DEMONSTRATION PROJECT
SOFFIT CATHODIC PROTECTION SYSTEM
IN A COASTAL ENVIRONMENT

Demonstration Project No. 923
DTFH71-83-923-OR-05

Interim Report

by

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FEDERAL HIGHWAY ADMINISTRATION
Washington, D.C. 20590

January 1987

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-OR-RD-87-04		

4. Title and Subtitle	5. Report Date
Demonstration Project Soffit Cathodic Protection System in a Coastal Environment	January 1987
	6. Performing Organization Code
7. Author(s) H. M. Laylor	8. Performing Organization Report No.
9. Performing Organization Name and Address Oregon State Highway Division Research Section 1174 Chemeketa St. N.E. Salem, Oregon 97310	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFH71-83-923-OR-05
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Research & Development Washington, D.C. 20590	13. Type of Report and Period Covered Interim Report Dec. 1984 - May 1986
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This demonstration project evaluates a contractor executed below deck cathodic protection system on two spans of a coastal structure. The first part of the project evaluated the construction phase and found that the contractor, working under the guidance of a technical representative, very adequately completed the project. The materials, with the exception of the rectifier, were readily incorporated into the project and resulted in a good operating system.

In addition to the contractor implementation of a cathodic protection system, materials and methods are evaluated. Specifically, design, construction, construction materials for cathodic protection systems, evaluation criteria, rectifiers and top of deck behavior are discussed.

The ongoing phase of the project is to evaluate the durability of the construction materials and the operating parameters of the system for both protection of the soffit areas and the effect of below deck application on the remote or top of deck area.

17. Key Words	18. Distribution Statement
Bridge Deck, Cathodic Protection, Conductive Paint, Corrosion, Rebar	No Restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	39	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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DEMONSTRATION PROJECT
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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 phenomena is observed above and below the deck. Consequently, the problems associated with the deterioration of steel in concrete has been identified as a national problem costing billions of dollars a year.

The objective of this Demonstration Project is to evaluate the methods and materials used in the application of cathodic protection to the bottom of the deck and beams and to evaluate the effectiveness of the protection to the steel by the system.

BACKGROUND

"Cathodic protection is perhaps the most important of all approaches to corrosion control. By means of an externally applied electric current, corrosion is reduced virtually to zero, and a metal surface can be maintained in a corrosive environment with out deterioration for an indefinite time." (1)

Corrosion occurs when local action cells are formed on a surface. A local action cell is composed of an anode and cathode. The corrosion of the metal occurs at the anode and is driven by the potential difference between the anode and cathode. "The mechanism of protection depends on external current polarizing the cathodic element of the local-action cell to the open circuit potential of the anode."(2)

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(1) Uhlig, H. H. and Revie, R. W., Corrosion and Corrosion Control, John Wiley and Sons, 1985, p. 217.

(2) R. Mears and R. Brown, Trans. Electrochem. Soc. 74, 519(1938)

The use of cathodic protection for corrosion abatement had its beginnings in protecting buried and/or immersed structures. As the technology and methods of measurement advanced the idea of using it on concrete structures was a natural outgrowth. In the 1970's Richard Stratfull emerged as a pioneer in applying cathodic protection to concrete structures. His first attempts were to apply the principles of cathodic protection by utilizing conductive overlays to protect bridge decks from deicing salts. Since that time advances in materials have made possible the conductive coating soffit systems such as the one being evaluated in this demonstration project.

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. This structure is similar to other concrete structures along the Oregon coast that were built in the early 1930's. Over the years chlorides from the coastal environment have penetrated the concrete in the below deck portion of the structure. As the chloride levels in the concrete reached the corrosion threshold concentration the reinforcing steel started to deteriorate. As the result there are many areas of the structure that have cracked, spalled and delaminated. The present condition of the structure is such that extensive repairs to the bottom of the deck and beams are required.

Two spans on the North end of the structure were selected to receive a cathodic protection system. 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. Even though these spans were in good shape compared to the rest of the structure the average chloride content was approximately three pounds per cubic yard.

The repair strategy selected for these spans was compatible with the use of a cathodic protection system. Only delaminated concrete was removed and replaced with a conductive patch material. (For long lasting repairs where cathodic protection is not used <u>all</u> salt bearing concrete should be removed.) During repairs all visible metal was either removed or covered with patching material.

The repairs were done by State forces at an approximate cost of $12,000 for the two spans. When the repairs were complete the cathodic protection project was put out for bid. The criteria used for the contract was based on the guidelines provided by Federal Highway Administration (FHWA). The total project was to provide cathodic protection for two spans of the structure or on a total of approximately 6800 sq. feet.

DESIGN PARAMETERS

The area to be protected was divided into four separate systems, (1, 2, 3, and 4,) each approximately 1700 sq. ft. Each system was to evaluate a different primary anode configuration (see figure 1). Additionally, each system was to have the option of being operated in a constant voltage, constant current or constant potential mode.

Conductive paint as a secondary anode, platinum-niobium primary anode wire, and pre-cast anodes were the major design parameters requested by FHWA. The choice of the anode configurations, local system size and construction details were supplied by the State.

Additionally, FHWA requested the rectifier be operational in constant voltage, constant current, or constant potential mode and be an integrated unit as opposed to several single circuit units. A ten circuit unit was chosen for the four system installation. This allowed the use of two circuits per system with two back-up circuits.

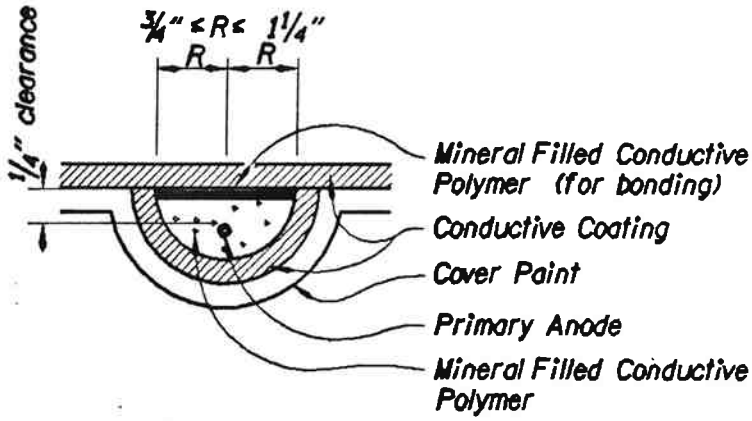
Primary anode placement was to be longitudinally along the bottom of deck between the beams and along the bottom of the beams. The resistance between the bottom of deck and bottom of beam anodes was expected to be high enough to warrant a separate circuit for each. This configuration was selected to obtain the widest latitude of control.

In addition to physical and electrical requirements of the contract the contractor was required by the specifications to have a technical representative. The duties of the technical representative were to provide technical assistance to the contractor and perform tests as outlined in the specifications.

CONSTRUCTION

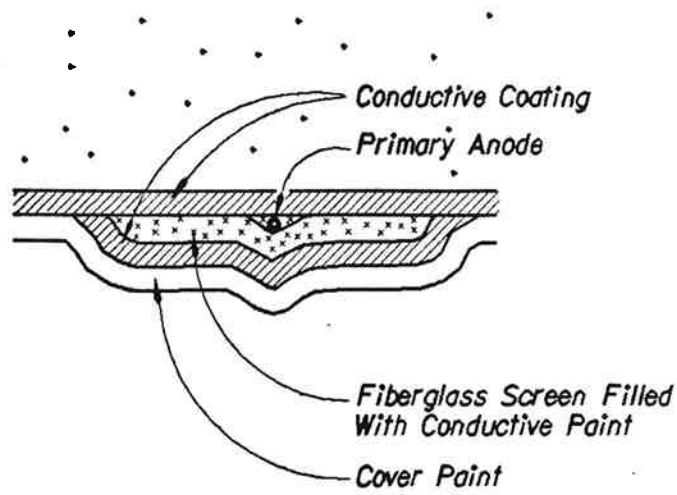
The first phase of the work consisted of blast cleaning the concrete to remove all laitance, dirt, oil or other deleterious material. The blast cleaning required much more effort than had been anticipated since, over the last fifty years, considerable contamination had accumulated on the structure.

At the conclusion of the blast cleaning the Contractor elected to build an enclosure around the work area. This consisted of erecting safeway scaffolding and mounting approximately 200 sections of 4 ft. by 12 ft. corrugated aluminum and fiber-glass panels. These panels comprised a system known as a "Kelly Klosure". This method of enclosing the work area proved to be environmentally excellent as well as weather worthy.

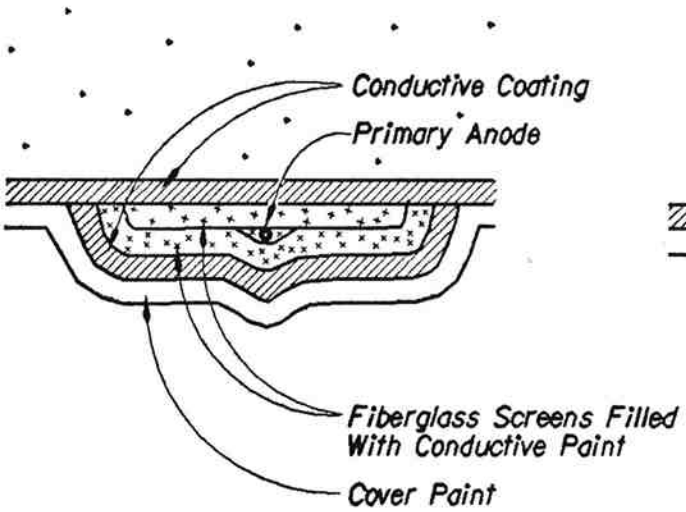


NOTE: The Primary Anode Assembly (Primary Anode embedded in Mineral Filled Conductive Polymer) shall be precast and have a semicircular cross-section with a radius equal to R.

