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Carderock Division
Naval Surface Warfare Center

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Survivability, Structures, and Materials Directorate

Technical Report

Verification of the Boundary Element Modelling Technique for Cathodic Protection of Large Ship Structures

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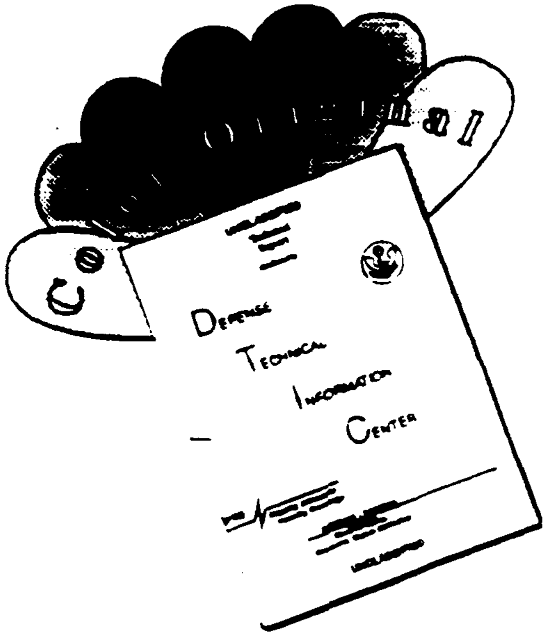

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ABSTRACT

Boundary Element computer modeling is gaining acceptance as a tool for predicting the distribution of cathodic protection potentials on a variety of large immersed structures. In particular, the offshore oil industry has used this technique to design cathodic protection systems for offshore oil platforms. This technique would also be valuable for placement of cathodic protection anodes and reference cells on ship hulls. Much has been published on this technique, including experimental verification on a laboratory scale. However, there has been little published information on experimental verification of the model predictions on large structures, especially for ships. Since the accuracy of any computer model depends on the polarization curves used as boundary conditions for the model, experimental verification is necessary to insure that the proper polarization conditions have been chosen.

This study is aimed at verification of this technique on large ship hulls. Specifically, a 42-ft (14-m) barge was outfitted with a steel "rudder", copper-based alloy "propeller", zinc sacrificial anodes, and an array of reference cells to measure the distribution of potential over the surface of the hull and appendages. The barge was exposed in natural seawater for 4 months. A computer model was developed to predict the distribution of protection, using a boundary element analysis program (BEASY) and long-term, potentiostatic polarization curves as boundary conditions. The model predictions are compared to the measured potential distributions, and the implications for coated hulls, larger ships, and motion of the hull discussed.

Polarization curves are presented which give good agreement between model predictions and the actual measurements on the uncoated steel barge hull under low flow conditions. More information on polarization behavior for coated surfaces and surfaces under flowing conditions is needed for accurate predictions to be made over a full range of ship operating conditions.

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ADMINISTRATIVE INFORMATION

This project was supported by the Carderock Division, Naval Surface Warfare Center, Ship and Submarine Materials Block Program under the administration of Code 0115. The program manager is Mr. Ivan Caplan. The work was conducted under work unit 1–2813–859 and satisfies the final milestone for fiscal year 1992. The work was conducted in the Marine Corrosion Branch, Code 613, under the direction of Mr. Robert Ferrara. Outfitting and testing of the barge was conducted by the staff of the LaQue Center for Corrosion Technology under the direction of Mr. Dennis Melton. Particular recognition is given to David East and John Feeley for performing the measurements. Help with computer programming difficulties was given by the staff of Computational Mechanics, Inc.

INTRODUCTION

Submerged steel structures, such as platforms and ships, usually require cathodic protection to minimize corrosion damage in seawater. This protection is provided by impressed current or sacrificial anodes located at discrete points on the structure. The level of protection is greatest near the anodes and falls off at large distances [1]. The non-uniformity of protection can lead to over-design of the protection system. This is because the overall level of protection must be increased until the point with the least protection on the structure is receiving adequate protection. This over-design can lead to wasted current or anode material and can also lead to paint blistering or hydrogen embrittlement in areas near the anodes. Cathodic protection system designers therefore strive for uniformity of protection on the structure.

Uniformity of protection was, until recently, arrived at in a cathodic protection system design primarily by the use of rules-of-thumb and empirical experience. More recently, construction of physical scale models has been used with some success to optimize placement of anodes [2]. In many cases the use of physical scale modeling will produce results of sufficient accuracy for optimizing anode placement. There is some theoretical basis for a belief that there are inherent inaccuracies in this type of modeling for large structures in seawater, however [3]. In addition, effects of flow on moving structures are difficult to reproduce in scale model tests. For these reasons, as well as for reasons of cost of model construction, the use of computers to predict uniformity of protection is emerging as a viable alternative. Although computer modeling accuracy has been verified in small scale laboratory situations[4–5], as of now there is little published evidence of verification of this technique on large structures.

