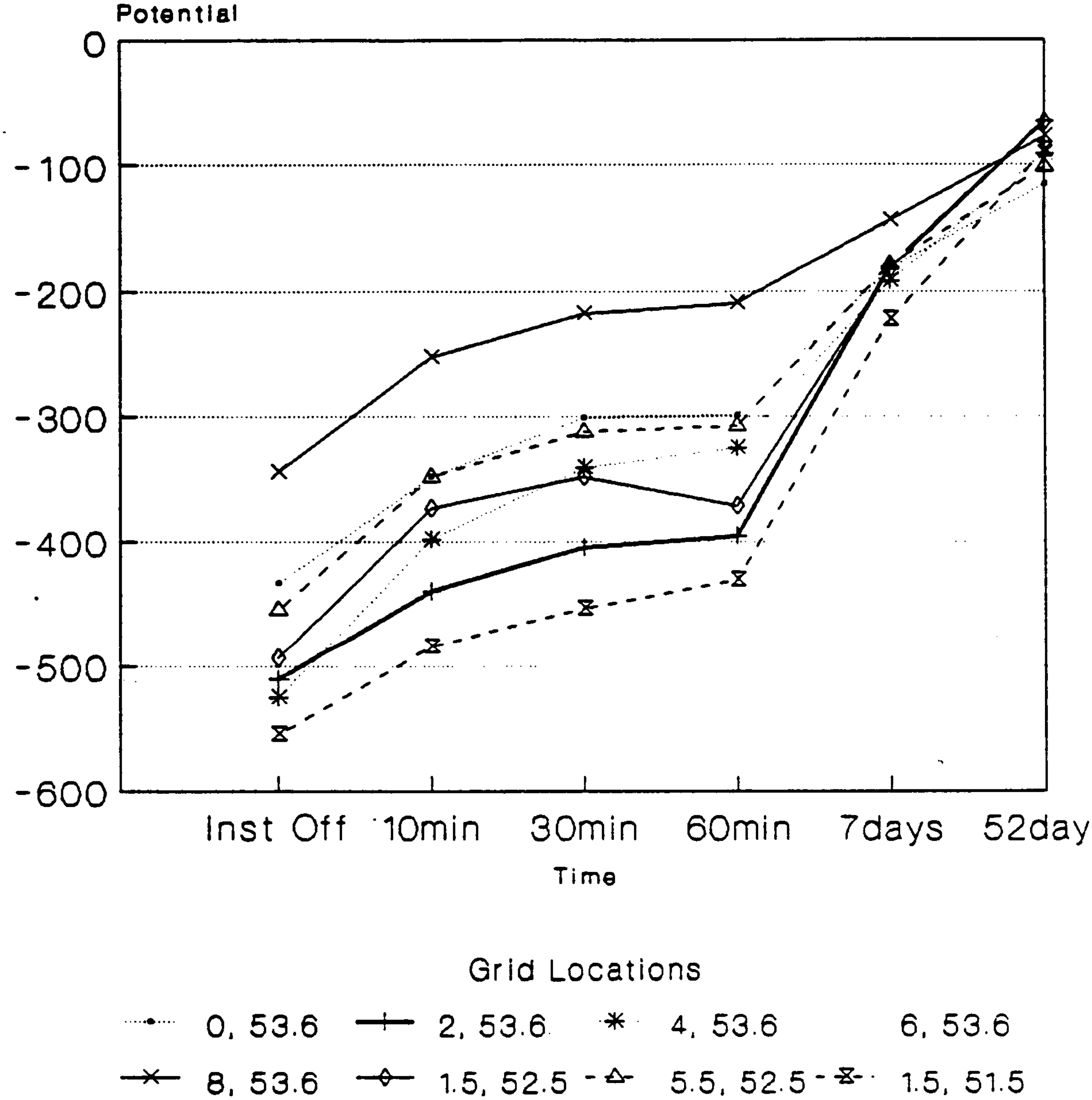


Figure 10 - Hood Canal Conductive coating system on Substructure Schematic of the system.



