DEMONSTRATION PROJECT
SOFFIT CATHODIC PROTECTION SYSTEM
IN A COASTAL ENVIRONMENT

Demonstration Project No. 923
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Final Report

by

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16. Abstract

Part one of this demonstration project evaluated a contractor executed below deck cathodic protection system on two spans of a coastal structure. It was found that the contractor, working with the guidance of a technical representative, very adequately completed the project. The materials and methods were evaluated and the result was a good operating system.

Part two of the project evaluates the durability of the construction materials and operating parameters of the system. The systems, operating in the constant voltage-current limited mode, continued to operate satisfactorily and the 100 millivolt depolarization criteria was satisfied.

During the course of the project the reponse of the Molybdenum trioxide permanent reference cells defraded until they were not suitable for any measurements. System monitoring is now done with fresh copper-copper sulfate half-cells.

Plots of depolarization versus log (time) indicate an alternate procedure for determining depolarization may be possible.

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PART 2 OPERATION AND EVALUATION

INTRODUCTION

Concrete structures in a coastal environment undergo accelerated deterioration when chlorides penetrate the concrete and come in contact with the embedded reinforcing steel. The chlorides lower the pH of the concrete covering the steel and act as a catalyst to produce corrosion of the steel. The corrosion products create internal pressures in the concrete. These internal pressures cause the concrete to crack, spall, and delaminate, a condition which permits more aggressive ions to reach the steel and further accelerate the deterioration.

On coastal structures in Oregon, this type of deterioration is generally limited to the bottom of the deck and beams because salt is not used for control of ice formation. However, where salt is used to control ice formation, similar deterioration effects are observed above and below the deck. Consequently, the problems associated with the deterioration of steel in salt contaminated concrete has been identified as a national problem costing public agencies billions of dollars each year.

Currently, Oregon is faced with extensive repairs on a number of its coastal structures. The results from this demonstration project have contributed to Oregon's acceptance of soffit cathodic protection of reinforced concrete structures as a viable maintenance strategy.

The design, construction and first year of operation of four soffit cathodic protection systems were covered in the report on part 1 of this project[1]. The practicality of a contractor-executed installation was demonstrated and protection criteria was met at lower than expected current densities.

The objectives of the part 2 report on this demonstration project are to:

1. Review the operational characteristics of the systems and equipment for the two plus years (June 1986 to September 1988) following the part 1 report.

2. Evaluate the equipment, materials, and systems.

1 Laylor, H. M., Demonstration Project, Soffit Cathodic Protection in a Coastal Environment, Part 1, January, 1987.

BACKGROUND

The subject structure for this demonstration project is the Yaquina Bay Bridge, located in Newport, Oregon at mile post 141.40 on the Oregon Coast Highway. Two spans on the North end of the structure received cathodic protection. These spans, though not the worst on the structure, were selected because they were relatively accessible from the ground and had a chloride content suited to the use of cathodic protection. The total project provided cathodic protection on approximately 6800 sq. ft.

Four separate systems were installed, each approximately 1700 sq. ft. Each system was to evaluate a different primary anode configuration. Additionally, each system was to have the option of being operated in a constant voltage, constant current, or constant potential mode.

Conductive paint was used for the secondary anode and the primary anode was platinum-niobium wire. Primary anode placement is longitudinally along the bottom of deck between the beams and along the bottom of the beams.

Molybdenum trioxide (MoO_3) permanent reference cells were installed for routine system evaluation and constant potential control.

From June 1985 until May 1986 the systems were operated with non-specification rectifiers. In May 1986, new rectifiers were installed. Also, a secondary junction box was added to facilitate connection of the system components to the rectifier and provide extended data gathering capability.

OPERATIONAL OVERVIEW

The systems were put into operation in June 1985. The rectifiers were set to operate in a constant-voltage, current-limited mode. The initial rectifier settings were based on data obtained from crude E-log I measurements. Six weeks after the systems were turned on, the first depolarization measurements were taken with values as high as 1100 millivolts (mv) being noted. Over the next few months the current density was reduced until the depolarization was closer to the 100 mv criteria (see Appendix 1, Summary of Systems Operating Parameters). By May 1986, operating current densities as low as 0.25 milliamps per square foot (ma/ft^2) were associated with 100^+ mv of depolarization.

In May 1986, new rectifiers were installed and were set to operate in the constant-voltage, current-limited mode. The output voltage of the rectifiers was set so that the current density for each system would be approximately 0.60 ma/ft^2. During the next two years, the current density, at constant voltage, continued a downward trend to approximately 0.40 ma/ft^2, indicating that further polarization was occurring. Depolarization measurements on all systems were greater than the 100 mv minimum criteria.

Even though the rectifiers have performed as programed, minor problems were noted. The waveform of the rectifier output has caused problems in determining the "instant off" voltage with an oscilloscope. Also, moisture from condensation and corrosion of some of the components in the hermetically sealed cabinets is evident. Refer to the "Rectifier and the Rectifier Enclosure" section for a detailed discussion.

By the end of the first year of operation, it was evident that the MoO_3 permanent reference cells were not stable. Depolarization tests with copper sulfate electrodes (CSE) as reference cells showed that the MoO_3 reference cells would only give an indication of depolarization values. In any case, the MoO_3 cells could not be used to operate the rectifiers in the constant potential mode. Later data, taken with a data logger, indicated the MoO_3 cells were giving unreliable depolarization data.

Identification and documentation of the log(time) behavior of the depolarization voltages (CSE) yielded a good method of determining "instant off" values. Further discussion is contained in the "Reference Electrodes and Depolarization" section.

Periodic physical inspection of the concrete did not reveal any delaminations that could be attributed to failure of the system. The only area where delamination was noted was overlooked when the initial repairs were made. This area appears to be getting worse, which was expected, since the impressed current cannot pass through a delamination.

From early in the project, brown staining was noted on the bottom of the beams where systems 3 and 4 were installed. Careful inspection of the stained areas has not revealed any delaminations or loss of coating integrity. The staining has continued to increase, but is considered to be only an aesthetic problem. A discussion of the staining and the results of scanning electron microscope analysis and energy dispersive X-ray microanalysis is in the "Brown Stain" section.

During the course of the project, the top of deck was also monitored. There was no attempt made in the system design or operation to influence the top of deck steel. It was found that soffit cathodic protection has a significant effect on the remote (top mat) steel. For details see the "Top of Deck" section.

Operationally, all of the systems have performed adequately. However, the simplest anode and rectifier configuration performed as well as or better than the more complex ones.

CONCLUSIONS

Cathodic Protection for reinforced concrete structures is a viable maintenance strategy.

EQUIPMENT

Molybdenum Trioxide Reference Cells

Side by side testing with CSE electrodes showed the MoO_3 reference cells to be unsuitable for long term or short term measurements.

Rectifiers

As the rectifiers age, the output waveform degrades, making "instant off" determinations with an oscilloscope unreliable. Filtered DC supplies with interrupters would aid in testing.

MATERIALS

Conductive Coating

No significant deterioration of the coating has been observed.

SYSTEM

Construction, Plans, and Specifications

Contractor-executed installations, with good technical support, are viable. However, a properly supervised bridge maintenance crew could install small systems.

General Operations

The rectifiers operated satisfactorily in the constant-voltage, current-limited mode. From all indications, the systems are providing protection for the steel.

General Operations, cont.

The simplest anode configuration performs as well or better than the other configurations evaluated. See figure 1 below.

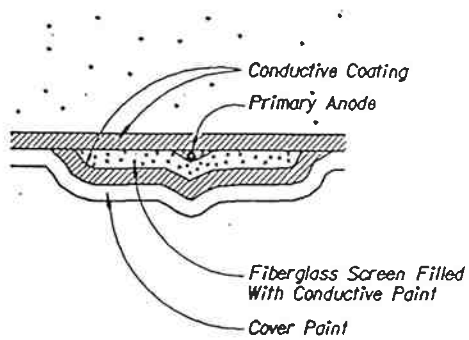


Figure 1

Log(time) Depolarization and "Instant Off"

Plots of depolarization voltage versus log(time) provide a method of determining the "instant off" voltage that is at least as good as that found using an oscilloscope.

RECOMMENDATIONS

EQUIPMENT

Further study of rectifiers, especially the switching type, should be investigated. This would provide improved output waveforms and make filtering much cheaper and simpler.

Stable permanent reference cells are needed. The double junction silver-silver chloride cells currently available look promising.

Rectifier enclosures should be heated to prevent condensation.

SYSTEMS

More log(time) studies should be made on other structures to verify this method of determining "instant off" and depolarization.

The "criteria for protection" should be examined. Behavior of the re-polarization curves suggests that an alternate "criteria for protection" may be developed. This would be based on the concept that, during impressed current operation, the chlorides migrate away from the steel and the pH at the steel becomes high enough to maintain passivity. The criteria for protection at that time would be to: "provide a potential that would suspend the chlorides away from the steel." This might be accomplished at much reduced voltage and current levels. Another possibility would be to operate a metallized zinc system in the impressed current mode and, after a period of time, convert it to a "passive" system.

Part 1, published in 1987, included the recommendation that the primary anode wires in the deck section could be omitted. The redundancy of having primary anodes on both the bottom of deck and the bottom of beams may be desirable. Also, this configuration minimizes the primary anode current and may result in improved overall performance.