Boundary element computer modeling was originally developed for mechanical problems such as deformation, but has found application in heat flow analyses. The method is similar to finite element analysis in that the LaPlace Equation is solved within the structure of interest after first defining conditions at the edge (boundary) [6]. The structure of concern is divided into small elements, or discretized, and a series of simultaneous equations is obtained from the LaPlace Equation, one for each element [7]. The boundary element method requires that only the edges of the structure be modeled, since Greene's Theorem is used to convert the volume integrals inherent in a 3D analysis to surface integrals [5]. The boundary element technique has found application in heat flow problems where the temperatures at the edges are the only variables known or of interest.

The parallel between heat flow and corrosion currents has recently been recognized and the boundary element technique applied to corrosion problems. The parallel is this: heat flow becomes electron flow (current) and temperature becomes electrochemical potential [8]. Thus, heat flow boundary element programs can be used for solution of corrosion problems. A complication arises when the conditions at the edges are considered. In heat flow analyses, boundary conditions are typically constant temperature, constant heat input, or convection (heat input versus temperature). In corrosion, the boundary conditions are the relationships between current and potential (called polarization behavior) for the materials and environment. Polarization behavior may not be single-valued or monotonic, requiring special consideration in programming [9]. This area of work is so new that only two companies have boundary element programs that can handle corrosion boundary conditions, and one of these programs has other limitations.[10] The other program, called Boundary Element Analysis System (BEASY) was used for this study.

The intent of this paper is to illustrate that computer modeling can accurately predict the distribution of cathodic protection on large structures resembling ship hulls in seawater. The polarization curves used to obtain the best agreement between the computer model and measurements on a large structure are also presented.

EXPERIMENTAL PROCEDURE

BARGE TESTS

Accuracy of computer modeling for ship hulls was investigated by using an 18 by 42–foot (6 by 14–m) steel barge to compare with the computer model. The same barge was first exposed without coatings for 4 months, then hauled, cleaned, and re-exposed with a coating system applied for an additional 4 months.

The barge, shown in Figure 1, was first hauled and sandblasted. It was then fitted with sacrificial anodes as follows: a group of six anodes at the stern midline, a group of eight anodes at the center midline with a group of four additional anodes on each end of the central grouping, and two groups of six anodes each at the outer edges on both sides. The anode groups were electrically isolated from the barge and externally connected to allow measurement of the protection current each group provided. A copper-nickel plate, roughly 32 by 36–in. (0.8 by 0.9–m) was suspended 0.9–ft (0.3–m) below the keel at the aft portion of the barge and oriented athwartships. This plate was designed to simulate a copper-alloy propeller and the plate-to-hull area was set to be representative of a real ship. A second plate, 37 by 38.5–in. (1.0 by 1.0–m) square made of steel, was suspended with its leading edge even with the stern, 3–ft (1–m) behind the first, and with its top edge parallel to the stern and at a height even with the keel. The area and orientation of this plate were set to simulate the rudder of a real ship. Both plates were wired back to the hull so that protection current could be measured. Finally, the barge was outfitted with an array of 34 silver/silver-chloride reference cells to measure the uniformity of protection. The locations of the anodes and reference cells are shown in Figure 2.

After outfitting, the barge was placed in the water at the shipyard facility, located on the Cape Fear River in Wilmington, NC, with the port and starboard anode groups disconnected. This facility has brackish water with a conductivity of 145–mmho/cm (0.81 ppt chloride). The barge was then towed to the test site in Banks Channel near Wrightsville Beach, NC. This location has full strength seawater with a conductivity of 50–mmho/cm (34.99 ppt chloride). The barge was moored at a location where the mean depth was roughly 11–ft (3.5–m). A series of current and potential measurements were then taken daily except for weekends until the total exposure period elapsed. Initially the anode groups at the edges of the barge were not connected, but it was determined that the barge required the additional anodes to get adequate protection, and so these anode groups were connected after 8 days. A total exposure period of 4 months was chosen because earlier tests at this location had shown that stability of protection current was reached in that time. [11] At the conclusion of the test, all but the aft set of zincs were disconnected to get a greater potential gradient along the barge length. Measurements were taken after the protection system had been allowed to stabilize for 7 days. The barge was then towed back to the shipyard where measurements were taken in the lower conductivity water for an additional 2 days.

Next, the barge was hauled, sandblasted, and coated with the standard Navy F–150/F–151 epoxy anti-corrosion coating system with a standard F–120 copper-based antifoulant topcoat. All anode groups were removed and the areas where they had been were intentionally left uncoated to simulate coating defects. The one exception was the stern group of six anodes, which was remanufactured into three groups of two anodes each using new anodes, and reattached in the same location. The plate that simulated the propeller was not coated, and a vertical strip on the forward edge of the rudder plate about 8–in. (0.20–m) wide, was left uncoated to simulate erosion damage to the rudder coating. The locations of the unpainted areas, anodes, and reference cells are shown in Figure 3.