Col 5 N, recitifier at 1.84V, 33mA

Figure 11 - Potential Decay vs Time for the Hood Canal Zone 1 CP system. Grid locations can be inferred from Fig. 10.

Yaquina Bay, Oregon

This was a conductive coating system applied to the underside of a deck that was suffering from sea salt spray. There were live structural cracks identified prior to application of the CP system.

The initial rectifier was modified after testing and eventually replaced due to poor performance and incorrect rating. A new 8V, 2amp system was installed after one year.The system was energized at 0.5 to 0.6mA/sq. ft. in 1986. In October 1990 the systems were running at 0.27 to 0.39mA/sq. ft.
Potential measurements were taken on the deck and on the soffit.

Figure 12 shows the potential decays after 4 hours. Four readings out of 138 (2.9%) were at less than 100mV decay when measured from the opposite side of the structure from where the anode was applied.

Figure 13 shows a comparison of the 4½ hour and 24 hour decays taken through windows in the conductive carbon based paint coating on the soffit. This shows that while 2 readings out of 32 (6.25%) had decayed by less than 100mV in 4½ hours, All decays were greater than 100mV after 24 hours, and 26 (81.25%) decayed by more than 200mV. The average potential had shifted from -387mV at instant off, to -186mV at 4½ hours to -100mV after 24 hours.

This suggests that, if it is the total polarization of the system that is important, the 4 hr. decay is a gross under estimate of the full depolarization of the system. Therefore 100mV decay in four hours is a suitable criterion for protection, particularly when achieved after several months of operation.

Figure 14 shows a comparison of chlorides from cores taken in areas with and without CP. It shows that the usual diffusion type curve can be seen for the no CP chloride content, whereas a lower level of chloride and a linear profile is exhibited by the chlorides in the core taken from a core with CP applied.

Spruce Grove, Highway 16, Alberta

This was a conductive cable system on a deck with a concrete overlay. Very low potentials and small potential shifts were identified. This may have been due to poor ground connections during testing rather than a problem with the system. Electrical discontinuity was noted in the conductive cable at several coring locations. When a temporary connection was made to the rectifier significant increases in polarisation were noted.