DETAILED EVALUATION

RECTIFIERS AND THE RECTIFIER ENCLOSURE

The four rectifiers[1] currently being used are housed in a common enclosure and mounted on a common panel. System operating voltage, amperage and permanent reference cell potentials can be read directly from the meters on the panel. The specifications for each rectifier unit are:

Voltage	- 8 Volts, max.
Amps	- 2 Amps, max.
Mode of Operation	- Constant Voltage
	- Constant Current
	- Constant Potential
Output Characteristics	- Short Circuit Protection
	- Lightning Protection

Since their installation in May 1986, the rectifiers have operated in a constant-voltage, current-limited mode. Because of the erratic permanent reference cells, the constant potential mode has not been evaluated. The rectifier's performance has been generally satisfactory except as noted below.

The rectifier is a fairly conventional, full wave regulated power supply design and has a pulsed DC output. CAD reproduction of the original rectifier output, taken from pictures of oscilloscope traces (upper trace), and the accompanying permanent reference cell voltage (lower trace) are shown in figure 2. The reproduction in figure 3 is of the rectifier output after approximately 2 years of operation.

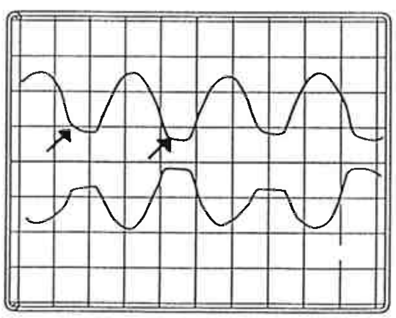


Figure 2

CAD Reproduction of the Original Rectifier Output (upper) and a Permanent Reference Cell (lower)

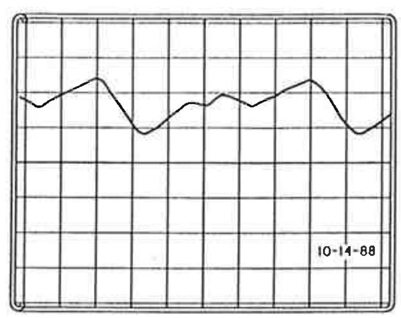


Figure 3

CAD Reproduction of the Rectifier Output After 2 Years of Operation

1 The term "rectifier" as used in the cathodic protection field refers to a "regulated power supply". Regulated power supplies are much more sophisticated than a simple rectifier.

The part of the curve indicated by the arrows in figure 2 are the "off" points of the direct current pulses. The corresponding points of the reference cell trace coincide with the "instant off" voltage. Since the adjacent "off" points are of different magnitude, it is clear that one or both of the triacs[2] used in the control circuit are leaking during the "off" period. This makes "instant off" determinations, for this type of rectifier, unreliable. Reliable "instant off" voltages can be obtained by physically disconnecting the anode lead wire from the rectifier. Turning the system off may not be an appropriate alternative to disconnecting the anode wire, since the "off" impedance characteristics[3] of the rectifier are unknown and may affect the depolarization.

In order to correct this problem, a rectifier with a filtered output and an "interrupter"[4] circuit could be considered. This would enable the operator to make reliable depolarization measurements without removing any wires.

An alternative to determining "instant off" as described above may be a log(time) method as discussed in the "Instant Off" section.

In the future, consideration should be given to switching-type[5] regulated power supplies. These supplies are reliable, smaller, lighter and less expensive than conventional supplies. Their reliability is reflected by their widespread use in personal computers.

2 A triac is an electronic switch that is turned on and off by the electronics to control the magnitude of the average output voltage.

3 An example of this would be when the rectifier output is capacitively filtered. The "instant off" reading would be shifted due to capacitive discharge.

4 An interrupter is a device that can be connected to the output of the rectifier that enables the user to control the rectifier "on" and "off" times. Traditionally, it has been used to detect stray current interference on structures that are near, but not part of, the cathodic protection system. Because the switch is usually the positive mechanical type, it would be useful in determining "instant off" on any type of rectifier.

5 See also "Regulated Power Supplies", third edition, by Irving M. Gottlieb, Howard W. Sams & Co., 1982.

Also new in the regulator (rectifier) field are small, lightweight DC to DC converters that offer the desired control, high reliability and high efficiency. Use of this type of regulator suggests the possibility of having a large, centrally located rectifier with slave regulators. This would eliminate the necessity of running 118 volt AC to the rectifier sites on the structure.

Another rectifier related problem that has been noted is condensate and corrosion on some of the components in the "hermetically sealed" cabinets. To correct this problem, thermostatically controlled heating strips can be installed and set to maintain a relative humidity in the cabinet of 50% or less. This would virtually eliminate any corrosion of the components.

CURRENT DISTRIBUTION IN THE SYSTEMS

When the rectifier was changed in June 1986, an auxiliary junction box was required to accommodate all the wiring. Extra shunts were included so that current throughout the systems could be monitored. The beam and deck anodes have separate shunts, as do the beam and deck rebar returns. The schematic for the shunts in the junction box is shown in figure 4 below. Typical results are in table 1 following the figure.

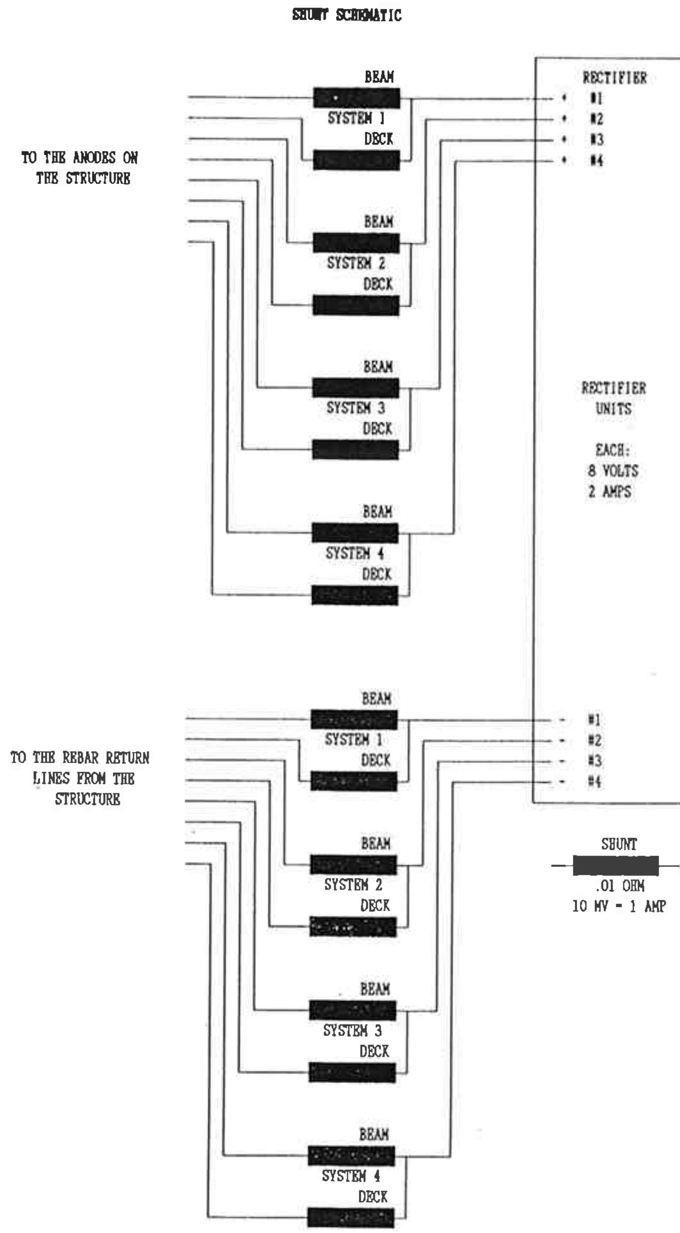


Figure 4

DISTRIBUTION BOX SHUNT CONFIGURATION

Table 1

CURRENT DISTRIBUTION

SYSTEM		1	2	3	4
ANODE AMPERAGE -	BEAM	0.43	0.48	0.45	0.64
(05/21/86)	DECK	0.33	0.51	0.34	0.53
	TOTAL	0.76	0.99	0.79	1.17
REBAR RETURN -	BEAM	0.26	0.54	0.35	0.63
	DECK	0.56	0.46	0.43	0.56
	TOTAL	0.82	1.00	0.78	1.19
DIFFERENCE, ANODE - REBAR[1]		-0.06	-0.01	0.01	-0.02
SYSTEM		1	2	3	4
ANODE AMPERAGE -	BEAM	0.39	0.22	0.55	0.84
(03/27/88)	DECK	0.36	0.51	0.00	0.00
	TOTAL	0.75	0.73	0.55	0.84
REBAR RETURN -	BEAM	0.26	0.38	0.24	0.46
	DECK	0.56	0.33	0.30	0.42
	TOTAL	0.82	0.71	0.54	0.88
DIFFERENCE, ANODE - REBAR[1]		-0.07	0.02	0.01	-0.04
SYSTEM		1	2	3	4
ANODE AMPERAGE -	BEAM	0.36	0.40	0.54	0.80
(06/23/88)	DECK	0.32	0.40	0.00	0.00
	TOTAL	0.68	0.80	0.54	0.80
REBAR RETURN -	BEAM	0.23	0.42	0.23	0.43
	DECK	0.50	0.42	0.29	0.39
	TOTAL	0.73	0.84	0.52	0.82
DIFFERENCE, ANODE - REBAR[1]		-0.05	-0.04	0.02	-0.02

1 Examination of the data shows that the net current from the anode circuit to the rebar return (cathode circuit) is not zero. This suggests that some of the current is leaking off to other grounds. The rectifier does have a common earth ground adjacent to system 1, a condition that would explain the higher system 1 differences. Small variations, up to 0.02 amps, can be attributed to variation in the resistance of the shunts.