After outfitting, the coated barge was placed in the water at the shipyard site and then towed to the same location in Banks Channel for testing. All three anode groups were connected initially, although the rudder plate was not connected for the first day due to the time it took to reconnect it. Current and potential readings were taken daily for 120 days, after which time the test was concluded and the forward two anode groups were disconnected, and data was collected for another two days. The barge was then towed back to the shipyard, where a final reading was taken in the brackish river water.

Besides monitoring currents from each bank of zincs, currents to the rudder and prop plates, and potentials of the reference cells, weight loss data was taken for each zinc in both barges to compare to integrated currents. This gave a check on the current measurement procedure and allowed for determination of zinc efficiencies.

COMPUTER MODELS

The exact barge geometry was modeled using the Boundary Element Analysis System (BEASY). This program is designed for corrosion problems and can handle time-dependent analysis[12] although that feature was not used in this study. The element structure used for the uncoated barge is shown in Figure 4. The grid used for the coated barge was similar but without the anode groupings and is shown in Figure 5. The model was symmetric about the centerline and waterline, and non-conducting surfaces were placed at the mud line and at a distance of 330 ft (100 m) around the barge. Three hundred thirty ft was chosen as it was expected that the potential gradients would be minimal at that distance. These surfaces, shown in Figure 6, were necessary since the program required that the model be totally enclosed.

The zinc surfaces were initially assigned the polarization conditions shown in Figure 7, the steel surfaces were initially assigned the conditions shown in Figure 8, and the copper-nickel surfaces assigned the conditions in Figure 9. These polarization curves were obtained from long-term potentiostatic polarization tests conducted in a previous project [11]. Later, when barge measurements were available, the discrepancies between the computer model results and the barge measurements were used to make minor modifications in the polarization curves used to improve the degree of fit. These modifications were kept within the limits of scatter of the original data from which the curves were generated.

RESULTS AND DISCUSSION

BARGE TESTS

Data taken during the uncoated and coated barge exposures are shown in Tables 1 and 2, respectively. Water temperature at the test site is also shown in Figure 10 for the uncoated barge test, and in Figure 11 for the coated barge test. The average water temperature was almost 10 degrees Celsius cooler during the coated barge test, which would lead to higher surface dissolved oxygen concentrations and different calcareous deposit and fouling deposit formation kinetics in the latter test as compared to the former. In fact, fouling in the cooler water on the barge with anti-fouling paint was found to be significantly less than that in warmer water, with an almost complete lack of hard fouling such as barnacles or clams, even on uncoated surfaces.

Figure 12 shows the current in amperes for each of the cathode surfaces. As expected, the current mostly went to the hull. Currents to all cathode surfaces initially began to fall, but jumped upwards after 8 days when the two edge anode groups were connected. Current continued to fall throughout the exposure, probably due to the buildup of calcareous deposits and fouling. Another drop in current was experienced near the end of the exposure when all of the anode groups except one were disconnected. Total current at the conclusion of the exposure was roughly one-third of the maximum current experienced after all anode groups were first connected.

Figure 13 shows the output of each of the anode groups during the same time period. Current output was zero from the two edge groups until they were connected at day 8 and was the highest thereafter, probably because each group was so far from any other group. Near the end of the exposure, when all other anode groups were disconnected, current from the aft group increased to try to make up for the difference.

Weight losses of each of the anodes are given in Tables 3 and 4 for the uncoated and coated barges, respectively. These values are summed for each group and compared to the integrated current for that group to calculate an electrochemical efficiency for each anode group and for all anodes on each barge. Efficiencies for each group ranged from 65 to 114 percent, indicating that the current measurement or integration technique was not sufficiently accurate. This is probably due to sampling times for current data of 1 to 3 days being too high. The average efficiencies for the anodes in the two tests were 86 to 88 percent, which is low for zinc anodes. Initial high currents occurred for several hours before the first readings were taken, and currents could not be read during the two towing operations for each exposure. Both of these would lead to lower measured efficiencies than were actually experienced by the anode material.

Figure 14 shows current data for the cathode surfaces of the coated barge. Hull currents were lower by a factor of about 20 due to the presence of the coating, with the remainder of the current likely going principally to the defect areas at the old zinc locations. After a rapid initial dropoff in the first 4 days, current dropoff was much slower than in the warmer water exposure, possibly indicating less blockage of current by hard fouling organisms during the later parts of the exposure. Disconnecting two anode groups caused a current drop of roughly 50 percent at the end of the test.

Table 1. Exposure data for uncoated barge.

CORROSION POTENTIALS AND GALVANIC CURRENTS FOR BARGE TESTS

POTENTIAL: millivolts vs Ag–AgCl

VOLTAGE DROP MILLIVOLTS / 0.01 OHM RESISTOR

DATE	DAY	1P	2P	3P	4P	5P	1S	2S	3S	4S	5S	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	1S	2S	3S	4S	5S	PROP	RUD	HULL	TEMP C
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

* Anode arrays 4 & 5 connected
** All anode arrays except 1 disconnected
*** Brackish water measurements

Table 2. Exposure data for coated barge.