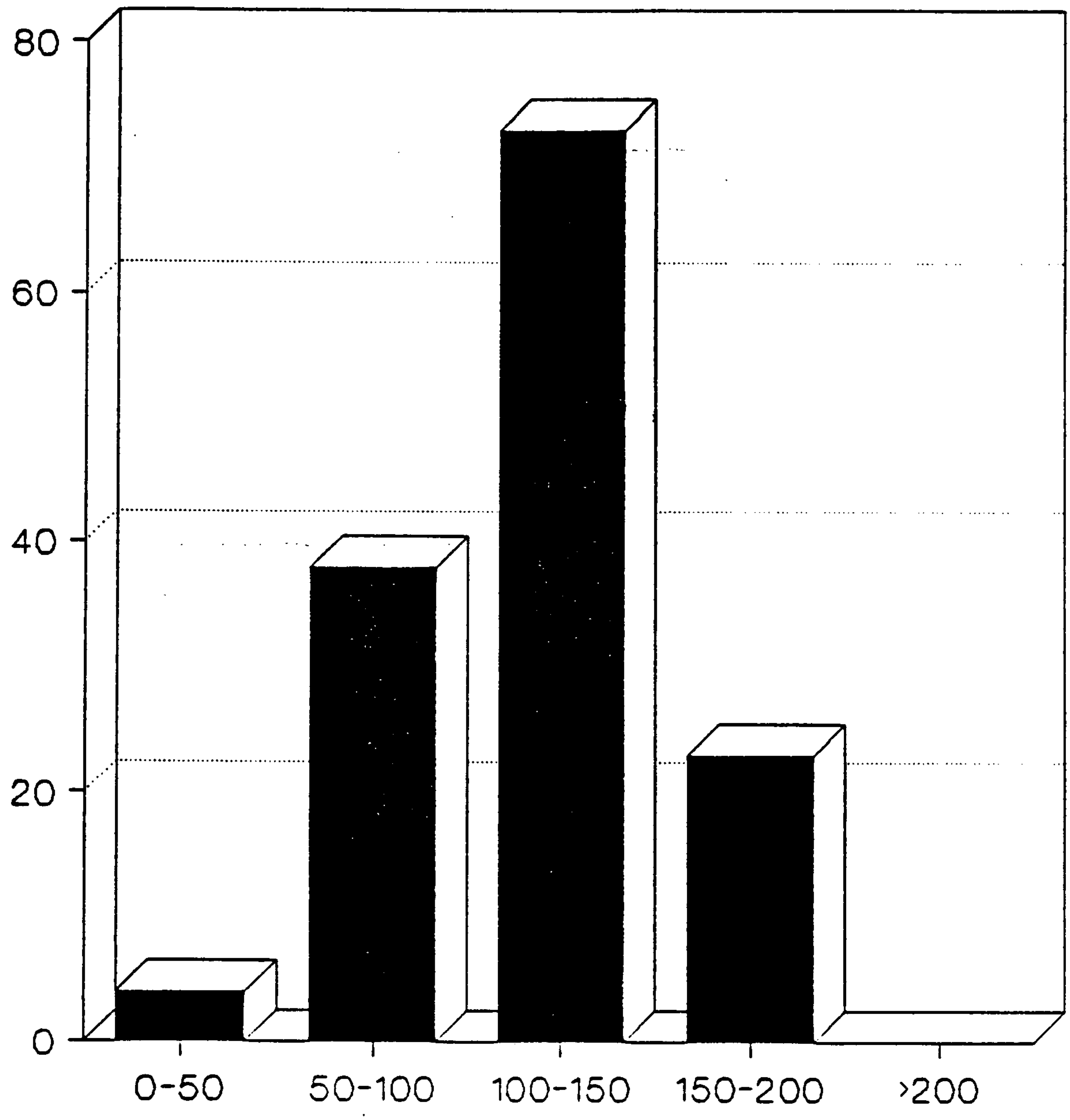


Figure 12 - Potential Decay after Approximately 4 hours, Yaquina Bay Soffit system reading on bridge deck