Examination of table 1 shows zero values for the anode current to the deck in systems 3 and 4 on 3/27/88 and 6/23/88. The deck primary anode had been purposely removed from the circuit to see if operation of the system from the beam primary anode would affect the operation of the systems. The data indicates there is no significant change in the ratio of the beam and deck return currents. Depolarization data and physical survey data did not indicate any problems. Since the brown stain started to appear on these systems before the deck primary anodes were disconnected, there is no reason to attribute all the staining to the anode configuration. The conclusion is that the conductive coating as a secondary anode performs well and displays excellent throwing power[1]. This fact is also evident by the relatively good balance between the current to and from the deck and beams.

Even though operation of the system is certainly possible with the deck primary anodes removed from the circuit, consideration should be given to including them in future designs. The additional cost of the deck primary anode material and installation is a very small part of the project cost. The value of the redundancy and lower primary anode currents, which may reduce the rate of staining, should be considered.

1 Throwing power is an expression used in cathodic protection work to describe the ability of the anode system to distribute current uniformly to all elements of the system.

REFERENCE ELECTRODES AND DEPOLARIZATION

MOLYBDENUM TRIOXIDE PERMANENT REFERENCE ELECTRODES

Before the systems were energized, the installed MoO_3 electrodes were compared to fresh CSE. The CSE equivalent could be obtained on seven of the eight electrodes by adding -300 mv to the measured potential of the MoO_3 electrode. The standard deviation for the seven electrodes was 16 mv. The eighth electrode displayed open circuit behavior.

Early in the project, permanent, long-term drift of some of the molybdenum trioxide (MoO_3) reference electrodes was noted. At first it was believed that the permanent drift did not affect short-duration depolarization measurements. After about three years of operation, erratic behavior during short duration measurements was noted.

To better understand the MoO^3 electrode behavior, simultaneous potential measurements were taken adjacent to the MoO^3 electrodes using fresh CSE. Holes were drilled next to the permanent electrodes to the median electrode depth. Care was taken to not interfere with the permanent electrodes. The data, taken with a data logger, was uploaded to a computer and plotted.

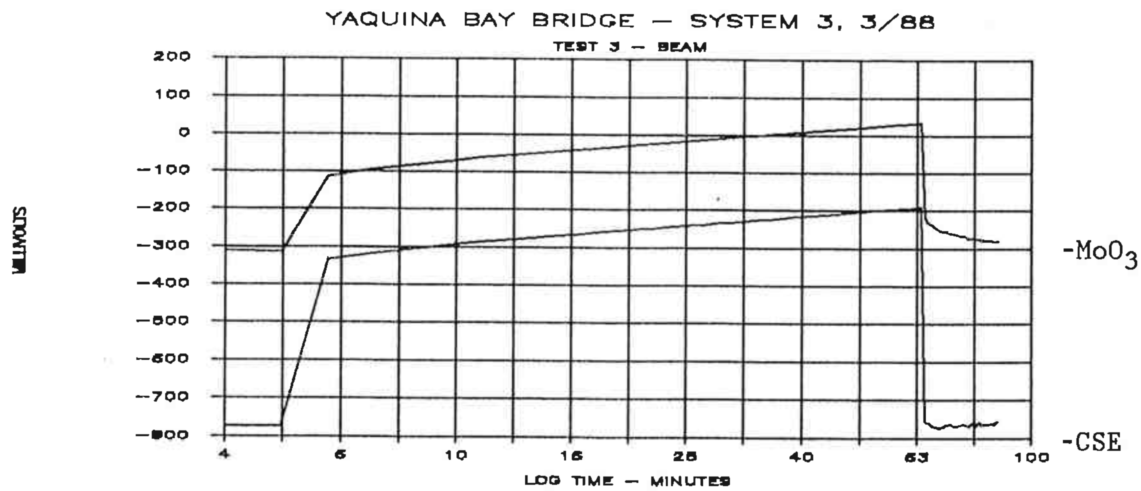
The first set of data was taken in March 1988. The sampling time interval was one minute. The systems tested were permitted to depolarize for 1 to 1 1/2 hours. Each test (Table 2) was performed on a different MoO_3 cell with an adjacent CSE. The results indicated problems with some of the cells.

Table 2
DEPOLARIZATION DATA, MARCH 1988

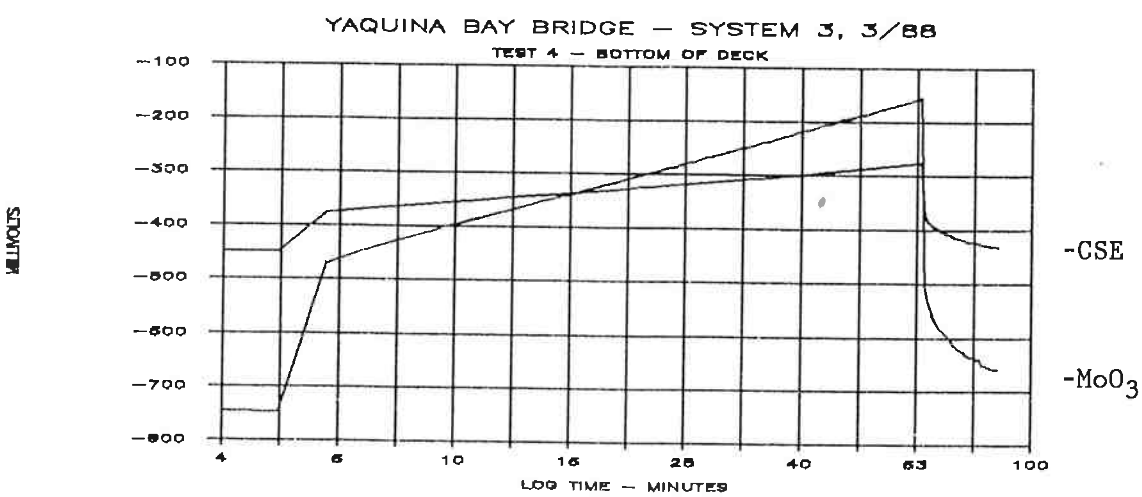
TEST	CELL TYPE	"INSTANT OFF" POTENTIAL	DEPOLARIZED POTENTIAL	CHANGE IN POTENTIAL	TOTAL "OFF" TIME MINUTES	DIFFERENCE IN CHANGE CSE - MoO^3
1	MoO_3	-244	-89	144	80	
	CSE	-489	-334	155	80	11
2	MoO_3	-240	-47	193	80	
	CSE	-432	-338	94	80	-99
3	MoO_3	-115	34	149	65	
	CSE	-335	-191	144	65	-5
4	MoO_3	-470	-156	314	65	
	CSE	-337	-276	101	65	-213
5	MoO_3	-172	-48	124	90	
	CSE	-444	-303	141	90	17
6	MoO_3	-283?	-48	235?	90	
	CSE	-464	-338	126	90	-109

The odd numbered tests were on the beams and the even numbered tests were on the bottom of deck. The beam electrodes are reasonably well behaved, even though they are not linear with the CSE. The deck electrodes in these tests were typically much more erratic than the beam electrodes.

The permanent reference cell and CSE potentials versus time for tests 3 and 4 are shown on graphs 1 and 2. The plot in graph 2 shows a major discrepancy between electrodes.

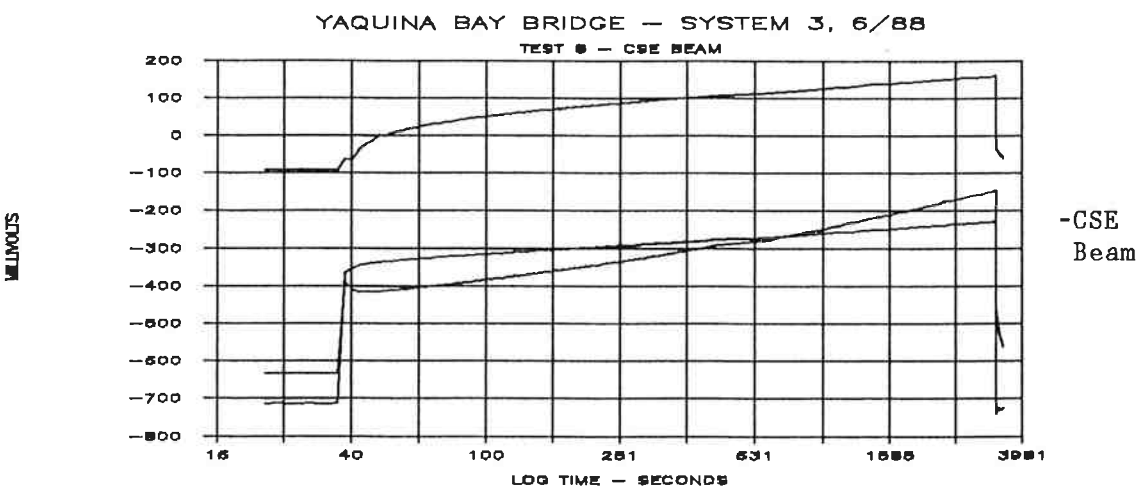


Graph 1



Graph 2

System 3 was retested, test 8 (Graph 5), so that it could be compared to the March data. Clearly what happens in the first minute after the system is turned off is significant and, depending on the instruments used, could be misleading.