DATE DAY 1S 2S 3S 4S 5S 1P 2P 3P 4P 5P 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 — VOLTAGE DROP MILLIVOLTS / 0.01 OHM RESISTANCE: 1S 2S 2S PROP RUD HULL — TEMP C

ANODES 2 & 3 DISCONNECTED READINGS TAKEN 30 MIN. AFTERWARDS

BARGE RELOCATED TO FRESHWATER (CAPE FEAR RIVER WILMINGTON, NC)

Table 3. Anode weight losses for uncoated barge.

Anode Number	Original Weight g	Final Weight g	Weight Loss g	Group Weight Loss, g	Theoretical Weight Loss from Currents g (efficiency)
1	4996.8	3794.6	1202.2		Stern
2	4768.0	3874.1	893.9		
3	4823.1	3862.0	961.1		
4	4813.0	3921.1	891.9		
5	4870.3	3946.4	923.9		
6	4801.2	3631.4	1169.8	6042.8	5180.6 (86%)
7	4862.2	3592.4	1269.8	Added	Ends
8	4932.1	3981.1	951.0	to	added
9	4724.4	3830.6	893.8	anodes	to anodes
10	4780.5	3859.8	920.7	19–22	19–22
11	4857.2	3991.9	865.3		Middle
12	4954.3	3962.0	992.3		
13	4863.7	3650.3	1213.4		
14	4929.8	4019.7	910.1		
15	4791.1	3859.9	931.2		
16	4905.3	3965.4	939.9		
17	4773.9	3889.2	884.7		
18	4809.3	3651.6	1157.7	7894.6	5098.1 (65%)
19	4850.2	4022.7	827.5		Ends
20	4844.2	4144.4	699.8		
21	4758.4	3939.8	818.6		
22	4983.6	3957.4	1026.2	7407.4	6089.0 (82%)
23	4462.2	3710.3	751.9		Starboard
24	4640.9	3977.3	773.6		
25	5000.8	4236.7	764.1		
26	5047.0	4242.7	804.3		
27	4978.9	4153.4	825.5		
28	4786.0	4023.2	762.8	4572.2	5228.2 (114%)
29	4842.0	4135.3	706.7		Port
30	4655.2	3926.3	728.9		
31	4875.2	3692.2	1183.0		
32	4666.1	3791.3	874.8		
33	4766.1	3885.1	881.0		
34	4914.2	4066.2	848.0	5222.4	5223.9 (100%)
Total	164327.2	133187.8	31139.4	31139.4	26819.8 (86%)

Table 4. Anode weight losses for coated barge.

Anode Number	Original Weight (g)	Final weight (g)	Weight Loss (g)	Group Weight Loss (g)	Theoretical Weight Loss from Currents (g) (efficiency)
1	4805.4	4337.5	467.90		Aft Stern
2	4697.6	435.5	342.1	810.0	802.4 (99%)
3	4852.8	4526.1	326.7		Mid Stern
4	4635.8	4321.9	313.9	640.6	521.8 (81%)
5	4887.5	4546.0	341.5		Fwd Stern
6	4523.9	4107.2	416.7	758.2	615.8 (81%)
Total	28403.0	26194.2	2208.8	2208.8	1940.0 (88%)

Figure 15 shows currents from each group of anodes over the same time period. The aft anode group delivered slightly higher currents, possibly due to its proximity to the uncoated propeller plate, while the least current was delivered by the central group of anodes as predicted by Dwight's equations[13]. The last set of data points, taken in brackish water, show a current decline of only about 20 to 30 percent.

Figure 16 shows the measured potential gradient longitudinally near the centerline of the uncoated barge. The level of protection is adequate and flat in the area of the zincs, and the amount of protection decreases, indicated by an electropositive shift in potential, at the forward end of the barge. Current demand from the prop and rudder plates caused a slight lessening of protection level at the aft end as well.

Figure 17 illustrates the transverse potential gradients at three points along the barge length. Since aft cells were located on both port and starboard sides, the data is plotted as the average of the cells on both sides, with an error bar indicating the individual cell readings. The midpoint line of cells goes past the edge anodes, resulting in increased protection at the vicinity of these anodes at nine feet distance. In general, the potential profile was symmetrical. Protection is best near the anodes and falls off towards the barge edges except near additional anodes.

Figure 18 shows longitudinal potentials for the coated barge. Even with many fewer anodes, the total protection is better than for the uncoated barge. In addition, the lower total current leads to less potential gradient and much better protection at the forward end of the barge. Transverse profiles in Figure 19 show gradients only for the aftermost line of cells that is adjacent to the zinc arrays. This profile is less than that of the uncoated barge. The protection level at the midline cells is flat due to their distance from the aft zincs and the lack of zinc groups at the barge edges. The small 10–mV increase in protection at the 9–ft distance is likely an artifact of the scatter in reference cell potentials rather than a real effect. Behavior of the forward cells should be considered flat, with the differences between cells due principally to scatter.