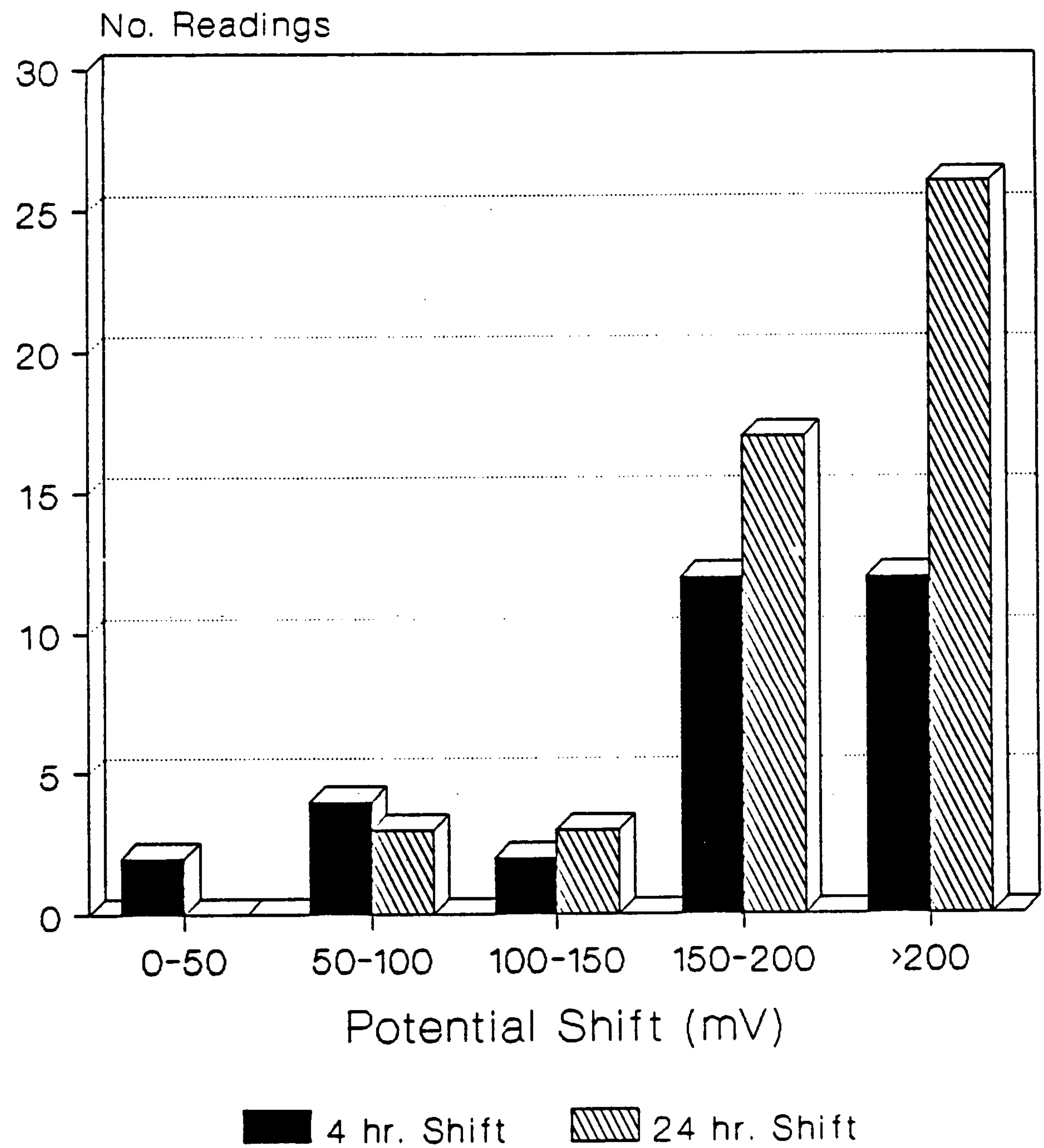


Figure 13 - Potential Decay after 4.5 and 24 hours, Yaquina Bay Conductive Paint on Soffit system, measured on soffit and columns