Graph 5

From the comparison between the MoO_3 and the fresh CSE electrodes, it can be concluded that the MoO_3 cells are no longer suitable for either short-term or long-term testing or constant potential operation. Reliable, permanent reference electrodes are needed.

"INSTANT OFF" AND DEPOLARIZATION

"Instant off" potential is the measured potential of the local cathode with respect to a specified local reference cell, when no impressed current is flowing in the system.

Some problems associated with the determination of the "instant off" voltage have already been discussed (see the "Rectifier" section, pages 8, Figures 2 & 3). Other methods, such as "open the circuit and take the value when the needle first slows down", clearly involve operator judgement.

A large part of this study involved taking depolarization measurements. Consequently, an attempt was made to correlate depolarizing potentials versus time with electrical (electronic) analogues. This was done by regression analysis, using SAS (Statistical Analysis System), for functions associated with electrical analogues. The best fit found was potential versus log(time). The r-squared values were from 0.97 to 0.99^{+}. Note that the potential versus log(time) is often associated with the discharge characteristics of a battery.

Graph 6 is a plot of the beam potential referenced to CSE versus log(time) on a beam in system 2. The r-squared value for this fit is 0.99. Examination of the plot shows a lack of linearity in the first few seconds. This brings up the question: what is the correct "instant off" potential? There are at least three possibilities:

1. The first detectable break in the "off" potential line (point A in graph 5).

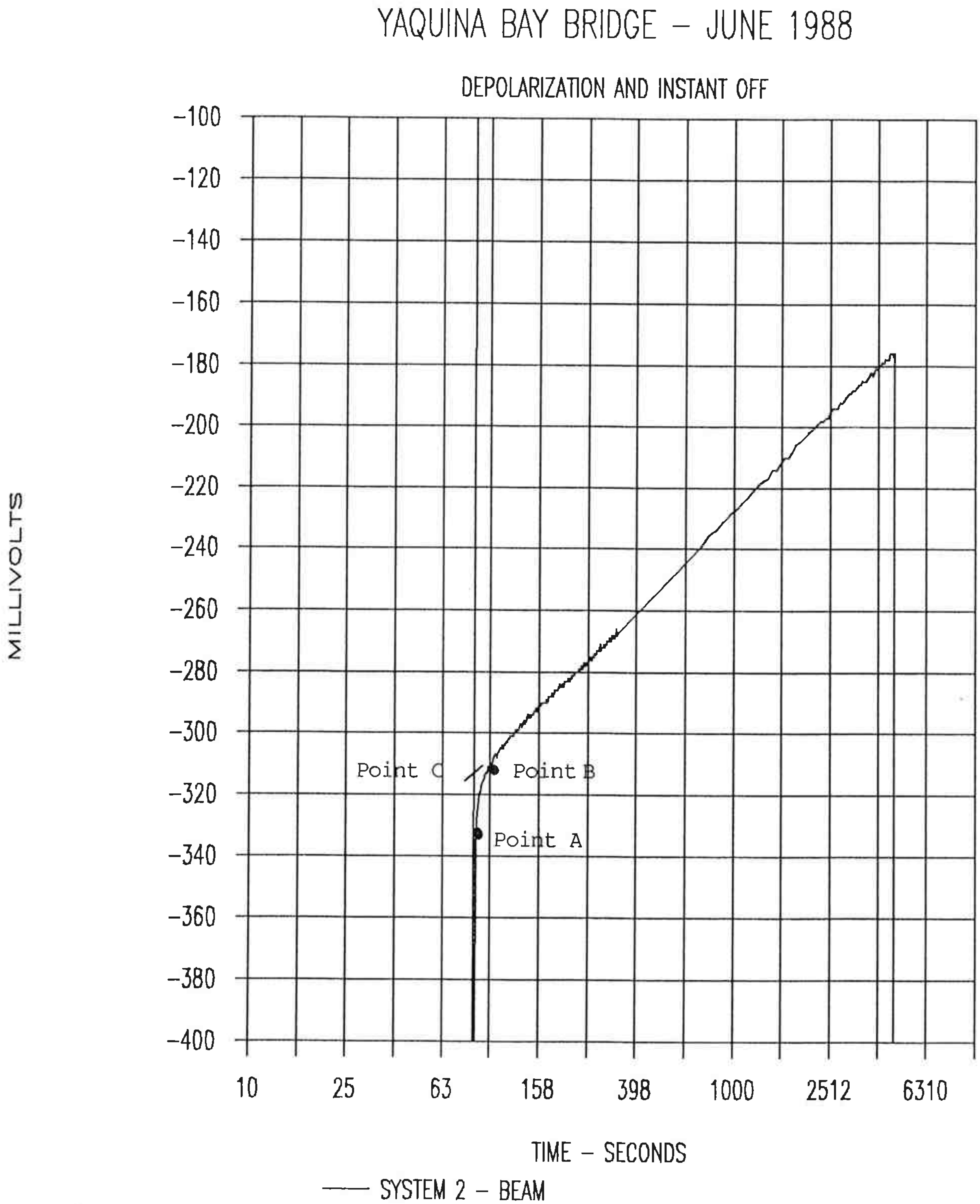
2. The point at which linearity begins (point B).

3. The intersection of the projection of the straight line with the "off" time line (point C).

The third possibility, which is clearly defined, may be useful in estimating depolarization against the 100 mv criteria.

If it can be shown that the potential versus log(time) relationship is valid for all reinforced concrete structures, the estimation of the "instant off" value may be simplified and performed with a simple high impedance[1] digital multi-meter and timer.

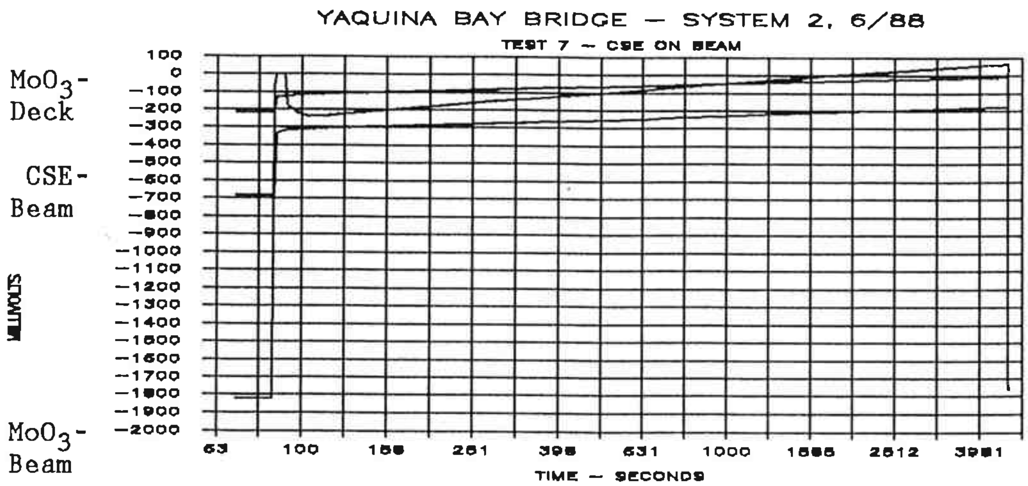
1 ASTM C-876 requires 10 megohm minimum input impedance for measurements involving CSE.



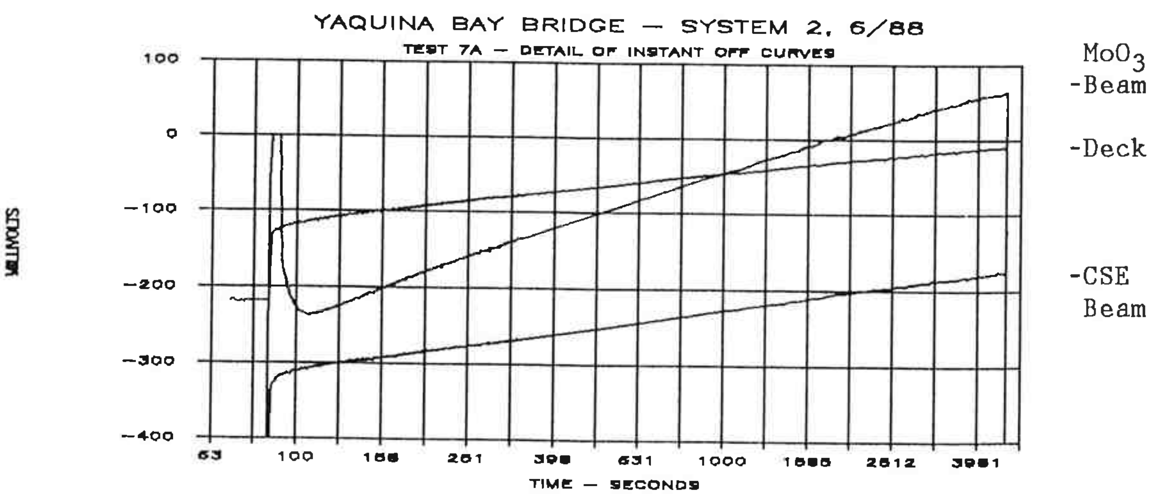
Graph 6

"INSTANT OFF" AND DEPOLARIZATION

To better document the behavior of the permanent cells, more data was taken in June 1988. The same holes were used, except the deck electrode did not have an accompanying CSE. To get more detail, the sampling rate was set to one second. Tests 7 and 7A, (Graph 3 and 4) are of the two MoO_3 electrodes that were not tested in March. Note that the deck electrode is better behaved, while the beam electrode is erratic (the wiring is **NOT** reversed).