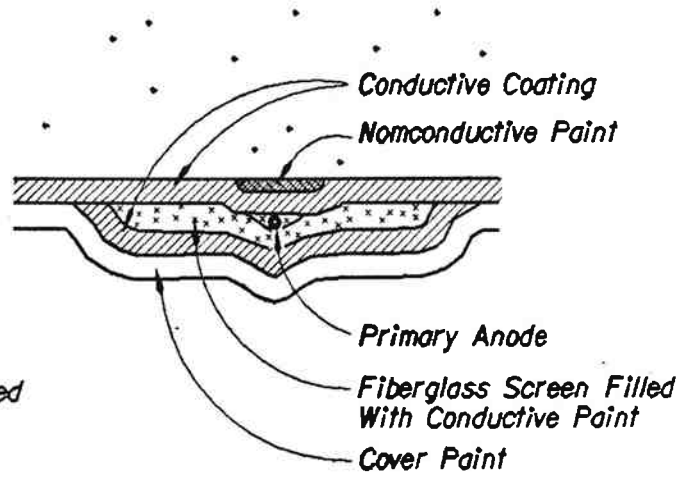
SYSTEM 1



SYSTEM 2



SYSTEM 3



SYSTEM 4

Figure 1 - Anode Systems

Before installation of the system all areas which were to receive the conductive paint were checked with a pach-o-meter to determine the depth of rebar and locate exposed tie wires. Very little rebar was found to have insufficient cover. Those areas that had insufficient cover were masked so that an electrical short would not be formed with the conductive paint. Many tie wires were found on or near the surface. Rather than remove existing sound concrete, the areas where the tie wires were a potential problem were either masked with tape or painted over with a non-conductive paint.

The ground lines, rebar probes and reference cells had to be placed before the structure was ready for painting. At the time the reference cells were installed it was noted that separate ground wires had not been required by the plans. Consequently, they had to be added to the contract.

Concurrent with the installation of the probes, reference cells and grounds, the primary anode system for system 4 was installed since it was to be placed before painting. All the wiring was routed to the central control box via rigid PVC conduit. The conduit was attached to the structure using plastic anchors called "Bantum Plugs". Holes were drilled into the concrete for the Bantum plugs, silicon sealant was injected into the holes and stainless steel screws were used to secure the PVC hold-down brackets. The screws were checked for electrical isolation from the structure and the isolation was found to be excellent.

Next the conductive paint was placed using airless equipment. A wet film thickness of 35 to 40 mils was obtained in a single application by using a tack and cross hatch spray pattern. This resulted in a theoretical dry film thickness of 20+ mils, which satisfied the requirements of the specifications. Unsuccessful attempts were made to determine the dry film thickness of the paint using a scratch gage called a "Tooke Gage". The lack of contrast between the paint and concrete made actual determination of the dry film thickness virtually impossible. The painting was accepted, based on the calculated dry film thickness, using the measured wet film thickness.

The paint appeared to be nearly cured within 24 hours so placement of the pre-cast primary anodes for system 1 was started. It was then noted the short pre-cast anodes for the diaphragm beams had not been supplied. The supplier of the cast anodes was contacted and indicated shipment of the missing anodes would take an additional 30 days. Since the Contractor had sufficient conductive polymer material at the job site he elected to construct the needed anodes in the field. Working from the suppliers shop drawings he was able to construct pre-cast anodes equivalent to or better than those received from the supplier. The total time to build the needed anodes was approximately 18 hours.

When the placement of the primary anodes for the systems and the wiring was completed up to the rectifier mounting area the system was tested using a 12 volt truck battery since the rectifier had not arrived. In order to check the system for shorts a/c resistance measurements were performed (see appendix 1, System Survey). After the resistance measurements were completed, each system was energized from the battery using dropping resistors to drop the voltage to an acceptable level. Voltage and current was recorded versus time to determine if that relationship was typical of a properly operating system. Once this was completed the voltage was removed from the system and depolarization (voltage decay vs. time) data was taken. The test results indicated there were no significant problems in any of the systems. The contractor placed the cosmetic paint coat and waited for the rectifier to arrive.

The construction time to this point was just less than 6 weeks.

CATHODIC PROTECTION - EVALUATION CRITERIA

Since cathodic protection of concrete structures is a relatively new technology, methods used for evaluation and testing are changing relatively rapidly.

E-Log-I measurements were to be used for establishing the operating parameters for the cathodic protection systems on this structure. This technique was once reported as a valid means of establishing the current requirements for a given installation. Field applications of the technique on concrete structures have shown it is difficult to use and has limited accuracy. By the time the structure was ready to put into operation E-Log-I was recommended for establishing "ball park" parameters of operation at the initial start up of the system. The parameters so determined are used for approximately one month and then the system is fine tuned using depolarization techniques.

The depolarization technique is a means of determining the polarization of the system while no IR losses are affecting the measurement.

First the instant off voltages of the reference cells being used to monitor the system are established. The most effective means of establishing this value is with a dual trace oscilloscope. One trace is used to monitor the rectifier's pulsed d/c output while the other trace monitors the reference cell. The rectifier trace is observed and when the "off" occurs the voltage of the reference cell is read.

Next the system is turned off and permitted to depolarize. The next value determined is the reference cell voltage when the voltage time rate of change is negligible.

Depolarization is the difference between the instant off voltage and the constant voltage just described. A voltage difference of 100 millivolt (mv), or greater, is the value that is reported to insure protection. (3)

Another major change was in the use of the 850 mv Cu-CuSO4 half-cell reference potential criteria. Application of this criteria can result in gross over-protection. Consequently, the present choice is to rely on the depolarization technique.

THE RECTIFIER

The rectifier arrived in mid May 1985. Before it was wired into the system an attempt was made to operate one circuit under a 2.2 ohm dummy load. This resulted in immediate failure of one fuse in each of the ten circuits. During dummy load testing it was noted the printed circuit boards in the rectifier were proto-type boards and as such were not suitable for permanent installation. That alone made it evident the rectifier did not meet the specification.

It was determined that the rectifier circuits were ground looping (a partial short from the rectifier outputs to the neutral and/or ground returns) with the test equipment even though the test equipment was operated from the same circuit as the rectifier. The manufacturer was contacted and recommended several circuits be removed by cutting specific wires in the power supply.

The field modifications were made and further testing was done with battery operated test equipment. This improved the situation as higher current output could be obtained, but the rectifier design criteria for amperage could not be met.

Potentials were measured between the rectifier ground, the rectifier cabinet, and earth ground. The values obtained were unacceptable (much greater then would normally be expected). Consequently, it was decided to return the rectifier to the manufacturer.

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3 Gummow, R. A., "Cathodic Protection Criteria - A Critical Review of NACE Standard RP-01-69", Paper Number 343, National Association of Corrosion Engineers Conference, Corrosion 86, Houston, Texas.

In June, 1985, the "corrected" rectifier arrived and the manufacturer indicated the modified printed circuit boards in the rectifier would be replaced with new boards in July. The rectifier with the modified boards was bench tested and, after several calls to the manufacturer, a wiring configuration was found that permitted constant voltage operation under dummy load. The rectifier was taken to the bridge and installed. Before the system was powered up a survey was made to determine the static parameters (see appendix 2, Operational Survey). E log I was performed, and the system voltages were set and operated in the constant voltage mode.

The replacement boards, which were still temporary, proto-type boards, were received in late July and installed. It became immediately obvious these boards would not satisfy specifications. Selection of a control mode (constant voltage, constant current or constant potential) could not be readily achieved, since rewiring was required to change modes. In addition, voltage and amperage readings on the panel meter were inconsistent with external test equipment readings. Reference electrode set-point, and display were not functional to 3 digits (the meters would not auto-range), and lack of a comprehensive operations manual made working with the system difficult.

The systems operation was reviewed and is reported in appendix 3. The next date for new boards was in September, then October, and finally renegotiated to November 1985.

When the boards arrived in November the system operation was reviewed and the boards were installed (see appendix 4). The operation of the boards was much improved, however, they still failed to meet specifications since the meters were not auto-ranging, did not provide the degree of accuracy required for some readings, and would not permit proper operation of the rectifier in the constant potential mode. Further the boards were still proto-types and clearly not production quality. The contractor attempted to field retro-fit new meters with the proper ranges for the available output voltages. After installing one of the two new meters it was apparent this approach would not solve the problem. The specifications were reviewed and checked against the rectifier's performance. Sufficient non-conformance with the specifications was noted, so the rectifier was rejected.

Since the intent of this Demonstration Project was to evaluate a cathodic protection system and not be a project for rectifier development, four, proven - off the shelf rectifiers, integrated into a single enclosure were supplied by the Contractor and put into operation. This new rectifier configuration required an external junction box to facilitate connection of the system components to the rectifier and provide the required test points. The reconfigured system added flexibility for taking test data and for connecting the systems to the rectifiers. In May, 1986 a fully operational system was turned over to the State.

TOP OF DECK DATA

During the June, 1985, rectifier installation, equipotential profiles were mapped for a section of the upper deck immediately above the soffit cathodic protection system. Profiles were obtained immediately prior to and immediately after energizing the cathodic protection system. During the July, 1985, board reinstallation and again in May, 1986, additional top of deck profiles were taken on the same section. The section of deck mapped is located in the north bound lane on the north end of the structure. The northern most edge of the map is approximately 42.4' south of the expansion joint at the first bent south of the north approach. The maps obtained extend west from the curb to the center line of the highway.

The potentials were obtained using a high impedance digital voltmeter with memory and a Cu-CuSO4 reference cell. The tests were performed in accordance with ASTM C876-80. Connection to the structure was achieved using a permanently exposed piece of rebar welded to the upper mat. The individual readings were taken on a 5.5 inch grid.

The data collected was directly transferred from the voltmeter to a computer which generated the maps. The maps and the technical representatives discussion are included in Appendix 6.

Grid 001 - "Off" - 1 hour before energizing the system

The most notable feature of this profile is the relatively electropositive potentials. The soffit, T-beams and diaphragms beneath the grid are coated with the conductive paint and top coat. This coat extends approximately 5 feet south of the southern most edge of the grid. The potentials observed are 100 to 150 millivolts more positive that the random potentials obtained in an adjacent area that has no cathodic protection. It is surmised that the electropositive potential shift may be caused by the impervious coating changing the oxygen balance in the deck.

Grid 002 - "On" - Within 1 hour after energizing the system

The most important features relating to this grid are:

1. The protective current impressed on the substructure was 0.85 ma/sq. ft.

2. Even though the cathodic protection system is designed and adjusted to protect the substructure and bottom of deck, significant current is being provided to the upper mat of rebar.