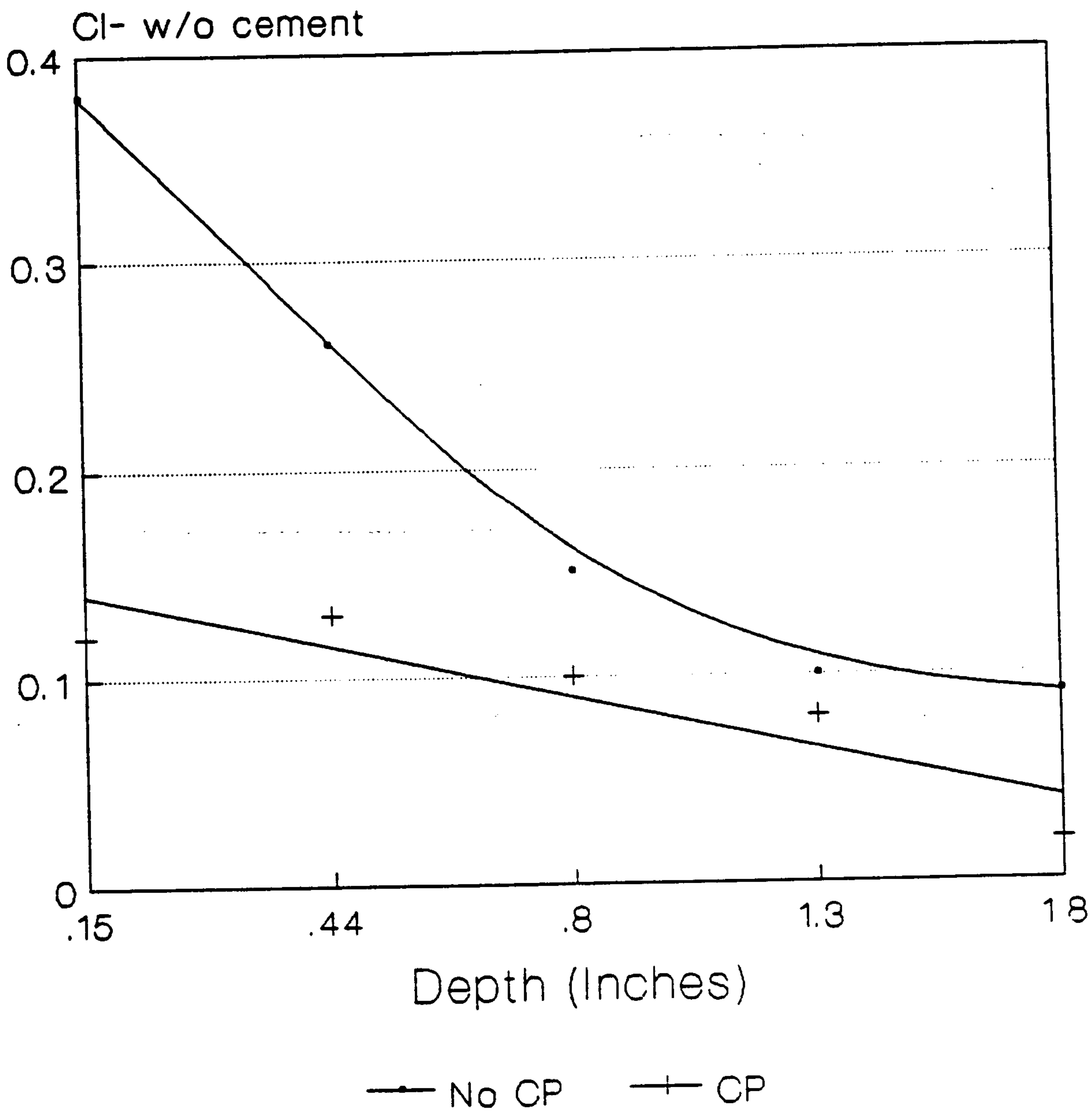


Figure 14 - Comparison of Chloride Profiles, Yaquina Bay Soffit System, CP and non-CP areas.

Samples of the cable removed from the deck were stiff and brittle compared with new sample of cable which had not been in service. No delaminations or spalls were found on the deck. There were a few shrinkage type cracks on the overlay close to the deck expansion joints. A small amount of patching had been done in this area (less than 0.2% of deck zone area in all four zones).

Bridge # 790139, Daytona, Florida

The cathodic protection system was three different conductive coatings applied to 18" piles. The systems were energized in 1983. The coatings had deteriorated near the water line, with 15 to 31% loss on six of the 14 bents surveyed. The platinum/niobium/copper primary wire was unaffected.

Several cracks were found in the concrete, but the survey team considered these to be old cracks, which existed prior to CP installation. There was some cracking due to loss of bond of patch material to the old parent concrete.

The current flow increased as the resistance decreased near the water line. Loss of coating was probably a combined effect of the water on the coating and the high current flow in low resistance areas.

Figure 15 shows the chloride content at different depths for four cores taken from the structure. These show high levels of chlorides. The peak at 0.5-1" down is because chlorides can concentrate due to evaporation just below the surface, but at the surface, the water will wash away excess salt. The linear rise in chloride content for core 15CW1-C, is because it was taken through a patch repair. No chlorides were present in the patch when it was placed in 1983.

Cores were taken four feet above the water line. Measurements of pH showed a low level (5.2-6.8 and 6.8-8.0) near the anode on two cores, but generally, results were pH 9.2-11.0.

Tampa Bay Bridge # 150107

This system consisted of a titanium mesh system and a conductive cable system, applied to bents with piles and going into the water. The concrete overlay was very thin and the anode pattern was visible on both systems.

Both systems exhibited some distress, with anode material visible through the overlay. There was a white paste like material adjacent to the conductive cable anode. A pH of 4.5 was measured at the distressed areas of both systems. Low cover was associated with the conductive cable anode distress. The titanium mesh had areas of high wetness. Both conditions are expected to lead to high current drain.