Graph 3



Graph 4

One possible test method would be as follows:

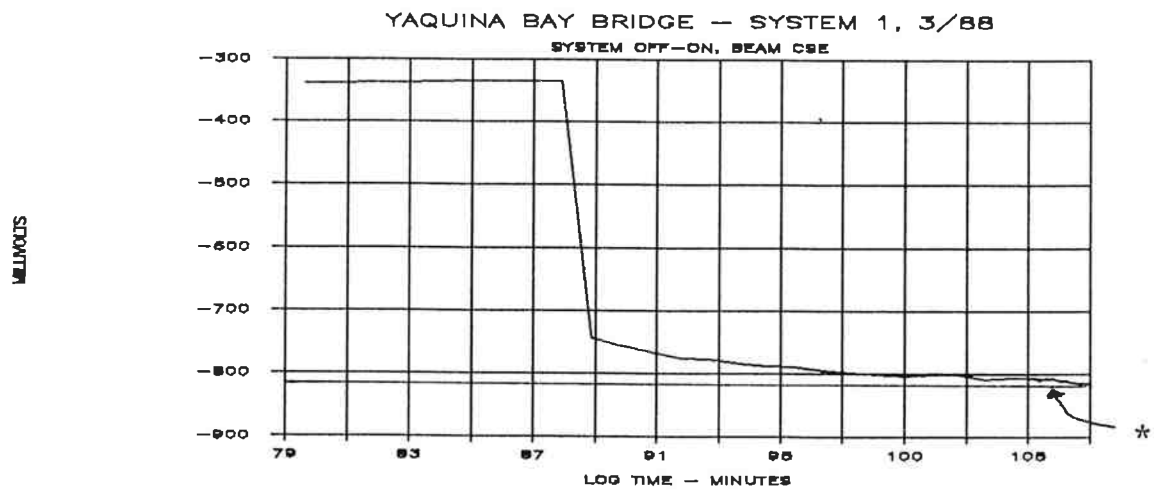
> Start the timer. Turn off the system(s) and record the elapsed time. Measure the potentials at several time intervals during the test. Plot the potentials versus time on semi-log paper. Draw a straight line through the data points and a vertical line at the time the system(s) were turned off. Take the estimated "instant off" potential from the graph (point C). The total depolarization for the test could be the last measured potential subtracted from the "instant off" taken from the graph, or simply an estimate based on the slope of the line.

The ability to determine the "instant off" potentials after the system has been off for a short period of time would enable a single operator to perform multiple depolarization tests simultaneously.

RE-POLARIZATION

When a system is originally turned on, polarization continues for a long period of time. After the majority of the polarization has occurred, the time to re-polarize, after an off period, is much shorter.

Graph 7 is typical of the CSE response when a system is turned on after an off period, e.g. some depolarization occurs. The relatively short period of time that is required for the system to return to the pre-off polarized state suggests a mechanism quite different from the one that controlled the original polarization. This rapid re-polarization may be the result of the chlorides in the concrete migrating away from the rebar as a result of the applied potential during routine operation.



Graph 7

*Voltage before Depolarization

Re-polarization

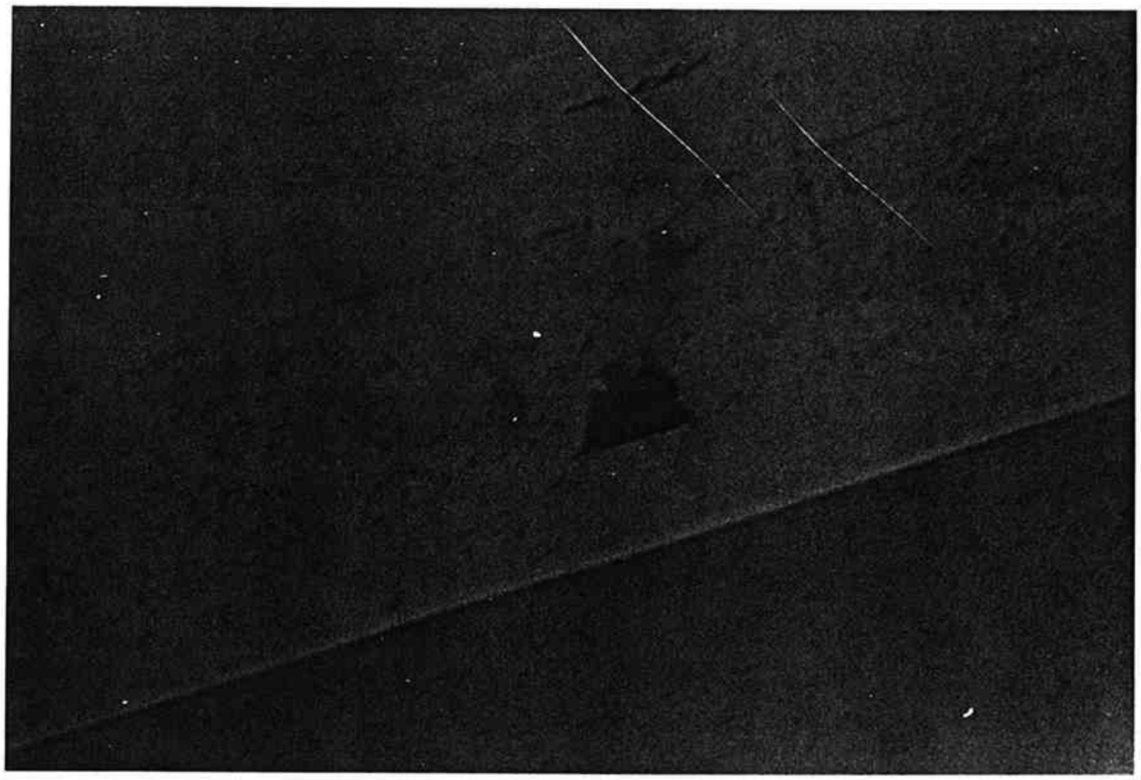
If the chlorides have migrated away from the rebar and the pH of the cement has returned to pre-chloride-contaminated values, the passivity of the rebar would be maintained by the alkalinity of the concrete. This implies that the criteria for maintaining long-term protection of the steel may be significantly different from when protection was first applied. One approach may be to apply only enough potential to immobilize the chloride ions in the concrete. This would result in an equilibrium between the diffusion forces, which causes the chlorides to migrate into the concrete, and the applied potential force which causes the chlorides to move away from the steel.

If the counter-balancing potential is sufficiently low, protection may be achievable by a passive system. This would represent a significant savings in rectifier and maintenance costs.

Worthy of investigation is the possibility of initially installing a zinc metallized coating or imbedded zinc anode system. This system would be powered with a rectifier until the chlorides had migrated away from the steel and passivity of the steel had returned. The rectifiers could then be removed and the system would be set up for passive operation. If the zinc-iron potential could maintain the chloride ion equilibrium, no further rectifier maintenance would be required.

BROWN (RUST) STAIN

Fairly soon after the systems were put into operation, slight brown staining was noticed in (on) the cosmetic coat around the beam anode wires in systems 3 and 4. The staining became worse with time, so an in-depth investigation was performed. The figure below shows the typical patterns observed. The large dark spot is where a sample of the paint was removed for analysis.



Picture 1

Brown Stain on the Bottom of a Beam

An in-depth visual examination of the area failed to reveal any tramp steel[1] at or near the surface. The coating was intact and there was no evidence of paint or concrete delamination.

1 Tramp steel is any steel in the concrete that is electrically isolated from the cathodically protected steel. Current from the cathodic protection system enters this steel and leaves it to return to the system. This causes the steel to experience accelerated corrosion termed "stray current corrosion".

Initially it was thought that the stain could not be caused by iron oxides, since Fe^{+2} or Fe^{+3} ions in the concrete would migrate toward the rebar, away from the conductive paint anode. In order to identify the stain, samples were taken and analyzed by scanning electron microscope and energy dispersive X-ray microanalysis.