3. Even in areas where there are geometric impediments (e.g. over the beams or diaphragms) potential shifts in excess of 100 mv are observed.

Grid 003 - "On 46 days"

The most important features relating to this grid are:

1. The protective current impressed on the substructure was 0.95 ma/sq. ft.

2. The Smoothing out of the current distribution. This is seen in the electronegative potential shift in the areas over the T-beams and diaphragms. See the histograms in Appendix 6.

3. Note also that the distribution of the data appears to be bimodal.

Grid 004 - "On one year"

The most important features relating to this grid are:

1. The protective current impressed on the substructure was 0.24 ma/sq. ft.

2. Since the level of impressed current is approximately 1/4 of that applied when grids 002 and 003 were taken it is not surprising that the mean potential for this grid is more electropositive then those obtained on grids 002 and 003.

3. The histogram for grid 004 does not reflect the bimodal distribution shown earlier, however the map still shows the effects of geometric impediments.

COST

The total area protected by the system was calculated to be 6828 sq. ft. The construction costs were:

Construction authorization	$87,130.45
Contingencies	4,768.67
total - project authorization	$91,899.12

Costs per sq. ft. for the demonstration project cathodic protection system was $13.46.

DISCUSSION

Construction, Plans, and Specifications

The construction phase went very smoothly and the Contractor was very cooperative. During the life of the project there were three price agreements, two of which were "no cost." The first change in the specifications was to permit field attachment of anode lead wires in lieu of "all factory attached lead wires. The second change was in system one where two different methods of anode attachment were permitted.

Price agreement No. 3 was in three parts and was for $4,768.67. The plans had omitted the 120 volt junction box to supply voltage to the rectifier. The special provisions did not call for the reference electrode and rebar probe ground wires to be run to the rectifier. This required extra labor and wiring. The rockers and roadway drains require grounding. This was overlooked in the specifications and required extra conduit, junction boxes, wire and labor.

General Operation

In spite of the problems encountered with the original rectifier much good information about conductive coating soffit cathodic protection systems has been obtained.

One important result involves the initial current densities as obtained from the E-Log-I testing. The initial current density settings resulted in exceeding the 100 mv criteria by as much as an order of magnitude. Consequently, after each rectifier modification the current density was reduced.

The technical consultant expected initial current densities of approximately 2 ma per sq. ft. This estimate was reasonably near the current densities indicated by the E-Log-I data as interpreted in the field. Surprisingly, the 100 mv criteria was realized very early on and always at voltages and current densities much lower than anticipated. The lowest operating current density experienced to date, is 0.2 ma per sq. ft.

Rectifiers

The problems with the original rectifier severely limited the operation of the system in various modes as originally proposed. Thus the wider scope of the project, to study the various operational modes and wiring configurations, has not been realized. Additionally, the malfunctions associated with the meters made record keeping difficult since accurate evaluations needed to be made with external equipment. With the new rectifier further studies will be made.

The specifications for the replacement rectifiers reflected the experience that was gained with the operation of the system up to the time the original rectifier was rejected. Although the replacement rectifier does not have all the features specified for the original rectifier, operation in the constant voltage, constant current and constant potential mode are possible. In addition to the replacement rectifier an external junction box was provided. The junction box makes more test points available and expands the operational flexibility of the systems.

The waveform output from the original rectifier was an area of concern. The pulsed output had a short "on" time, a relative large amplitude and significant transients associated with each pulse. The technical consultant expressed concern that the electrical "shock" associated with the high amplitude and short on time of the pulse might have adversely affected the primary anode life. The transients made it difficult to determine the instant off points and there was a transient component in the reverse polarity region.

The replacement rectifier output waveform has a longer "on" time and a lower amplitude. Additionally, the output circuit has a choke in the output circuit to suppress transients and provide protection against a direct short condition. Output from this circuit is easier to study, has negligible transients, and less electrical "shock" to the system.

Secondary Anode

The conductive paint for the secondary anode is proving to be a very effective means of distributing current over the surface of the structure. Voltage measurements were made between the beam primary anodes and disconnected deck anodes. These measurements indicated losses in the coating were very low.

The condition of the conductive paint after 16 months of service is good. The only failure areas are where there are leaking cracks in the structural concrete or where tramp steel had been very near or in contact with the coating. The overall assessment of the coating indicates less than 0.1% failed areas.

There is some brown staining in isolated areas, especially on the bottom of the beams in systems three and four. These areas were closely examined and the areas were swept for tramp steel. No steel was located and mechanical destruction of the coating revealed a coating that was strongly adherent, very tough and durable. No explanation for the stain is available at this time.

The projected life of the coating, when considering the above observations along with the much lower than expected current density, is at least ten years. At some time between the seventh and tenth year of operation, minor repairs should most likely be made so that operation of the system would not be impaired at a later date. This estimate is based on the expected time required to keep the system in economic operation for long term operation.

Top of Deck

The information obtained on the top of deck from this below deck application indicates that further studies should be made. Studies should concern the observed electropositive potential shift before the system was activated and the trend of the upper mat to behave more equipotentially with time.

The below deck conductive coating may act as an oxygen barrier. The top mat of steel would then become cathodic to the lower, now anodic, mat of steel. This phenomena, known as the differential aeration cell, is well documented in text books on corrosion. If there are chlorides present in the concrete around the bottom mat of steel, current flow would be established between the upper and lower mat. The differential aeration cell would be formed and production of a ferrous chloride corrosion product would occur in the anodic area. Under some conditions this phenomena could shift the attack from the top mat to the bottom mat of steel. This condition could lead to accelerated corrosion of the bottom mat when the cathodic protection system is off or otherwise inoperable.

Even though there was no direct attempt to affect the top mat of steel, the trend of the upper mat to become more equipotential with time indicates current is being received by the steel. The practical application of a below deck system designed for control of the top steel should be considered.

CONCLUSIONS

Construction, Plans, and Specifications

Contractor executed installations are viable. However, a properly supervised bridge maintenance crew could install small systems.

General Operation and Rectifier Selection

Each structure's electrical characteristics should be evaluated. The methods used on this project are good for obtaining the operating parameters.

Rectifier selection for new systems should be based on the electrical characteristics of the structure. The rectifier choice should be the simplest available unit that is compatible with the electrical characteristics.

Anodes

System one, cast anodes, were the most expensive to install and do not offer any operational advantage. Systems two, three and four are similar, but system 2, the simplest, is operationally equal to the others.

The conductive coating is providing excellent current distribution. The low resistance of the coating system indicates bottom of beam primary anodes would be sufficient.

Molybdenum Trioxide Reference Cells

These reference electrodes were easy to install and, with the exception of the system 4 beam electrode, initially operated satisfactorily. Readings were difficult to take because of the transients in the original rectifiers output. Long term stability of the electrodes is not good, but short term tests can be taken without re-calibration.

Rebar Probes

The rebar probes indicated current flow as anticipated, however, the information gained from them does not justify the cost of installation.

System Size

System size, per rectifier, can be in the four to seven thousand square foot range. Breaking the system into 4 to 7 - 1000 square foot subsections would simplify initial trouble shooting.

Cost - Future Installations

This demonstration project had features that would not be included on a routine installation. It also provided information for design guidelines that were not available at the projects onset.

During construction the entire area was enclosed because of inclement weather. This is not a normal constraint and its cost would not be reflected in the cost of future projects. There was also additional cost in bringing all four systems into the same enclosure at an area where ease of testing and evaluation was the aim. Placing two rectifiers "back-to-back" for adjacent systems should be considered.

It is believed that routine installation costs, not including repairs, would be on the order of $5.00 per sq. ft. as opposed to the $13.46 experienced in this demonstration.

RECOMMENDATIONS

1. Select rectifiers that are simplest and adequate for the area to be protected. One rectifier per 4000 to 7000 sq. ft. or as other geometrical restraints dictate.

2. Delete the bottom of deck primary anodes and power the system with bottom of beam anodes.

3. The primary anode configuration as depicted in figure 1, system 2, is completely adequate and is the most economical to install.

4. Delete the rebar probes as they are not necessary and expensive to install.

YAQUINA BAY BRIDGE
NEWPORT, OREGON

APPENDIX 1

SUMMARY
SYSTEM OPERATING CHARACTERISTICS

The rectifier was operated in the constant voltage mode during this time.

(DATE) SYSTEM	VOLTS	AMPS	RESISTANCE OHMS*	(MoO_3) REFERENCE POTENTIAL DECK	BEAM
				mv	mv
06/08/85					
1	3.14	1.48	2.21	-500 to -700	-520 to -600
2	1.73	1.08	1.60	-160	-600
3	2.95	1.43	2.06	-700	-440
4	3.76	1.75	2.15	-480	-410
07/24/85					
1	3.27	0.91	3.59	-600	-920
2	1.81	0.38	4.76	-100	-1000
3	3.05	1.17	2.61	-960	-580
4	3.82	1.95	1.96	-1000	-500
07/25/85					
1	3.76	0.91	4.13	-670	not obtained
2	2.67	0.91	2.93	-180	-1380
3	2.92	0.93	3.14	-1040	not obtained
4	2.77	0.92	3.01	-700	not obtained
11/12/85					
1	3.62	0.70	5.17	-1150	-1100
2	2.63	0.69	3.81	-740	-1250
3	2.80	0.83	3.37	-1230	-630
4	2.67	0.76	3.51	-1000	-402
02/20/86					
1	2.11	0.38	5.55	-260	-230
2	1.77	0.38	4.66	-401	-206
3	1.87	0.4+	4.68	-102	-440
4	1.89	0.4+	4.73	-175	-54
03/25/86					
1	2.43	0.38	6.39	-263	-257
2	1.94	0.38	5.10	-177	-673
3	1.94	0.41	4.73	-432	- 48
4	2.21	0.55	4.02	-150	-143

*these values are calculated from volts/amps

YAQUINA BAY BRIDGE
NEWPORT, OREGON

APPENDIX 1
(continued)
SUMMARY
SYSTEM OPERATING CHARACTERISTICS

(DATE) SYSTEM	VOLTS	AMPS	RESISTANCE OHMS*	(MoO_3) REFERENCE DECK	POTENTIAL BEAM
				mv	mv
05/19/86 (Original Rectifier)					
1	2.38	0.36	6.58	-40	-24
2	1.97	0.37	5.37	-42	-750
3	1.98	0.39-0.41	5.08-4.83	-440	-220 to +120
4	1.24	0.52-0.54	2.39-2.30	too unstable	-400 to +180
05/21/86 (Replacement Rectifier)					
1	3.47	0.758	4.58	-456	-435
2	2.82	0.990	2.85	-1820	-482
3	2.29	0.791	2.90	-192	-740
4	2.82	1.164	2.42	-265	-956

APPENDIX 2

SYSTEM SURVEY - JANUARY 1985

The Contractor had completed the work with the exception of installing the rectifier and the cosmetic top coat of paint that was to go over the conductive paint. Before placing the top coat it was felt the system should be tested. The Contractors Technical Representative decided to evaluate the system using polarization rate measurements and resistance values.