Both systems showed delamination or debonding of the overlay. The delaminated area amounted to 3% of the total anode area on the Ti mesh system (an 8% increase from the previous year), and the conductive cable system showed 6.3% delamination, a 10% increase from a year before. The current density was 1.5mA/sq. ft. to the cable system (averaged out), and 2mA/sq. ft. for the mesh. Both systems showed more than 100mV decay over a depolarization period of 17 hours.

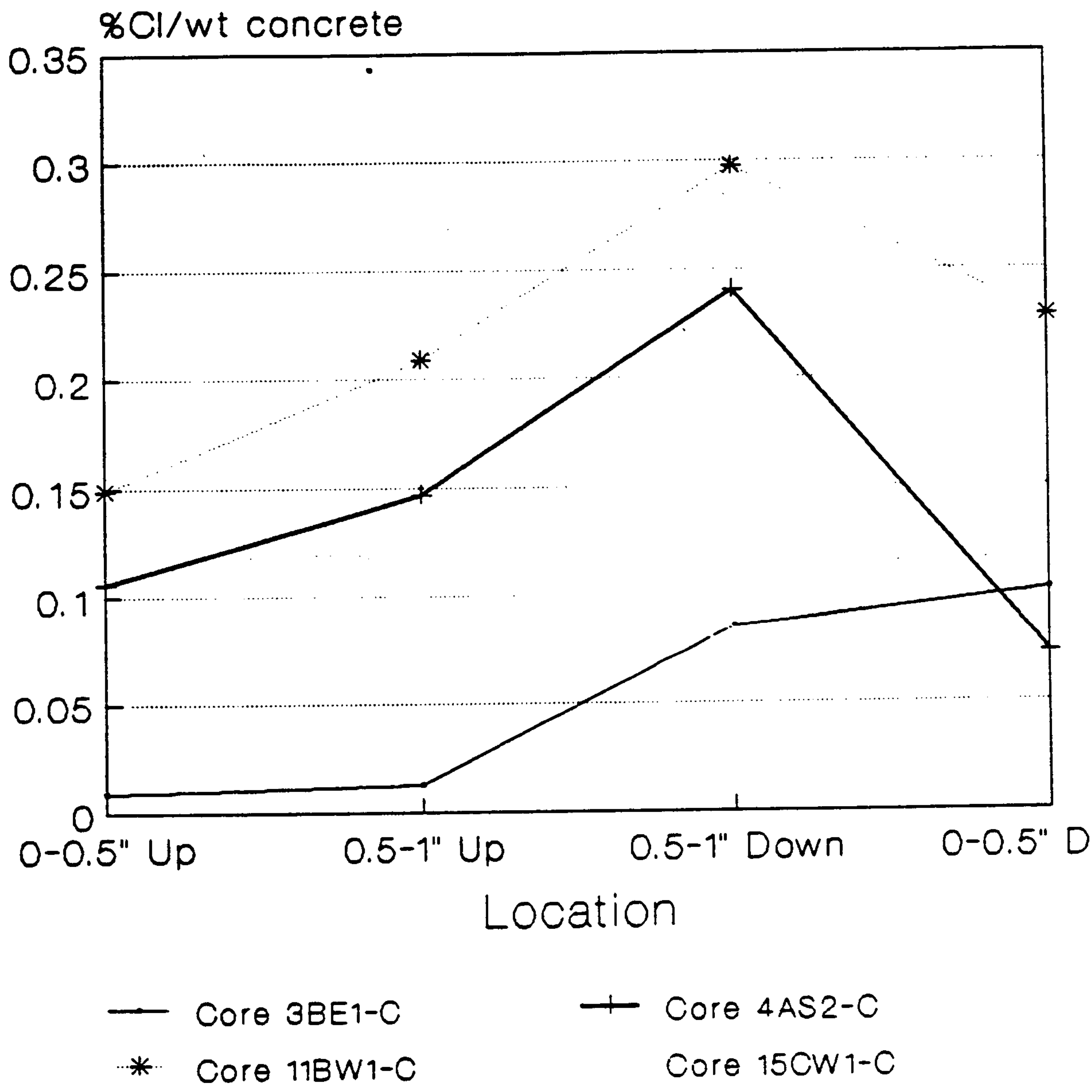


Figure 15 - Chloride Concentration with Depth on Cores taken from Daytona Bridge, Florida

V

Overall Conclusions

The following conclusions can be drawn from the three sets of investigations reported.