The samples taken for examination (the dark spot in Picture 1) were a combination of the conductive paint and the top coat. Figure 5 is the scan of the atmospherically exposed surface of the sample. The outside coating was high in titanium (Ti), iron (Fe), and silica (Si). The conductive inside coating, figure 6, was high in iron, chlorine (Cl), silica and aluminum (Al).

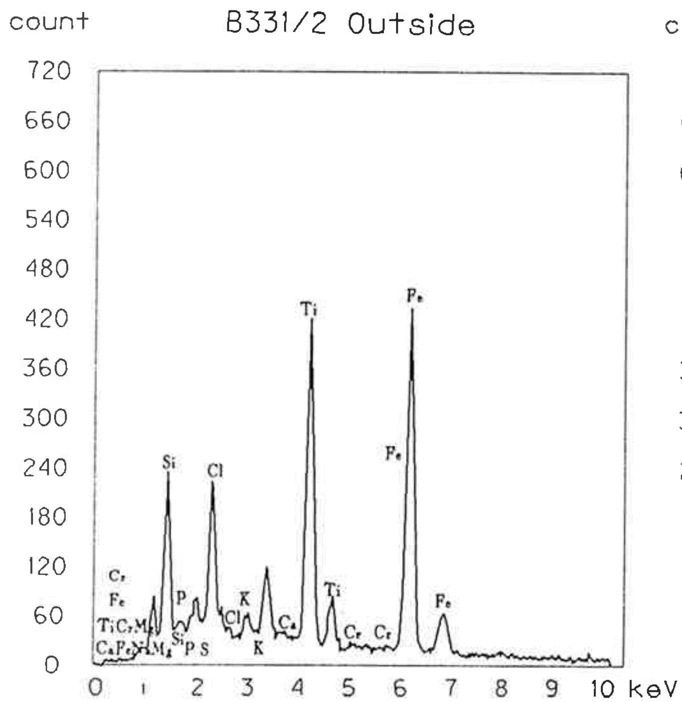


Figure 2

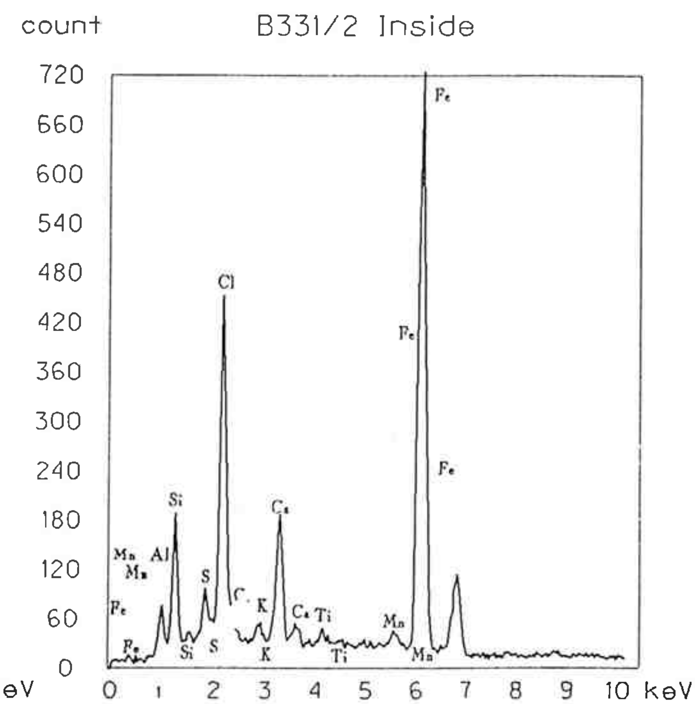


Figure 3

The presence of titanium, silica and calcium (Ca) in the top coat would be expected, since they are normal components of that type of paint. The chlorine would be expected since it is negatively charged in the ionic state and would be attracted to the anodic conductive paint and enter the top coat by diffusion. The iron would not normally be expected, since it is a positive ion and would migrate toward the cathode (rebar). The presence of iron in the top coat is evidence of rust.

The presence of silica, aluminum and chlorine in the conductive paint was expected. The high iron concentration was not expected. The high iron concentration in the conductive paint further supports the evidence that the brown stain is rust.

In order for the iron to migrate to the anode, it would have to be negatively charged. The Fe^{+2} and Fe^{+3} ions are clearly positive. In order for these ions to migrate to the anodic surface they had to have been in an ionic state that had a net negative charge. The most probable explanation would be the formation of an iron-chlorine complex with a net negative charge. Once the complex reached the surface it would oxidize and appear as rust on the surface.

Although this analysis supports the position that the stain is rust, there is no explanation of where the iron came from. The area has been carefully checked for delaminations and tramp steel. The stained areas are, to date, sound.

TOP OF DECK

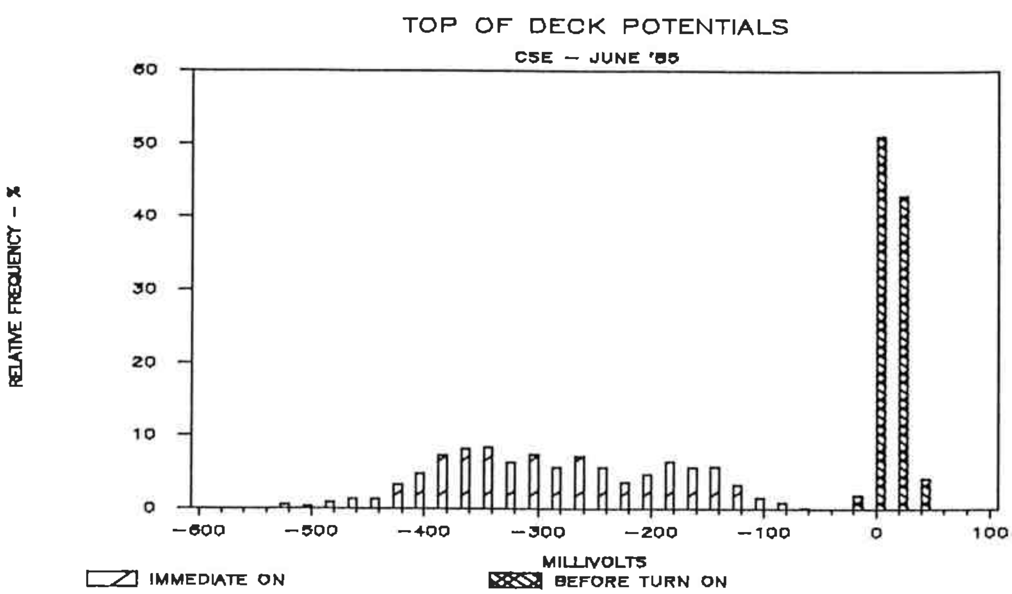
In June 1985, potential profiles were taken on a section of the top deck immediately above one of the soffit cathodic protection systems. Profiles were obtained immediately prior to and immediately after energizing the cathodic protection system. Additional profiles were taken in July 1985, June 1986, and June 1987.

The section of deck profiled is located in the north-bound lane on the north end of the structure.

Potentials were taken on a 5.5 inch grid pattern using a data logger and CSE. Testing was performed in accordance with ASTM C876-80. Connection to the structure was made via a permanently exposed piece of steel that had been welded to the upper rebar mat.

The data was transferred from the data logger to a computer, and has been put into histogram form. The histograms, or bar graphs, are plots of the relative frequency (% occurrence) of the potentials in 20 mv increments. This enabled the relative potential shifts with time to be clearly seen.

The terms "immediate on" and "immediate off" indicate the readings were taken as soon as possible. Because of the number of readings taken (132 to 528 per graph), significant time lapse occurred between the first and last measurements. Thus, the "immediate off" measurements would not approximate "instant off" measurements.



Histogram 1 - 1 hour "before turn-on" and "immediate on" (approximately 1 hour after turn-on.)

The most notable features of this histogram are:

1. The "before turn-on" profile had potentials in the -20 mv to +40 mv range. Potentials in this range were not expected. Thus, before the systems were turned on, random potentials were obtained in an adjacent area of the deck where the soffit is not coated. The potentials measured were as expected, -50 mv to -200^{+} mv.

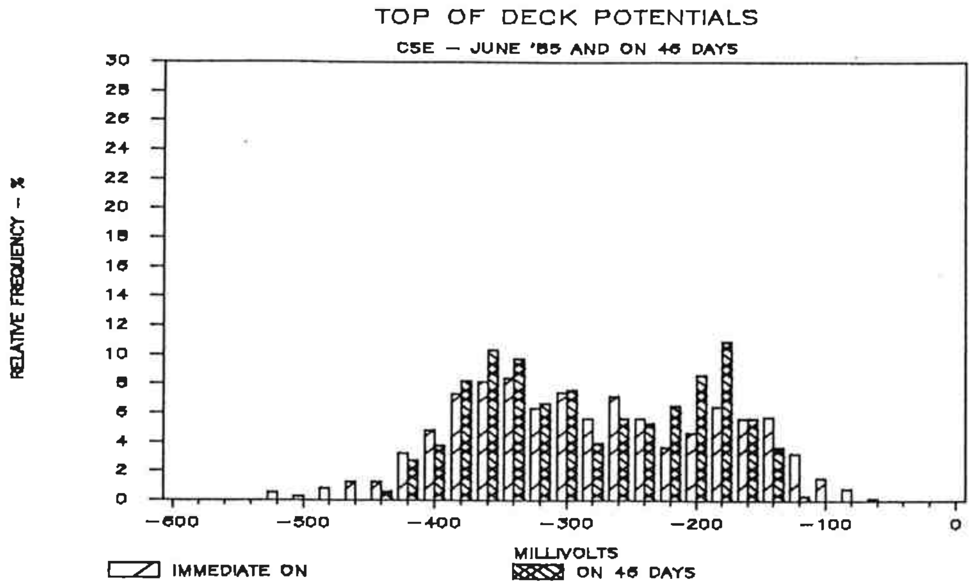
   The conductive paint and top coat had been placed several months earlier. The electro-positive potential shift may have been caused by the paint changing the oxygen permeability of the bottom of the deck. A change in the permeability would affect the oxygen balance in the deck and change the electro-chemical characteristics of existing oxygen cells.