COMPUTER MODELS

It was desired to determine the sensitivity of the computer solutions to changes in the input polarization curve shape in order to see how accurately polarization behavior must be determined in order to get an accurate solution. To this end, a number of variations in polarization curve shape were tried during the modeling effort for the uncoated barge. These included changing current magnitudes for the anodic and cathodic materials individually by multiplying the currents for all points for a given material by the same factor, and changing currents for individual points on the steel cathode in order to change the magnitude and slope of the curve in the 900 to 1000 mV range.

Changing the magnitude of the cathodic currents changed the total current delivered to the component made from that material and shifted the potential of all points on the structure in the same direction. The difference between the predicted potential of the most positive and the most negative reference cells was directly proportional to the total current, but the points on the structure predicted to receive the most or the least protection did not change. Changing the magnitude of the anodic currents changed the predicted potentials without appreciably changing the magnitude of the predicted currents.

Changing the magnitude of the currents in an area of the curve in which the final predicted potentials did not lie had no effect on the results, but did change the convergence time for the computer to reach a solution. Changing the slope of the cathodic curve in the region where predicted potentials did lie had little effect on predicted potentials or currents, whereas changing current magnitudes in this area of the curve had similar effects to changing the magnitude of the entire curve. Various modeling changes were tried, and a general observation was that it was easier to predict potentials accurately than to predict currents accurately with inaccurate polarization data.

In summary, the shape and magnitude of the polarization curves used in the analysis had little effect on which area of the structure was predicted to receive the most or the least cathodic protection. Curve shape and magnitude outside of the range where the predicted potentials will lie also had no effect on the results of the analysis. Cathodic curves will affect the predicted currents more than predicted potentials. The opposite is true for the anodic curves, where the predicted potentials are affected more than the predicted currents. Finally, it was easier to predict potentials accurately than to predict currents accurately.

COMPUTER PREDICTIONS VERSUS ACTUAL MEASUREMENTS

Protection Potentials

Use of the original polarization curves for uncoated, unfouled steel did not result in good agreement between the computer prediction and the measured potentials for the uncoated barge. The best agreement was obtained if the computer model was run under the assumption that 50 percent of the cathode surfaces were electrochemically blocked by fouling. This is consistent with the amount of hard fouling observed visually (see Figures 20 and 21), and was accomplished by reducing the current densities of the cathode surfaces by 50 percent in the polarization curves used as boundary conditions. The result of this assumption was an agreement between measured and predicted potentials at the various reference cell locations which was within 20 mV except for three locations which were within 60 mV. These three locations, at cells 6, 11, and 23, were all predicted to have more protection than actually measured. Since these cells were all at the waterline, this effect could be due to wave action wetting more hull surface than was modeled. This is excellent agreement considering the number of reference cells and complexity of the barge structure. The measured and predicted potentials are plotted together in Figure 22.

The reference cells in this figure are in no particular order. The detailed potential distribution for the uncoated barge under these conditions, as generated by the computer model, is shown in Figure 23.

The best agreement in potential between the computer prediction and the measured potentials for the coated barge was obtained if the computer model was run under the assumption that none of the cathode surfaces were electrochemically blocked by fouling. Visually, the surfaces either had no hard fouling, as in the anti-foulant-painted areas and the uncoated rudder area, Figures 24 and 25, or were covered in soft fouling which could be inefficient in blocking the electrochemical currents, such as the uncoated hull areas and rudder plate, Figures 26 and 27. The differences in degree and type of fouling on uncoated surfaces of the two barge runs may be due to the difference in the season of the year during which the exposures took place. Figures 10 and 11 show the water temperature during the two exposures. Figure 28 shows that agreement between the measured and predicted potentials at the various reference cell locations for the coated barge was best (always within 15 mV, better agreement than for the uncoated barge) if the polarization behavior for the copper-nickel propeller plate was assumed to have roughly twice the current density at a given potential than the curve used for the uncoated barge. Using the same polarization curves as for the uncoated barge gave a uniform potential discrepancy of about 30 mV, and if a 50 percent fouling factor was also used, the resulting uniform potential discrepancy was 50 mV. The detailed potential distribution for the barge under these optimum conditions, as generated by the computer model, is shown in Figure 29.

Currents

Table 5 lists the measured and the predicted currents for the uncoated barge hull, rudder plate, propeller plate, and currents from individual zinc groupings. The predicted currents were always a factor of 1.4 to 1.5 higher than those measured, and the relative amount of current from or to each area is the same for the predictions and the measurements. This shows that current distributions are easier to predict than absolute values of current. The factor of 1.4 to 1.5 is reasonable, and is in the right direction for a conservative design for a cathodic protection system. The detailed current distribution for the uncoated barge under these conditions, as generated by the computer model, is shown in Figure 30.