A 12 volt lead-acid battery with an 18 ohm series resistor was used for a current source. The voltage and current were determined using a Miller B3-A corrosion multimeter. Current "on" data was taken at 0, 1, 3, 5 and 10 minutes followed by current "off" data at 10, 11, 13, 15 and 20 minutes. The positive lead of the volt meter was connected to the rebar and provided the negative sign convention. Resistance measurements were made using a "Nilsson 600" square wave ohm meter. The results are summarized in the table below.

Anode Circuit	Total Ten Minute polarization mv	Total Ten Minute decay mv	Initial D. C. Circuit Resistance ohms
System 1 -Beam	-760	+635	0.95
System 1 -Deck	-900	+680	0.95
System 2 -Beam	-660	+638	0.85
System 2 -Deck	-760	+630	0.82
System 3 -Beam	-1120	+742	0.82
System 3 -Deck	-1100	+820	0.84
System 4 -Beam	-950	+580	0.78
System 4 -Deck	-840	+595	0.82

In order to understand the effects of a short between the coating and rebar an artificial short was created. This reduced the total ten minute polarization by 15% and lowered the circuit resistance by 5%.

Examination of the polarization and decay data indicates that the system has been properly installed and there are no blatant indications of coating to reinforcing steel shorts.

When the beams were tested, the voltage of the adjacent deck electrodes were measured and found to be virtually the same as the voltage on the beams. This implies the deck anodes could be left unconnected and the entire structure could be protected from the bottom of the beams alone.

In conclusion, the systems were considered functional. The conductive coating displays a much lower ohmic resistance than anticipated and has outstanding "throwing power".

APPENDIX 3

OPERATIONAL SURVEY - JUNE 1985

The first test was for the static reference cell potentials and is summarized in the table below.

NATIVE (STATIC) POTENTIALS
MoO3 REFERENCE CELL INSPECTION

Anode Circuit	lead wire str	lead wire ref	MoO3 to Cu-CuSO4	structure to MoO3	Cu-CuSO4 Equivalent	structure to Cu-CuSO4
	#	#	mv	mv	mv	mv
System 1 -Beam	50	52	-291	+11	-280	-272
System 1 -Deck	49	51	-320	+69	-251	-283
System 2 -Beam	42	44	-308	+87	-221	-219
System 2 -Deck	41	42	-272	+82	-190	-185
System 3 -Beam	19	21	-309	+68	-241	-229
System 3 -Deck	18	20	-289	+41	-248	-255
System 4 -Beam	13	10	+/-	- 7	+/-	+/-
System 4 -Deck	14	9	-309	+78	-231	-217

The mean Cu-CuSO4 reference potentials to the MoO3 embedded reference cells was -300 mv with a standard deviation of +/- 16mv. These values agree with those given in the literature. Thus, adding -300 mv to the MoO3 readings gives the potential that would be obtained if a Cu-CuSO4 half-cell had been used directly.

The Cu-CuSO4 equivalent potentials and directly read Cu-CuSO4 potentials indicate there is some possibility of active corrosion. (Potentials more negative than -230 mv.) This condition is not unexpected since the system was ready to receive current in February and the repair strategy did not anticipate a long period without protection.

As indicated in the table above the system 4 - beam reference electrode would not give stable readings and, as such, may be faulty.

The resistance between the anode system and the structural steel in the concrete were obtained using an a/c ohm meter. The results are summarized and compared with the January values below.

Anode #	Resistance - OHMS	
	Jan.	June
1	0.95	0.92
2	0.95	0.89
3	0.85	0.96
4	0.82	1.00
5	0.82	1.00
6	0.84	1.03
7	0.78	1.23
8	0.82	1.09

The increase in the average resistance from January to June is consistent with expected seasonal variation.

The system was put into operation while taking E-Log-I data. Reference cell potentials were obtained using an oscilloscope so the potentials would reflect applied current off or an "IR Free" condition. The rectifier's output was an asymmetric wave form which resulted in two different readings per cycle. This made interpretation of the E-Log-I plots difficult. (Depolarization data taken later indicates that the results interpretated from the E-log-I plots were fairly unreliable.) After the system was in operation, measurements were taken on the rebar probes and are summarized below.

System No.	Current ma
1	0.16
2	-
3	0.10
4	-

Rebar probes 2 and 4 were inadvertently polarized by the digital multimeter being on the Ohm range. This effect is temporary. Data taken later indicated probes 2 and 4 are operating normally and probes 1 and 3 were clearly receiving current.

The system was shut down and permitted to depolarize. System "off" and system "on" data was taken the next day on the top of the deck. The data was reduced by the Contractors Technical Representative. The data indicates that the cathodic protection system has a significant effect on the top rebar mat. (see appendix 7)

The system was set using "best guess" parameters as determined from the E-log-I data which is summarized below.

E-LOG-I TABULATION

System 1
approximately 1440 sq. ft.

Potential mv	Average potential	ma/ft^2
-30 to -50	-40	0.026
-55	-55	0.031
-80	-80	0.087
-90	-90	0.118
-110	-110	0.139
-130	-130	0.241
-160	-160	0.239
-175	-175	0.381
-210	-210	0.482
-270	-270	0.615
-320 to -380	-350	0.699
-370 to -420	-395	0.817
-430 to -490	-460	0.918
-500 to -540	-520	1.029

System 2
approximately 1800 sq. ft.

Potential mv	Average Potential	ma/ft^2
-300 to -380	-340	-0-
-380 to -440	-410	0.311
-480 to -600	-540	0.404
-600 to -650	-625	0.488
-640 to -720	-680	0.601

System 3
approximately 1540 sq. ft.

Potential mv	Average potential	ma/ft^2
-8	-8	0.071
-60 to -150	-105	0.266
-150 to -220	-185	0.421
-195 to -295	-245	0.592
-275 to -360	-318	0.768
-325	-325	0.802
-370	-370	0.931

System 4
approximately 2050 sq. ft.

Potential mv	Average Potential	ma/ft^2
-40	-40	0.083
-80	-80	0.210
-130	-130	0.307
-220	-220	0.548
-260	-260	0.651
-310	-310	0.779
-335	-335	0.853

Note: MoO_3 reference cell potentials were obtained using an oscilloscope to obtain the true instant off values. Where no potential or two potentials occur is the result of the asymmetric wave forms output by the rectifiers.

Current per surface area (ma/ft^2) was calculated from the total current output by the rectifier of each system and divided by the estimated area for the system.

The system operating characteristics are summarized in Appendix 1.

APPENDIX 4

NEW BOARD INSTALLATION AND OPERATION - JULY 1985

The system's operating characteristics were determined and reported in Appendix 1. The system was turned off and the following depolarization data was taken.

DEPOLARIZATION

Anode Circuit	MoO3 cells Instant off-mv	Off 2.75 Hr. mv	Potential shift mv	Cu-CuSO4 equivalent mv
System 1 -Beam	-920	+83	+1003	-1220
System 1 -Deck1	-600	+73	+673	-900
System 2 -Beam4	-1000	+64	+1064	-1300
System 2 -Deck	-100	+63	+163	-400
System 3 -Beam	-580	+115	+695	-880
System 3 -Deck	-960	+142	+1102	-1260
System 4 -Beam	-500	+33	+533	-800
System 4 -Deck	-1000	+61	+1061	-1300

Instant off potentials were obtained using an oscilloscope. They reflect averaged values with the system "on" but at times when no impressed current was flowing. If the 100 mv potential shift criteria is applied to this data it is evident over protection is being observed.

After the depolarization data was taken, the new, temporary, printed circuit boards were installed. The systems were set in the constant voltage mode so approximately 0.9 amps was being delivered and with the current limited to 1.5 amps.

APPENDIX 5

NEW BOARD INSTALLATION AND OPERATION - NOVEMBER 1985

When the replacement printed circuit boards arrived they were examined and found to still be "proto-type" quality. Also, the corrosion resistant protective coating on the boards was lower quality than expected.

The system operating parameters were taken and are in appendix 1. The system was permitted to depolarize and the depolarization data was taken and is presented below.

DEPOLARIZATION

Anode Circuit	MoO3 cells Off Instant off-mv	2.75 Hr. mv	Potential shift mv	Cu-CuSO4 equivalent mv
System 1 -Beam	-570	-35	+535	-870
System 2 -Beam	-1330	+127	+1457	-1630
System 3 -Deck	-1240	-40	+1200	-1540
System 4 -Deck	-970	-85	+885	-1270

In view of the 100 mv change criterion it is still evident over protection is being experienced.

After the system was depolarized the new boards were installed. When the Rectifier was energized, the digital meters still did not auto-range or display the required number of significant digits.

Attempts to adjust the cards so the meters would read correctly were unsuccessful. The Contractors Technical Representative then measured the voltages feeding the meters and decided to obtain more sensitive, auto-ranging meters.

The meters were obtained and one was installed. There was sufficient fluctuation problems with the voltages feeding the meter and with the sensitivity to moisture that the field retro-fit was aborted.

APPENDIX 6

NEW RECTIFIER INSTALLATION - MAY 1986

May 19, 1986

The contractor, the technical representative and the project manager reviewed the shop drawings and the as constructed wiring of the system. Problems with the wiring as depicted on the shop drawings were identified and resolved. A copy of the revised junction box wiring diagram is attached.