2. The "immediate on" profile was taken with an impressed current of 0.85 ma/ft^2. Even though the cathodic protection system was designed and adjusted to protect the substructure and bottom of deck, significant current was received by the upper mat of rebar, as is evidenced in the rapid shift in potentials.

3. The potentials of the "immediate on" profile had a:

mean	-279	mv
standard deviation	96	mv
coefficient of variation	34.5	%
maximum	-67	mv
minimum	-522	mv

4. Examination of the "immediate on" data shows that it is bi-modal (see also Histogram 2). This bi-modality correlates with the soffit geometry. The least electro-negative shifts are over the beams and diaphragms located below the deck.



Histogram 2 - "on 46 days" and "immediate on"

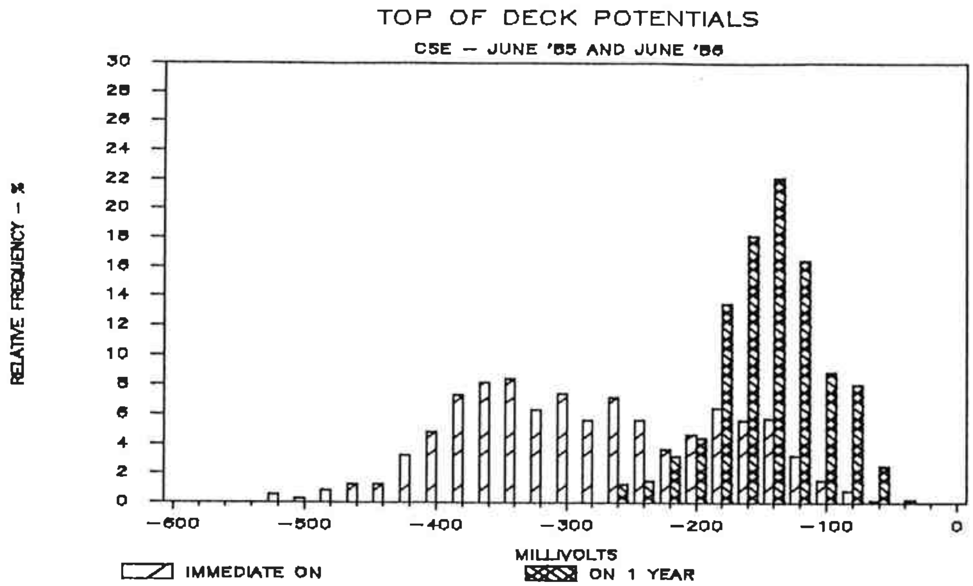
The interesting features relating to this histogram are:

1. The mean potential had not changed since the systems were turned on. The potentials of the "on 46 days" profile had a:

mean	-277	mv
standard deviation	82	mv
coefficient of variation	29.6	%
maximum	-117	mv
minimum	-445	mv

2. The data is strongly bi-modal as discussed above.

3. The standard deviation has decreased by 15%.



Histogram 3 - "on 1 year" and "immediate on"

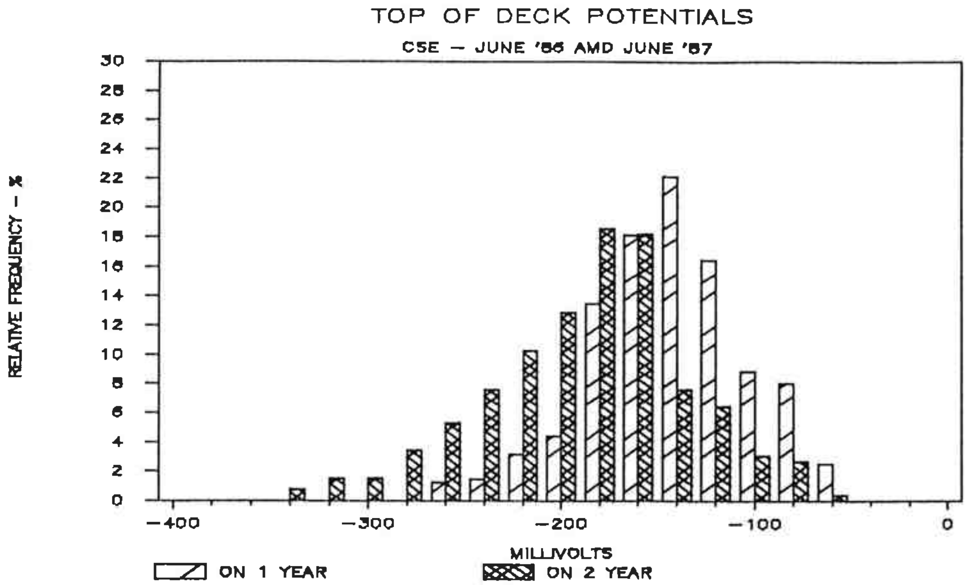
Features of this histogram are:

1. The mean potential had shifted 145 mv in the electro-positive direction. This may have been due to the impressed current being reduced to 0.24 ma/ft^2. The potentials had a:

mean	-133	mv
standard deviation	40	mv
coefficient of variation	30.2	%
maximum	-39	mv
minimum	-251	mv

2. The data was no longer strongly bi-modal: e.g., the effects of the beam and diaphragm mass on the potential distribution is significantly reduced.

3. The standard deviation has decreased by 60%.



Histogram 4 - "on 1 year" and "on 2 years"

The features of this histogram are:

1. The mean potential had shifted approximately 50 mv in the electro-negative direction. This may have been due to the impressed current being increased to 0.43 ma/ft^2 from a previous 0.24 ma/ft^2. The potentials had a:

mean	-185	mv
standard deviation	53	mv
coefficient of variation	28.5	%
maximum	-67	mv
minimum	-335	mv

2. The data is still mono-modal, though slightly skewed in the negative direction.

3. The standard deviation has decreased from the original by 45% (though greater than the previous year). However, the coefficient of variation was the lowest to date.

Examination of histograms 2, 3, and 4 suggests a relationship between the applied current density and the CSE potentials.

Table 3

ON TIME VS MEAN POTENTIAL AND CURRENT DENSITY

Histogram	on time	mean potential	current density
2	46 days	-277 mv	0.95 ma/sq ft
3	1 year	-133 mv	0.24 ma/sq ft
4	2 years	-185 mv	0.43 ma/sq ft

After the data for histogram 4 was taken, the cathodic protection was shut off. Since potentials change rapidly when the system is turned off, the test area was divided into 4 quadrants and re-mapped. Quadrant 1 was mapped in the first 15 minutes, quadrant 2 in the 15 to 30 minute interval, etc. The system was left off overnight and re-mapped. As soon as the system was turned on, a third map was taken. The table below summarizes the potentials measured during this time.

Table 4

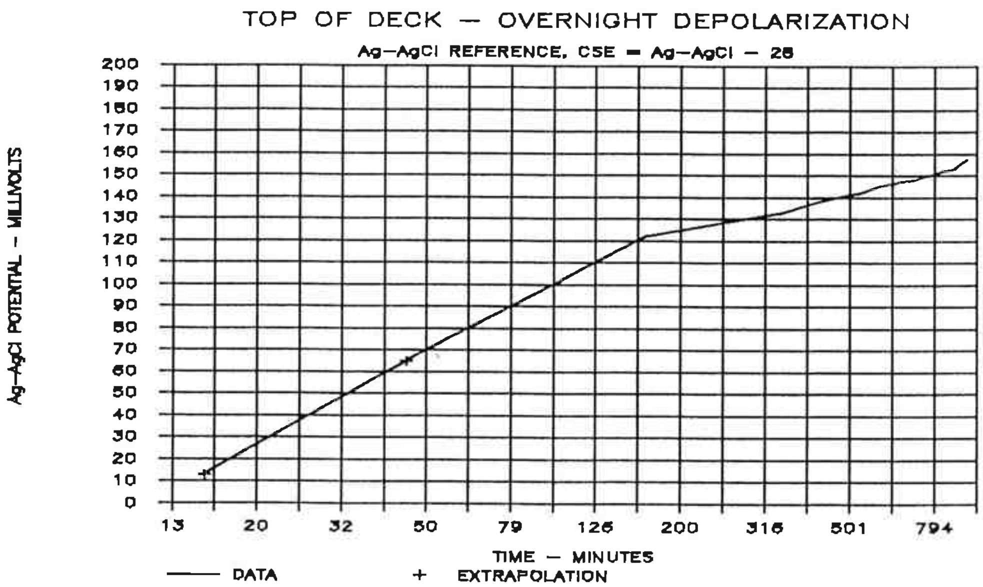
MEAN POTENTIALS AND POTENTIAL SHIFT, mv

Quadrant ==>	1	2	3	4
Time - minutes=>	0 - 15	15 - 30	30 - 45	45 - 60
ON - mean potential		-185		
"IMMEDIATE OFF" -	-100	-61	13	-23
OFF OVERNIGHT -	-68	-80	-61	-52
potential shift	32	-19	-74	-30
"IMMEDIATE ON"	-95	-284	-229	-214
potential shift	-27	-204	-168	-162

Quadrant 1, the first measured, is the most electro-negative, with Quadrants 2 and 3 being more positive, as would normally be expected. Quadrant 4 shows a negative shift with respect to quadrant 3, for no apparent reason.