Table 5. Currents for uncoated barge, amperes

Component	Measured	Predicted	Difference Factor
Hull	4.20	5.79	1.38
Propeller Plate	0.08	0.11	1.38
Rudder Plate	0.07	0.10	1.43
Outboard Zincs	−0.92	−1.26	1.37
Aft Zincs	−0.74	−1.12	1.51
End Midships Zincs	−0.96	−1.43	1.49
Center Midships Zincs	−0.81	−1.24	1.53

Table 6 lists the measured and the predicted currents for the coated barge hull, rudder plate, propeller plate, and currents from individual zinc groupings. The anode groups are somewhat different from the uncoated barge. Three prediction assumptions are listed. Agreement between prediction and measurement is not as good as for the uncoated barge if 50 percent fouling is assumed, as was assumed for the best fit with the uncoated barge data. The agreement does not improve significantly under the assumption of no-fouling conditions with increased copper-nickel current density that gave the best agreement in potentials. The best agreement between predicted and measured currents occurred if the surfaces were assumed to be unfouled, using the same polarization conditions as for the uncoated barge predictions. Regardless of the prediction assumptions, the relative distribution of current between zinc groupings was accurate, and the distribution between cathode surfaces less so. This is likely due to the difficulties associated with treating painted surfaces as pure insulators with no holidays or paint defects. In fact, even small paint defects will have a significant effect on the amount of current that is delivered to a painted surface. The detailed current distribution for the coated barge under the conditions where the best agreement in total cathode current was obtained, as generated by the computer model, is shown in Figure 31.

Table 6. Currents for coated barge, amperes

Component	Measured	Predicted (assumptions listed) 50% Fouled Uncoated Barge Polarization Curves that gave best Agreement	Not Fouled Increased Current Density to give best Potential Agreement	Not Fouled Same Current Density as Uncoated Barge
Hull	0.015	0.045	0.090	0.089
Propeller Plate	0.328	0.112	0.410	0.223
Rudder Plate	0.017	0.026	0.102	0.051
Aft Stern Zincs	–0.126	–0.098	–0.261	–0.167
Mid Stem Zincs	–0.102	–0.075	–0195	–0.126
Forward Stern Zincs	–0.132	–0.088	–0.226	–0.148
Total Cathode	0.388	0.176	0.602	0.363

Given the difficulty in getting simultaneous agreement between measured and predicted potentials and currents, it is difficult to conclude what the best polarization conditions are to make optimum computer predictions on a coated hull. The authors prefer to use the same polarization conditions as for an uncoated hull, with the degree of fouling being a variable which will be added depending on location and season. Using these assumptions will give the most accurate current predictions, and potential predictions which are off by only 40 mV. Current distributions and potential distributions should be accurately predicted regardless.

SUMMARY

The intent of this work was to illustrate that computer modeling can accurately predict the distribution of cathodic protection on large structures resembling ship hulls in seawater. The polarization curves used to obtain the best agreement between the computer model and measurements on a large structure were also to be determined. A detailed summary of this work follow:

BARGE MEASUREMENTS

Fouling in the cooler water on the barge with anti-fouling paint was significantly less than that in warmer water, with an almost complete lack of hard fouling such as barnacles or clams, even on uncoated surfaces.

The average efficiencies for the anodes in the two barge exposures were 86 to 88 percent, which is low for zinc anodes.

Hull currents were lower by a factor of about 20 on the coated barge relative to the uncoated barge, with the remainder of the current likely going principally to the defect areas at the old zinc locations.

Even with many fewer anodes, the total protection on the coated barge was better than for the uncoated barge. The lower total current on the coated barge led to less potential gradients and much better protection at the forward end of the barge.

MODELING

Changing the magnitude of the cathodic currents changed the total current delivered to the component made from that material and shifted the potential of all points on the structure in the same direction.

The difference between the predicted potential of the most positive and the most negative reference cells was directly proportional to the total current, but the points on the structure predicted to receive the most or the least protection did not change.

Changing the magnitude of the anodic currents changed the predicted potentials without appreciably changing the magnitude of the predicted currents.

Changing the magnitude of the currents in an area of the curve in which the final predicted potentials did not lie had no effect on the results, but did change the convergence time for the computer to reach a solution. Changing the slope of the cathodic curve in the region where predicted potentials did lie had little effect on predicted potentials or currents, whereas changing current magnitudes in this area of the curve had similar effects to changing the magnitude of the entire curve.

It was easier to predict potentials accurately than to predict currents accurately with inaccurate polarization data.

Changing cathodic curves will affect the predicted currents more than predicted potentials, whereas the opposite is true for the anodic curves.

MODEL PREDICTIONS

The best agreement between measured and predicted potentials and currents for the uncoated barge was obtained if the computer model was run under the assumption that 50 percent of the cathode surfaces were electrochemically blocked by fouling. This is consistent with the amount of hard fouling observed. This resulted in an agreement between measured and predicted potentials at the various reference cell locations which was within 20 mV except for three locations which were within 60 mV.

The best agreement in potential between the computer prediction and the measured potentials for the coated barge was obtained if the computer model was run under the assumption that none of the cathode surfaces were electrochemically blocked by fouling, which was verified visually.