System Distribution

- o There were about 300 cathodic protection systems installed on reinforced concrete bridges in the USA and Canada on the major highway systems at the time of this investigation (1989). Two hundred and eighty seven of those systems are reviewed here.

- o The majority of systems are working well, and protecting the reinforcement from corrosion. Of the 10% failures in the questionnaire and 10% found in the field survey, most failures could be easily and inexpensively rectified.

- o Thirty systems are on bridge substructures, with the balance on the decks.

- o Site visits were made to 30 deck and 19 substructure systems in 14 states. Of the 151 zones inspected 18 (11.9%) had failed. This is in addition to the failures reported in the questionnaire, indicating an overall failure rate of approximately 22%.

Anode and Electrical Hardware Performance

- o Anode failures reported in the questionnaire responses
  - Three coatings showing signs of debonding
  - Three polymer slot systems showing pull out
  - One conductive cable with a delaminating overlay
  - One cast iron with conductive asphalt system showing high resistance.

- o Anode failures reported from brief site visits
  - Conductive paint coating failures in splash zones
  - Pop out and loss of anode concrete bond in slot systems

- Overlay delamination on decks and substructures with mesh and cable anodes (not always leading to loss of performance of system).

- o A filed examaniation of mesh and cable systems found debonding of the overlay adjacent cable system and titanium mesh systems on marine piles. Some damage was found on to the cable system anode where there was inadequate cover to the overlay. However, both systems appeared to be working adequately.

- o There were failures of transformer/rectifiers, housings, cables, conduits and embedded probes. Some were due to under design, others were field failures. No systematic reasons were identified.

- o It was apparent that some agencies were unable to provide the necessary maintenance to ensure proper operation of the systems. Some were unaware of failures that had occurred prior to the survey. No maintenance had been carried out on some systems, even when problems were minor and could have been easily rectified.

Control and Performance Characteristics

- o Where anode to rebar resistance exceeded 100 ohms, the system was unable to achieve the 100mV in four hour decay criterion for adequate protection of the reinforcing steel.

- o A detailed examination of a deck system showed that current demand and the polarization of the reinforcement was extremely dependent upon the condition on the zone.

- o Current demand and damage to anode followed the relationship ponded areas>ponded and patched>no pond or patch.

- o Two systems showed a wide range of polarized potentials due to variations across the anode, some potentials moved to more negative potentials shortly after switch off, to "equilibrate" with the others.

- o The potential decay after four hours was only an indication of the full depolarization of the system, which went from 100mV shift in three hours to more than 400mV in 90 days.

- o The average potential after 90 days was 200mV more positive than the potential before CP was applied.

- o A comparison of chloride profiles in CP and non-CP areas on a soffit in a marine environment, shows a depletion of chloride after the application of CP for four years. The profile had changed from the "Ficks Law" diffusion curve to a straight line.

VI

Recommendations

From the conclusions in chapter V, the following recommendations are made.

- There must be adequate mechanisms and budgets for regular servicing and maintenance of CP systems by personnel who are properly trained in cathodic protection. If not, then systems will fail for trivial reasons, and major expense incurred later.

- System design should consider the differing conditions across the structure. Zones should be designed for probable current demand rather than the convenience of geometry.

- Conductive carbon based paint coatings should not be used in areas of continuous or regular wetting. However they are inexpensive to apply and repair, and can work successfully if applied with care and adequate surface preparation. Attention must be given to their maintenance needs.

- High circuit resistance leads to inadequate polarization of the steel. When the rebar to anode resistance exceeds 100 ohms, it the cause should be investigated.