May 20, 1986:

Top of deck potential profiles (appendix 7) and system operating parameters (appendix 1) were obtained. The existing rectifier was then shut off and removed from the system. Existing junction boxes were removed from the system as required. The existing 2" PVC conduit was extended approximately 4 feet to connect to the new junction box and rectifier. The new junction box was field retro-fit to reflect the revisions and the new rectifier was mounted.

May 21, 1986:

All the wiring was connected in and/or through the junction box and to the rectifier. A new 115 volt a/c service line was run to the rectifier. Eight splices were made with crimp-on connectors, treated with silicon sealant and sealed in shrink tube. All wires were correctly relabeled as required. The system was turned on and tested. Operation of the rectifier was checked and found to be satisfactory.

New System Operation:

The technical representative recommended the rectifiers be in the constant voltage mode with the initial voltage setting to provide an amperage of 0.6 milliamps per square foot in each system. The amperage was permitted to float with a maximum of 1.5 amps. The constant potential feature was set so that it would not interfere with the constant voltage operation. The beam reference electrodes were connected directly to the rectifier and can be read from the panel meters. The deck reference electrodes were terminated at test points in the junction box. The initial operating parameters were calculated as follows:

SYSTEM	SQ. FT.	X AMPS/SQ. FT.	= AMPS TOTAL
1	1438	x .0006	= 0.863
2	1798	x .0006	= 1.079
3	1540	x .0006	= 0.924
4	2052	x .0006	= 1.231

The systems were activated and the following settings were made. Panel refers to the readings from the meters on the rectifier. Instrument indicates the readings obtained by an external meter.

SYSTEM	PANEL AMPS	PANEL VOLTS	INSTRUMENT VOLTS	PANEL REFERENCE	INSTRUMENT VOLTS
1	.825	3.3	3.47	-.45	-.456
2	1.06	2.8	2.82	-1.70	-1.82
3	.92	2.2	2.29	-.18	-.192
4	1.18	2.8	2.82	-.25	-.265

Everything appeared to be operating properly so the system operating parameters were taken from the test points in the junction box.

The added junction box gives added flexibility since the anode circuits for the beam and deck and the structure (rebar) circuits for the beam and deck can be easily measured.

The following table is data taken from the test points in the junction box. The system amperages are computed from the voltage read across a 0.0100 ohm shunt. Thus, I= 100 x E, where E is in volts, or I = .1 x E, where E is measured in millivolts.

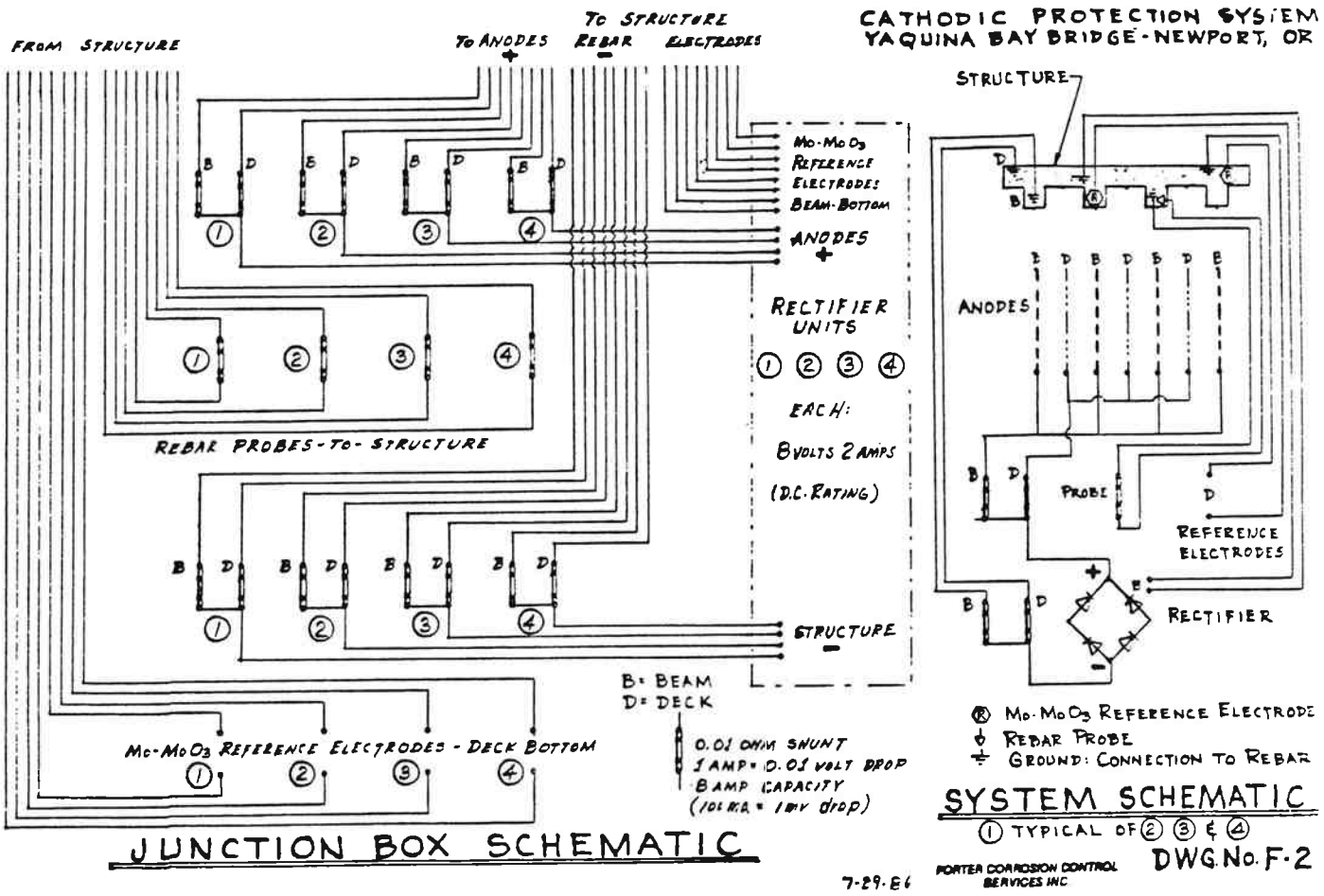
	ANODE			STRUCTURE			REFERENCE
SYSTEM	BEAM AMPS	DECK AMPS	TOTAL AMPS	BEAM AMPS	DECK AMPS	TOTAL AMPS	CELL - DECK MILLIVOLTS
1	.425	.333	.758	.258	.562	.820	-435
2	.482	.508	.990	.544	.455	.999	-482
3	.453	.338	.791	.348	.429	.777	-740
4	.635	.529	1.164	.631	.559	1.190	-956

The relatively good agreement between the totals for the anode and structure indicate there is relatively little current going to areas that are not in the system.

Other Comments:

The system appears to be working properly, provides flexibility for operation and monitoring.

At this time the conductive coating was visually inspected. Most questionable areas were examined and the coating was found to be sound. The failures in the coating that were noted could be attributed to either leaking cracks in the deck or steel in contact with the coating. In the areas where brown staining has ocurred, a pach-o-meter was used to check for tramp metal and none was found. The cause of the staining is unknown at this time. The coating was given a good rating with less than 0.1% of the area rated as failed.


CATHODIC PROTECTION SYSTEM
YAQUINA BAY BRIDGE - NEWPORT, OR
FROM STRUCTURE
TO ANODES +
TO STRUCTURE REBAR ELECTRODES −
Mo-MoO3 REFERENCE ELECTRODES BEAM-BOTTOM
ANODES +
RECTIFIER UNITS
① ② ③ ④
EACH:
8 VOLTS 2 AMPS
(D.C. RATING)
REBAR PROBES-TO-STRUCTURE
STRUCTURE −
B: BEAM
D: DECK
0.01 OHM SHUNT
1 AMP = 0.01 VOLT DROP
8 AMP CAPACITY
(100 MA = 1 MV DROP)
Mo-MoO3 REFERENCE ELECTRODES - DECK BOTTOM
JUNCTION BOX SCHEMATIC
7-29-86
STRUCTURE
ANODES
PROBE
REFERENCE ELECTRODES
RECTIFIER
Mo-MoO3 REFERENCE ELECTRODE
REBAR PROBE
GROUND: CONNECTION TO REBAR
SYSTEM SCHEMATIC
① TYPICAL OF ② ③ & ④
PORTER CORROSION CONTROL SERVICES INC
DWG. No. F-2

APPENDIX 7

POTENTIAL PROFILES - TOP OF DECK
CONSULTANTS REPORT

YAQUINA BAY BRIDGE
EQUIPOTENTIAL PROFILES

INTRODUCTION:

On June 8, 1985, Norton Corrosion Limited, Inc. (NCL) personnel conducted equipotential profiles on a section of the Yaquina Bay Bridge upper deck immediately above a recently installed soffit and substructure cathodic protection system. Potentials were obtained immediately prior to and immediately after energizing that cathodic protection system. On July 24, 1985, and again on May 21, 1986, NCL personnel obtained additional profiles of the same section. During all four tests NCL was assisted by Mr. H. M Laylor, Oregon State Highway Division Research Project Coordinator, and by Highway Division traffic control personnel.

DESCRIPTION OF AREA MAPPED:

The section of deck mapped is located in the north bound lane of U.S. Highway 101 on the north end of the Yaquina Bay Bridge. The northern most edge of the three profiles is approximately 42.4' south from the expansion joint at the first bent south of the north approach plaza. The profiles obtained extend west from the east curb to approximately the centerline of the highway.

TEST PROCEDURES:

Potentials were obtained using a high internal impedance electronic voltmeter in conjunction with a $CuCuSO_4$ reference

cell. The voltmeter has internal electronic data storage. The reference cell was fitted with a sponge and the concrete wetted with a soap solution in accordance with ASTM C876-80. Connection to the structure was achieved using a permanently exposed piece of rebar welded to the upper mat. The exposed piece of rebar is located at the curb and equates to the upper right hand corner of all four profiles. Individual potentials were obtained on a grid basis, 5.5 inches on center.

The data collected was directly transferred from the voltmeter to a computer which generated the maps using a modified surveying program. On the attached maps and data sheets chainage is in inches and potentials are in millivolts D.C.