Agreement between the measured and predicted potentials at the various reference cell locations for the coated barge was always within 15 mV, better agreement than for the uncoated barge, if the polarization behavior for the copper-nickel propeller plate was assumed to have roughly twice the current density at a given potential than the curve used for the uncoated barge. Using the same polarization curves as for the uncoated barge gave a uniform potential discrepancy of about 30 mV, still very good. If a 50 percent fouling factor was also used, the resulting uniform potential discrepancy was 50 mV.

The predicted currents were always a factor of 1.4 to 1.5 higher than those measured for the uncoated barge, and the relative amount of current from or to each area is the same for the predictions and the measurements.

Current distributions are easier to predict than absolute values of current.

The best agreement between predicted and measured currents on the coated barge occurred if the surfaces were assumed to be unfouled, using the same polarization conditions as for the uncoated barge predictions.

Regardless of the prediction assumptions, the relative distribution of current between zinc groupings was accurate, and the distribution between cathode surfaces less so on the coated barge.

The best modeling procedure overall was to use the same polarization conditions as for an uncoated hull, with the degree of fouling being a variable which will be added depending on location and season. Using these assumptions gave the most accurate current predictions, and potential predictions which were off by only 40 mV. Current distributions and potential distributions were accurately predicted regardless.

The computer model accurately predicted the protection currents and potential distribution on a large barge in brackish water and in seawater after a 4–month exposure. The zinc, steel, and copper-nickel polarization curves used to get the good agreement are presented.

CONCLUSIONS

Based on the BEASY computer model predictions and actual measurements on a 42–ft (14–m) barge simulating a steel ship, the following conclusions can be drawn:

1. Computer modeling accurately predicts potential distributions and currents for coated and uncoated barges when the polarization curves are adjusted for fouling under low flow conditions.
2. It is easier for a computer model to accurately predict potentials than currents.
3. If inaccurate polarization data is used in the computer model, resulting in disagreement between predicted and actual magnitudes of potentials and currents, the areas of the most and the least protection are still predicted accurately.