- Given the reduction in chlorides in the concrete and the reduction in the depolarized potential after several years of operation, current demand will decrease with time.

- Current should at all times be kept to the minimum necessary to protect the steel as damage to anodes (particularly carbon based anodes), and to the anode/concrete interface, is a charge related phenomenon.

- It may be possible to run a zinc anode as a sacrificial anode after a short period of operation as an impressed current anode, as long as the circuit resistance remains low (e.g. in marine environments).

- A high resistance deposit was observed between the zinc and the concrete on sprayed zinc systems. This may limit the long term viability of the sacrificial anode system proposed above.

ADDENDUM

CATHODIC PROTECTION WORLD WIDE

Table A1 gives a summary from the questionnaire responses received by July 1989

Table A1 Summary of International Responses

Country	Number	System	Location	# x Area
Austria	1	Ti Mesh	Piles (Brenner)	$1450m^2$
Belgium	None			
Denmark	4	Cable	Piles (marine)	$3x23m^2$
		Ti Mesh	"	$2x23m^2$
		Galv.	Piles (underwater)	$3x23m^2$
		Paint	Tunnel Wall	$1x50m^2$
Finland	1	Ti Mesh	Piles	$31x155m^2$
Germany (West)	2	Ti Mesh	Soffit	$6000m^2$
		Cable	Retaining Wall	$170m^2$
Ireland (Republic of)	None			
Japan	1	Cable)	Beams	Not Given
		Ti Mesh)		
		Paint)		
Mexico	None			
Netherlands	None			
Sweden	4	Ti Mesh	Marine Piles	$1x180m^2$
		Al. galv	Piles below water	$1x70m^2$
		Zn. galv	"	$1x80m^2$
		Magnetite	"	$3x80m^2$
Switzerland	3	Ti Mesh	Piles	$200m^2$
		"	"	$80m^2$
		Cable	Piles	$30m^2$
United Kingdom	4	Cable	Marine Piles	$1000m^2$
		Cable	Beams	$100m^2$
		Paint	"	"
		Paint	"	"
		Tiles	"	"

As waterproof membranes are mandatory on major bridges in most Western countries other than North America, the application of CP to bridge decks is rare. In the two years since the survey, the number of installations in Europe has mushroomed, with major applications on bridge substructures and tunnels. Reports have been published of major installations in Italy the UK.

In Denmark, on consultant reports[1] that there are 40 systems, about 10 of which are trials, and the rest are full scale installations. Not all are applied to highway structures. There are at least four large installations on bridge structures in the UK, and a major motorway interchange is presently having CP applied to over 1000m^2 of support beams.

There are also large numbers of structures in the Middle East with CP applied to them. Most of these are marine structures, and very few are bridges.

Thus it can be seen that cathodic protection is now a routinely applied method of combating corrosion of reinforced concrete bridge structures. It has been applied worldwide to a number of bridge components and other structures.

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[1]Private Communication with author JPB

Bibliography

Preface

This is a bibliography of Cathodic Protection (CP) of steel in concrete. It was compiled by the author over three years in the UK and three years at SHRP. It is not totally comprehensive, and no database searches have been carried out, other than of the author's own 1000 references on corrosion of steel in concrete.

In some cases a brief synopsis of the paper is included with the reference. In all cases a series of key works are included. A fixed vocabulary of key works has been used to make cross referencing more easy. The major key words with reference to CP are:

Anodes	Some information on a particular anode or comparison.
Decks	Information on Bridge Deck CP systems
Substructures/ Nonbridge	Information on systems applied to vertical or soffit surfaces
Criteria	Information on the criteria used to control CP systems
Site/Field	Information about specific installations
Lab.	Laboratory testing associated with CP
Side Effects	The consequences of CP on reinforced concrete
NDT	Nondestructive testing associated with CP installation
Sacrificial	Information about Galvanic/Sacrificial anode systems
Cost	The cost of systems or repair generally
Prestress	Cathodic Protection associated with prestressed concrete

The bibliography was completed and indexed in April 1991, so no references published after that date are included.

John Broomfield

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