PROFILES:

June 8, 1985 - "Off" (Grid 001):

The most notable feature of this profile is the relatively electropositive potentials. The soffit, T-beams and diaphragms beneath Grid 001 are coated with a cathodic protection/conductive material and a top coat. This coating extends approximately 5 feet south of the sourthern most edge of Grid 001. Excepting the negative potentials associated with the exposed rebar (structure connection) at N121:E165, the potentials observed for Grid 001 are about 100 to 150 mv more electropositive than potentials obtained on a random basis in an area about 5 to 10 feet south of the southern end of the cathodic protection coating system. This grid was taken less

than on hour prior to energizing the cathodic protection system.

June 8, 1985 - "On" (Grid 002):

This profile was obtained within an hour after energizing the cathodic protection system. The most notable feature of this grid is that even though the cathodic protection system was designed for and adjusted to protect the substructure and bottom deck mat reinforcement, significant current is being provided to the upper mat as well. Even in areas where there exist geometric impediments (e.g. over the T-beams) potential shifts in excess of 100 mv from "off" are observed. IR voltages are included in this grid. However, over T-beams and diaphragms this spurious voltage inclusion may reasonably be expected to be small. For this grid the protective current averaged 0.85 ma/ft^2 of concrete as applied to the soffit.

July 24, 1985 - "On 46 Days" (Grid 003):

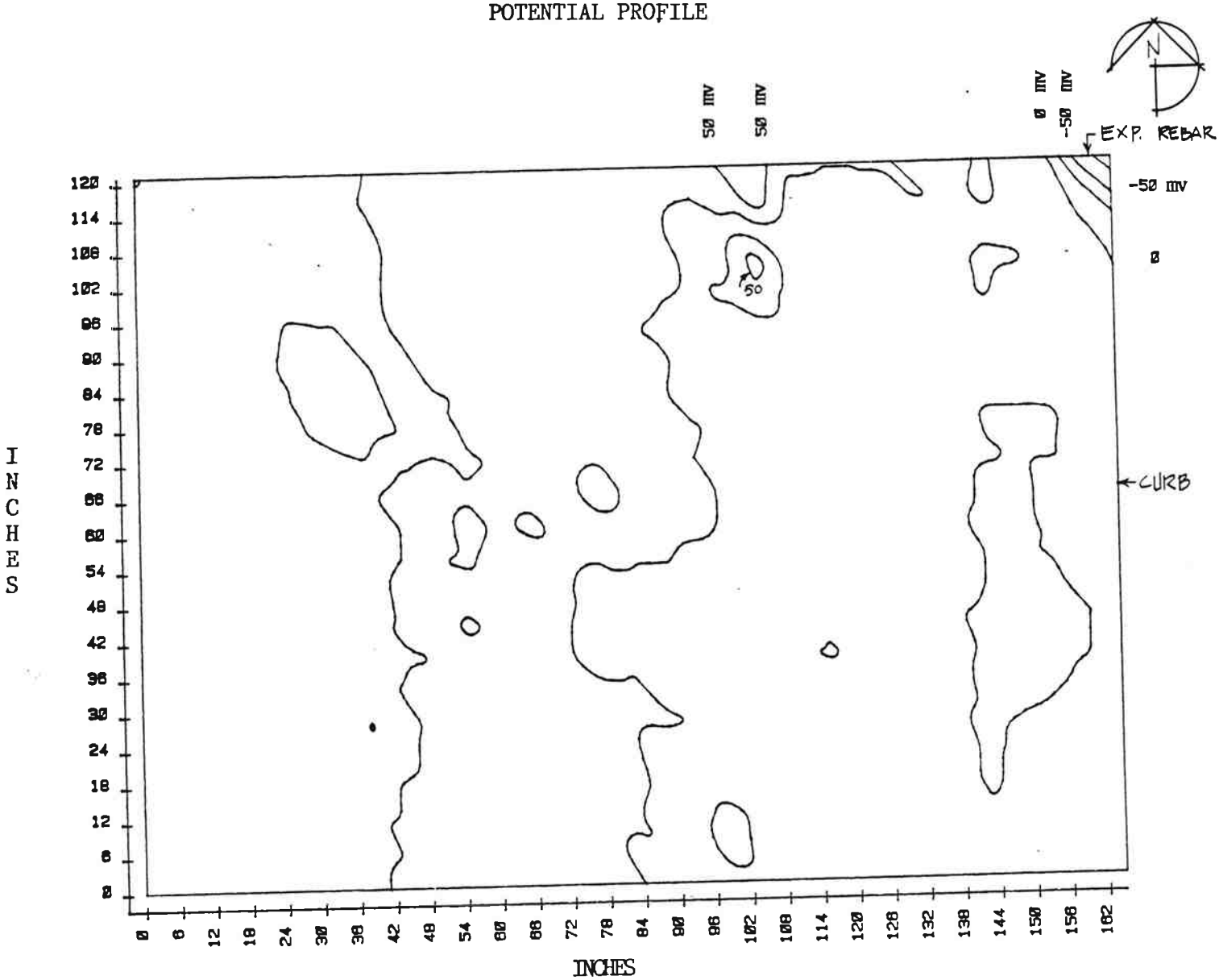
The most notable feature of this grid is the evening out of current distribution. This is seen by the electronegative shift in potentials in areas over the T-beams and diaphragms and electropositive potential shift elsewhere for Grid 003 relative to Grid 002. To assist in seeing this improvement in current distribution with time, histograms for Grids 002 and 003 are included. The histogram cells are 10 mv wide. The histogram Y-axis are the number of readings observed within the cell. The histogram X-axis are the potential readings (negative millivolts). Normal curves are superimposed on each histogram. Note that the mean potential for the two

are within 2 mv of each other. Also note the significant reduction in coefficient of variance and standard deviation. The distribution of the data appears bimodal in both cases. For Grid 003 the current averaged 0.95 ma/ft^2 of concrete as applied to the soffit.

May 21, 1986 - "On One Year" (Grid 004):

In November of 1985 the protective current output to the soffit area beneath the region appearing in Grids 001 through 004 was reduced. The protective current output to the soffit when Grid 004 was obtained averaged 0.24 ma/ft^2 of concrete. This level of output is approximately one-quarter of that applied when Grids 002 and 003 were obtained. Therefore, that the mean potential for Grid 004 is more electropositive than those obtained for Grid 002 and 003 is not surprising. The histogram for Grid 004 does not reflect the bimodal distribution seen for Grids 002 and 003. However, the map itself does show the effect of geometric impediments (stringer beam) in the area NO:EO--N108:E60.