Examination of the overnight potential shift finds quadrants 2, 3 and 4 with negative shifts. This occurs when the maximum depolarization (maximum positive shift) occurs at some time during the off period, and the areas in question then shift in the negative direction.

During the depolarization test, a silver-silver chloride (Ag-AgCl) reference cell was used to monitor the potential at a point near the curb (away from traffic). The first data point recorded, +65 mv (Ag-AgCl), was taken 45 minutes after the system was turned off. After 16.5 hours, the potential was +157 mv, for a change of +92 mv.



Graph 8 - Silver-Silver Chloride Reference Electrode Depolarization Potential vs. Log(time)

If the depolarization potentials in the first one to two hours are a straight line when plotted on semi-log paper, as discussed in the "Depolarization and Instant Off" section, then the line can be extrapolated to the off time (in this case time 0). This has been done on graph 8. Depolarization in excess of 100 mv is indicated.

This data shows that the top mat of steel in the deck is significantly influenced by the soffit cathodic protection system. At at least one point, the location of the Ag-AgCl reference cell, 100+ mv of depolarization was observed.

Since the major thrust of this work was to study the effects on the bottom steel, no attempt was made to vary the impressed current to influence the top mat. Further study should be made on a deck where the salt is concentrated in the top of the deck and the goal is to control the corrosion of the top mat of steel from the bottom of the deck. If this can be demonstrated as being practical, the need for traffic control during installation, and protection for the anode system from traffic during operation, could be eliminated.

Intuitively, it would seem that a greater concentration of salt around the upper mat of rebar would improve the current distribution and further reduce the standard deviation of the potential profiles observed here.

YAQUINA BAY BRIDGE
NEWPORT, OREGON

APPENDIX 1

SUMMARY OF SYSTEM OPERATION

(DATE) SYSTEM	RECTIFIER VOLTS (E)	RECTIFIER AMPS (I)	CALCULATED RESISTANCE OHMS (E/I)	CURRENT DENSITY MILLIAMPS/SQ FT	BEAM DEPOLARIZATION MV	BEAM DEPOLARIZATION HOURS	DECK DEPOLARIZATION MV	DECK DEPOLARIZATION HOURS
06/08/85 SYSTEMS TURNED ON								
1	3.14	1.48	2.12	1.03	N		N	
2	1.73	1.08	1.60	0.60	N		N	
3	2.95	1.43	2.06	0.93	N		N	
4	3.76	1.75	2.15	0.85	N		N	
07/24/85								
1	3.27	0.91	3.59	0.63	1000	2.75	670	2.75
2	1.81	0.38	4.76	0.21	1060	2.75	163	2.75
3	3.05	1.17	2.61	0.76	700	2.75	1100	2.75
4	3.82	1.95	1.96	0.95	530	2.75	1060	2.75
07/25/85 SYSTEM TURNED BACK ON								
1	3.76	0.91	4.13	0.63				
2	2.67	0.91	2.93	0.51				
3	2.92	0.93	3.14	0.60				
4	2.77	0.92	3.01	0.45				
11/12/85								
1	3.62	0.70	5.17	0.49	540	2.75	N	
2	2.63	0.69	3.81	0.38	1460	2.75	N	
3	2.80	0.83	3.37	0.54	N		1200	2.75
4	2.67	0.76	3.51	0.37	N		890	2.75
02/20/86								
1	2.11	0.38	5.55	0.26	N		150	2.00
2	1.77	0.38	4.66	0.21	N		320	2.00
3	1.87	0.40	4.68	0.26	N		150	2.00
4	1.89	0.40	4.73	0.19	N		150	2.00

(DATE) SYSTEM	RECTIFIER VOLTS (E)	AMPS (I)	CALCULATED RESISTANCE OHMS (E/I)	CURRENT DENSITY MILLIAMPS/SQ FT	BEAM DEPOLARIZATION MV	HOURS	DECK DEPOLARIZATION MV	HOURS
03/25/86								
1	2.43	0.38	6.39	0.26	280	0.25	150	0.25
2	1.94	0.38	5.11	0.21	210	0.25	210	0.25
3	1.94	0.41	4.73	0.27	310	0.25	200	0.25
4	2.21	0.55	4.02	0.27	370	0.25	70	0.25
05/19/86 (Original Rectifier)								
1	2.38	0.36	6.61	0.25	N		N	
2	1.97	0.37	5.32	0.21	N		N	
3	1.98	0.39	5.08	0.25	N		N	
4	1.24	0.52	2.38	0.25	N		N	
05/21/86 (New Rectifier)								
1	3.47	0.83	4.21	0.57	N		N	
2	2.82	1.06	2.66	0.59	N		N	
3	2.29	0.92	2.49	0.60	N		N	
4	2.82	1.18	2.39	0.58	N		N	
07/01/86								
1	3.43	0.68	5.07	0.47	N		230	1.00
2	2.83	0.70	4.04	0.39	N		270	1.00
3	2.29	0.54	4.24	0.35	N		390	1.00
4	2.83	0.93	3.05	0.45	N		310	1.00
08/18/86								
1	3.43	0.82	4.20	0.57	200	1.50	N	
2	2.84	0.80	3.57	0.44	600	1.50	N	
3	2.30	0.53	4.32	0.35	210	1.50	N	
4	2.85	0.94	3.03	0.46	210	1.50	N	
10/23/86								
1	3.43	1.04	3.29	0.73	240	1.00	350	1.00
2	2.83	1.00	2.84	0.56	740	1.00	590	1.00
3	2.29	0.58	3.98	0.37	270	1.00	540	1.00
4	2.84	0.98	2.91	0.48	240	1.00	270	1.00

(DATE) SYSTEM	RECTIFIER VOLTS (E)	RECTIFIER AMPS (I)	CALCULATED RESISTANCE OHMS (E/I)	CURRENT DENSITY MILLIAMPS/SQ FT	BEAM DEPOLARIZATION MV	BEAM DEPOLARIZATION HOURS	DECK DEPOLARIZATION MV	DECK DEPOLARIZATION HOURS
12/02/86								
1	3.42	1.07	3.20	0.74	420	18.00	550	18.00
2	2.83	0.90	3.14	0.50	620	18.00	760	18.00
3	2.29	0.64	3.58	0.42	420	18.00	620	18.00
4	2.85	1.02	2.79	0.50	310	18.00	200	18.00
12/24/86								
1	3.40	1.12	3.04	0.78	N		N	
2	2.80	1.02	2.75	0.57	N		N	
3	2.40	0.60	4.00	0.39	N		N	
4	2.90	0.98	2.96	0.48	N		N	
01/13/86								
1	3.41	0.88	3.86	0.61	N		N	
2	2.81	0.82	3.44	0.45	N		N	
3	2.28	0.52	4.42	0.34	N		N	
4	2.83	0.83	3.42	0.40	N		N	
03/25/87 ERRATIC PERMANENT HALF CELL DATA - RESULTS NOT CONSIDERED RELIABLE								
1	3.40	0.80	4.23	0.56	61	0.60	98	0.60
2	2.82	0.72	3.94	0.40	680	0.60	130	0.60
3	2.28	0.52	4.35	0.34	45	0.60	49	0.60
4	2.83	0.82	3.45	0.40	1	0.60	25	0.60
06/22/87 ERRATIC PERMANENT HALF CELL DATA - RESULTS NOT CONSIDERED RELIABLE								
1	3.42	0.84	4.07	0.58	370	16.00	170	16.00
2	2.83	0.78	3.65	0.43	320	16.00	230	16.00
3	2.29	0.56	4.12	0.36	210	16.00	470	16.00
4	2.84	0.89	3.18	0.43	180	16.00	300	16.00
03/27/88 '(DATA TAKEN WITH DATA LOGGER AND CSE)								
1	3.40	0.78	4.34	0.55	160	1.23	120	1.23
2	2.81	0.66	4.23	0.37	N		N	
3	2.27	0.53	4.30	0.34	140	1.00	95	1.00
4	2.83	0.83	3.42	0.40	141	1.67	126	1.67
06/23/88 '(DATA TAKEN WITH DATA LOGGER AND CSE)								
1	3.42	0.67	5.10	0.47	N		N	
2	3.07	0.71	4.32	0.39	150	1.10	N	
3	2.29	0.51	4.49	0.33	140	1.10	N	
4	2.85	0.78	3.65	0.38	N		N	