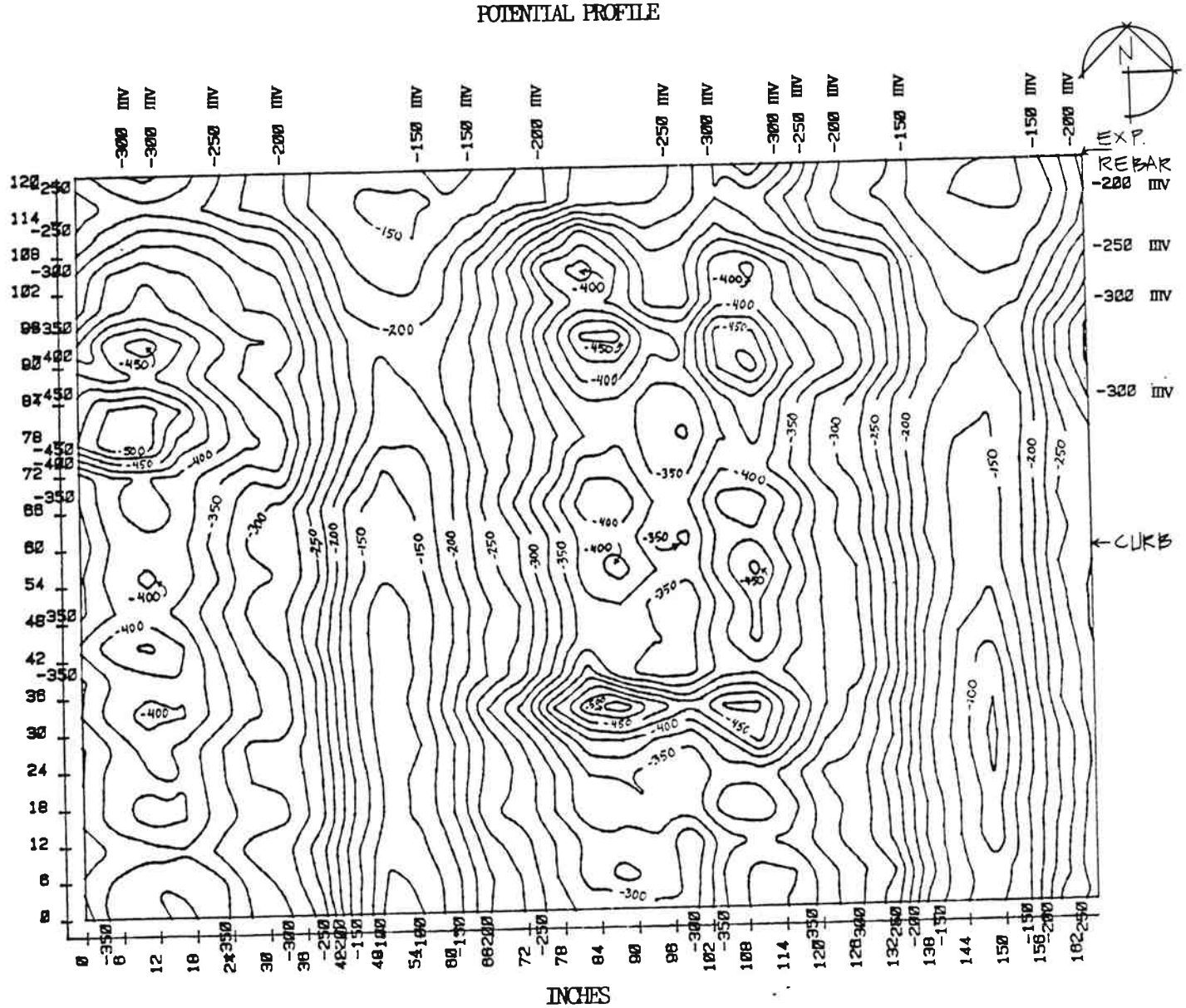
POTENTIAL PROFILE



SYSTEM OFF - June 8, 1985

GRID 001

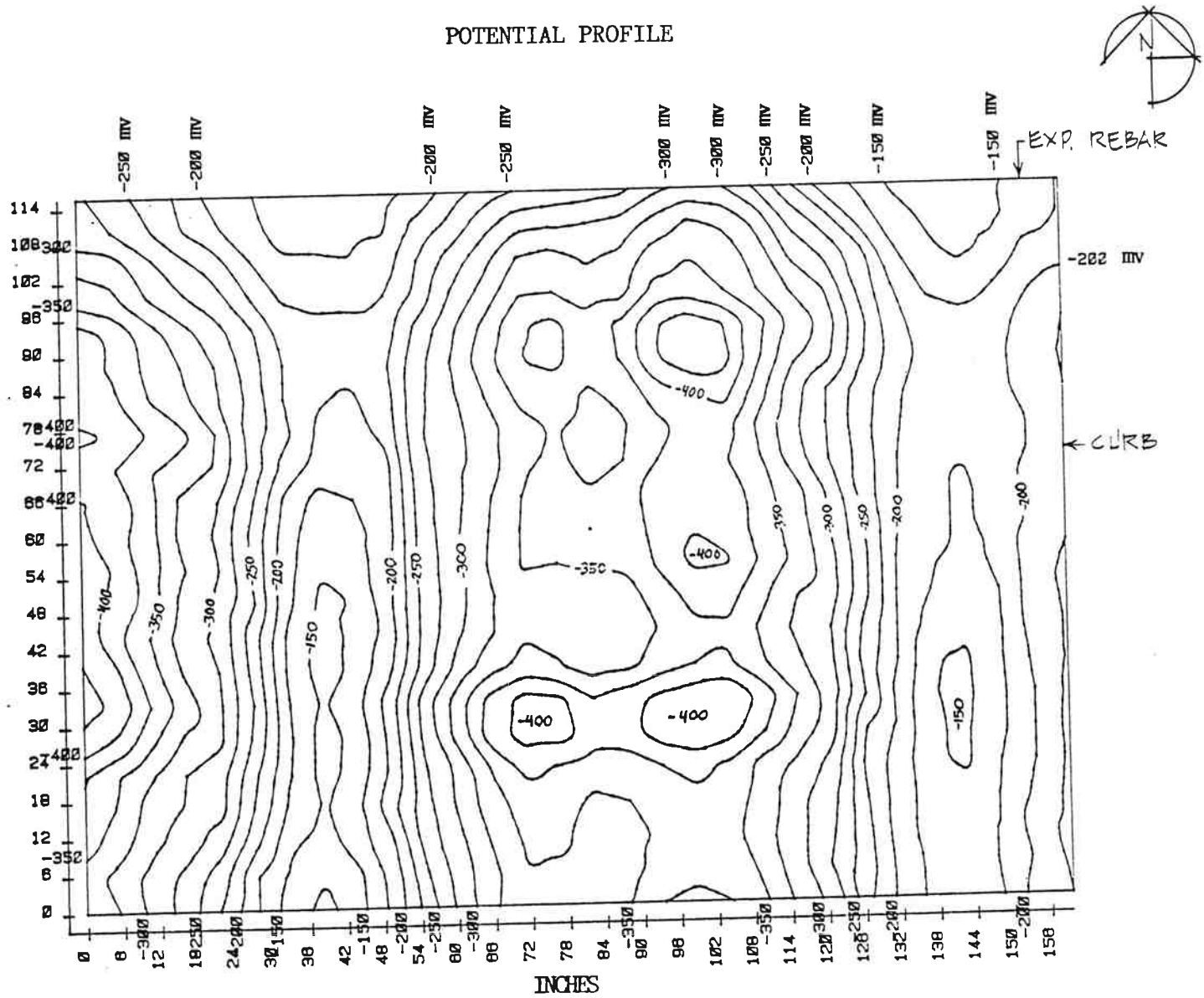
POTENTIAL PROFILE



SYSTEM ON - June 8, 1985

GRID 002

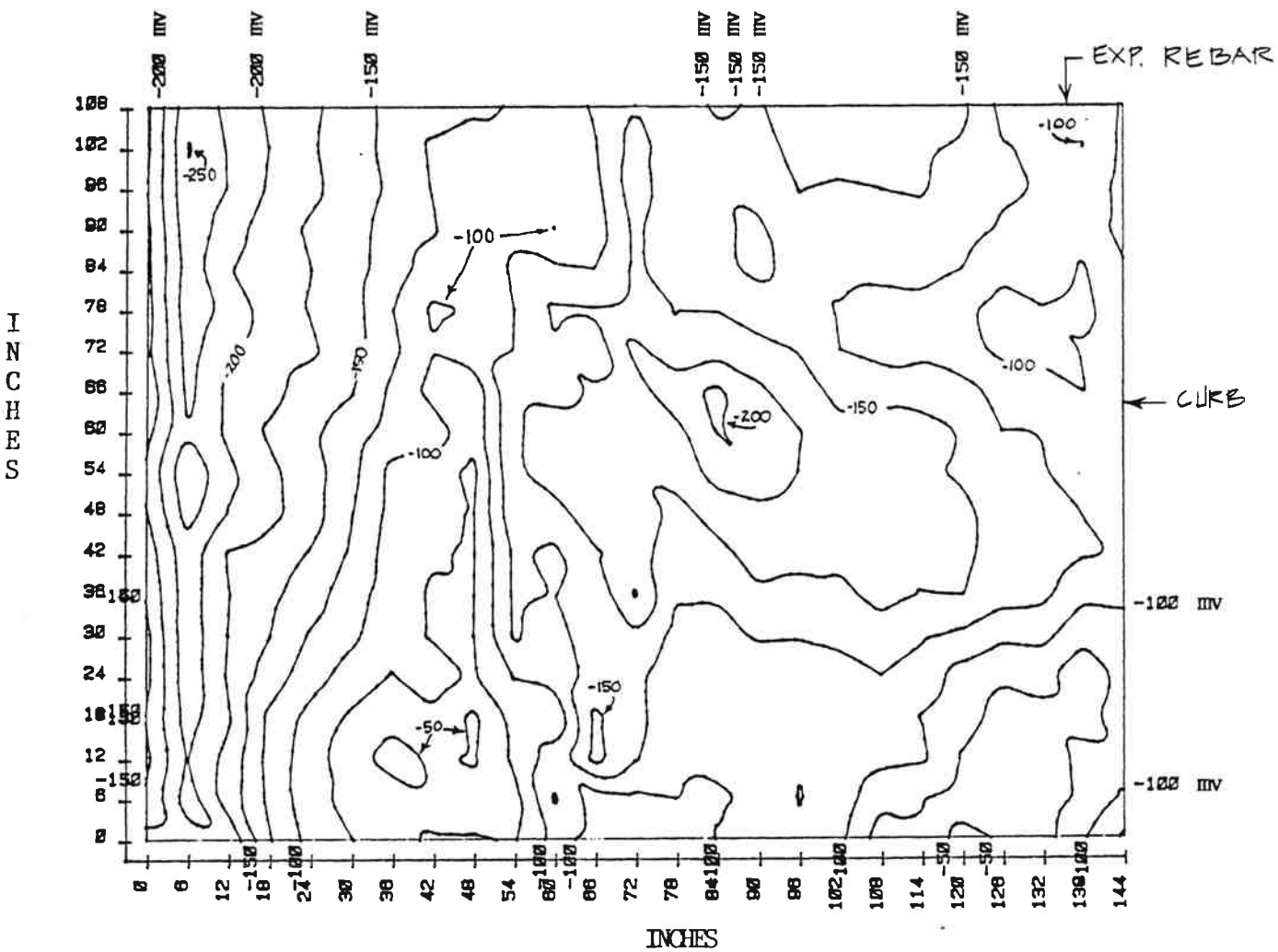
POTENTIAL PROFILE



SYSTEM ON 46 days - July 24, 1985

GRID 003

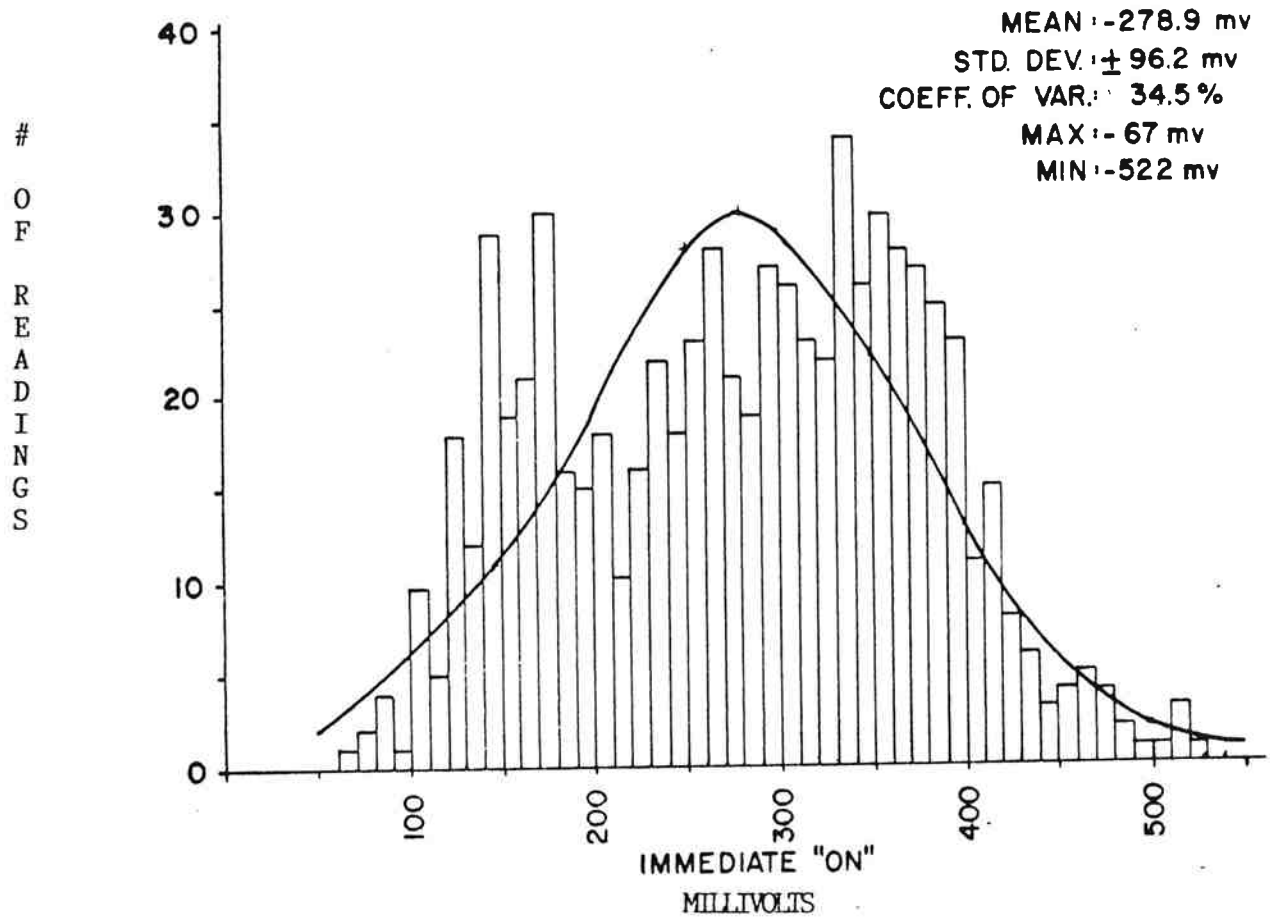
POTENTIAL PROFILES



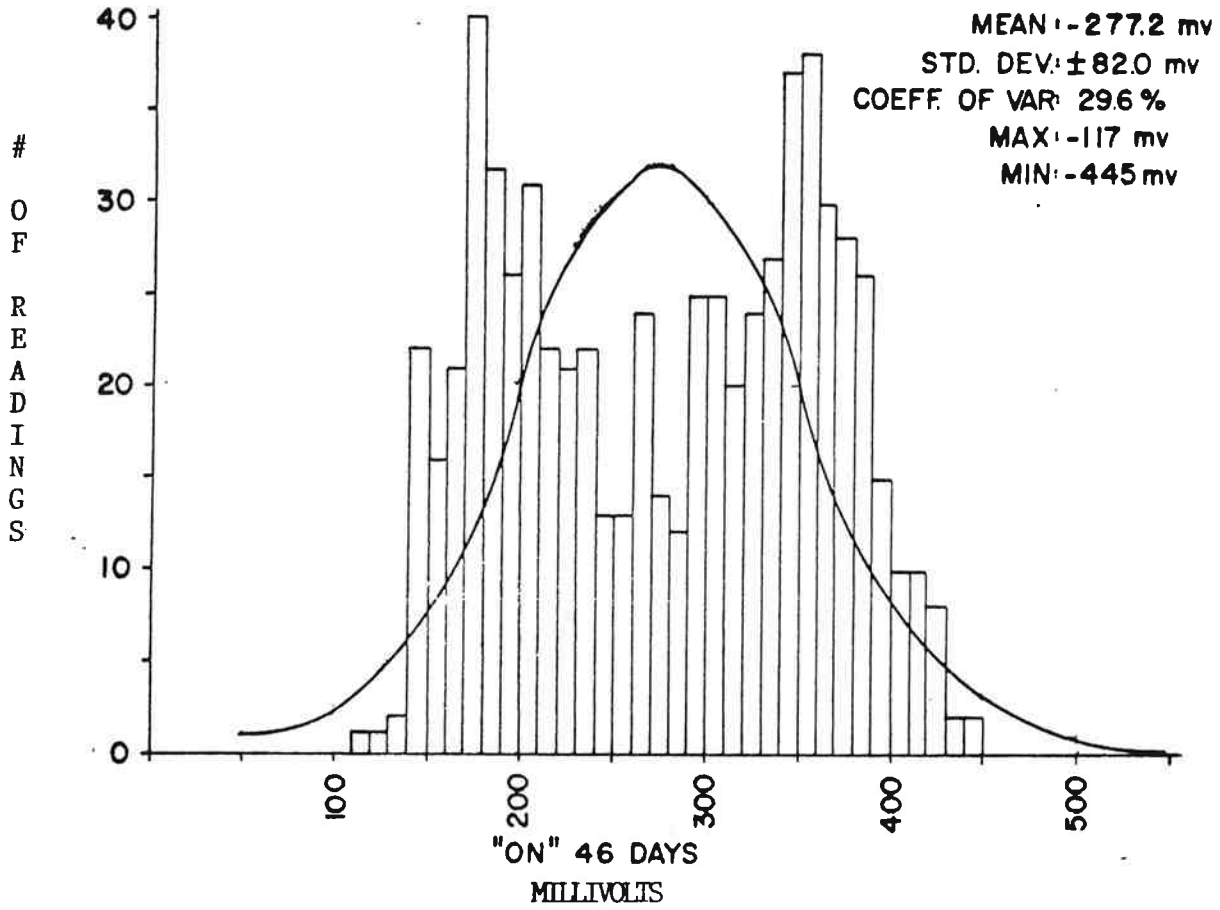
SYSTEM ON ONE YEAR - May 21, 1986

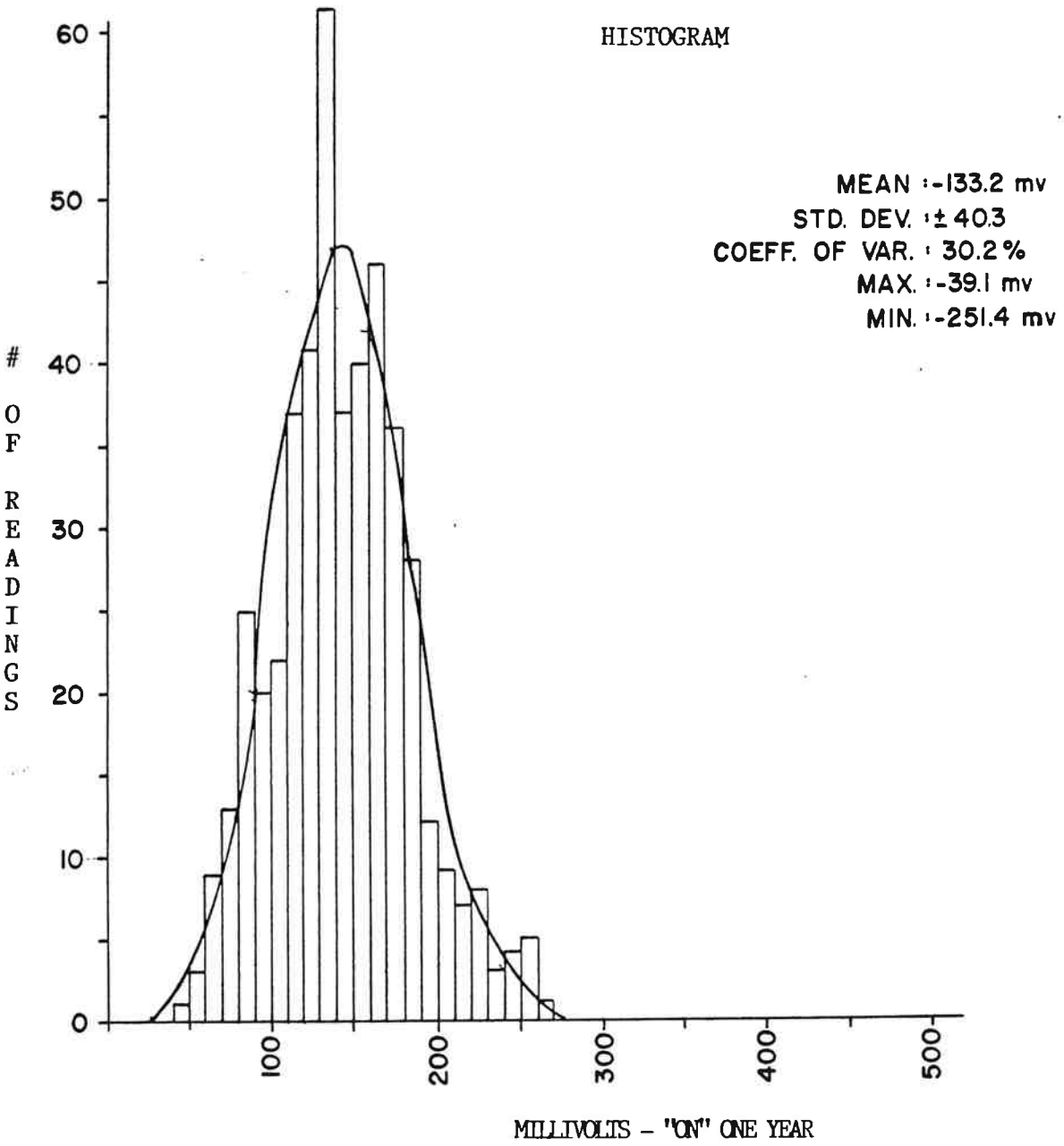
GRID 004

HISTOGRAM


MEAN : -278.9 mv
STD. DEV. : ± 96.2 mv
COEFF. OF VAR. : 34.5 %
MAX : - 67 mv
MIN : -522 mv
OF READINGS
40
30
20
10
0
100
200
300
400
500
IMMEDIATE "ON"
MILLIVOLTS

HISTOGRAM


MEAN: -277.2 mv
STD. DEV.: ±82.0 mv
COEFF. OF VAR: 29.6 %
MAX: -117 mv
MIN: -445 mv
OF READINGS
40
30
20
10
0
100
200
300
400
500
"ON" 46 DAYS
MILLIVOLTS


HISTOGRAM
MEAN : -133.2 mv
STD. DEV. : ± 40.3
COEFF. OF VAR. : 30.2 %
MAX. : -39.1 mv
MIN. : -251.4 mv
OF READINGS
60
50
40
30
20
10
0
100
200
300
400
500
MILLIVOLTS - "ON" ONE YEAR