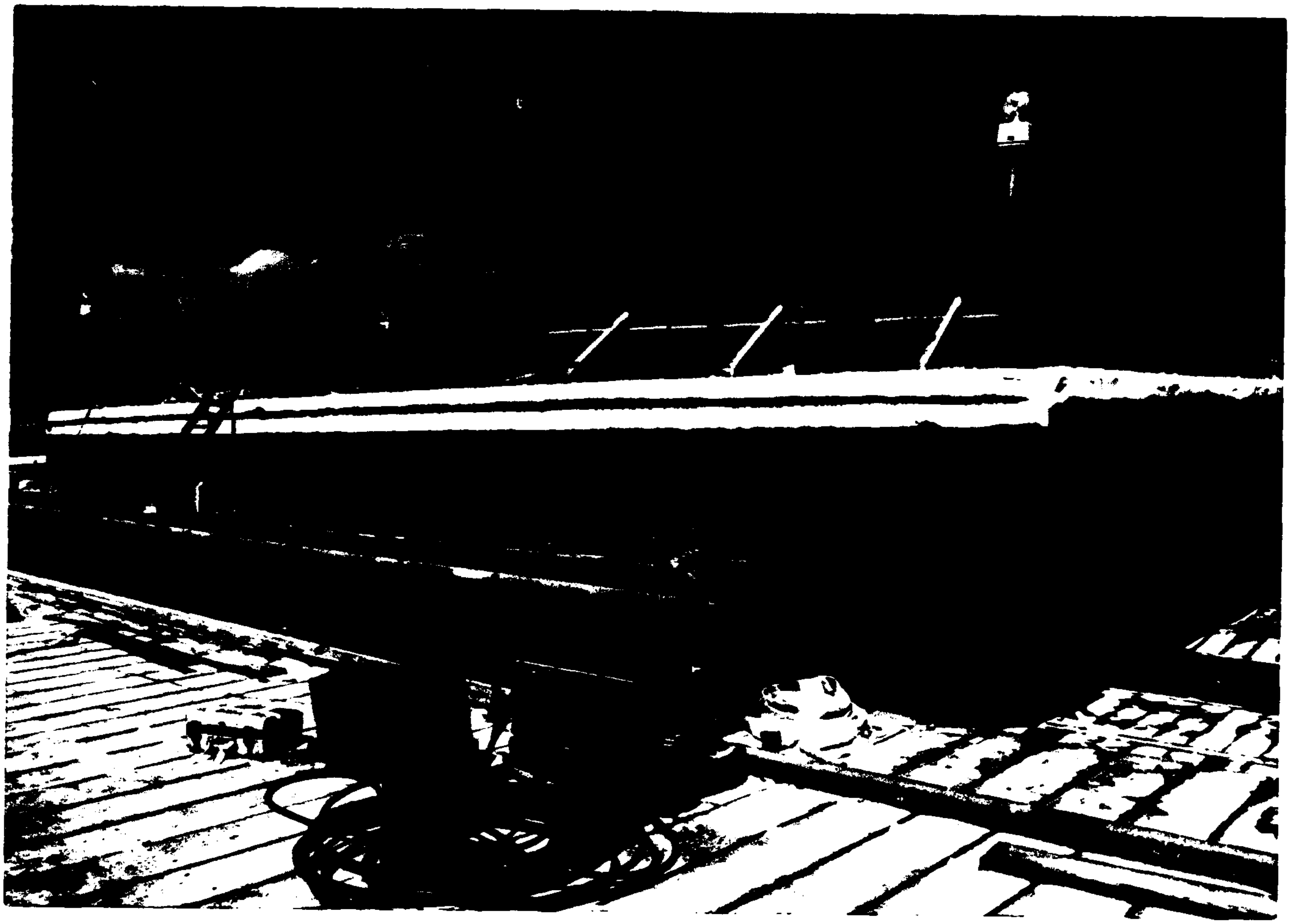

Figure 1. Test barge.

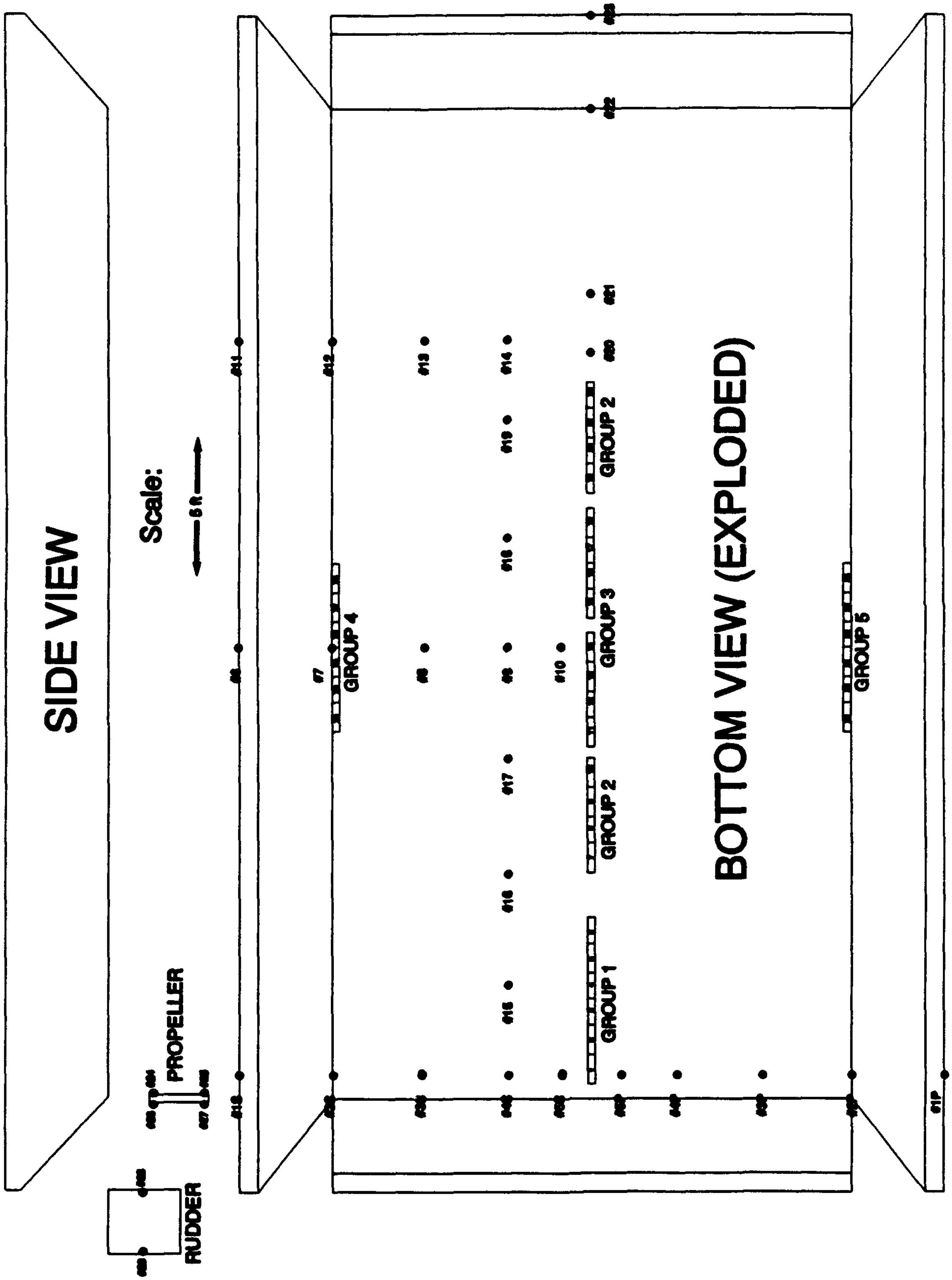

Figure 2. Anode and reference cell locations—uncoated barge.

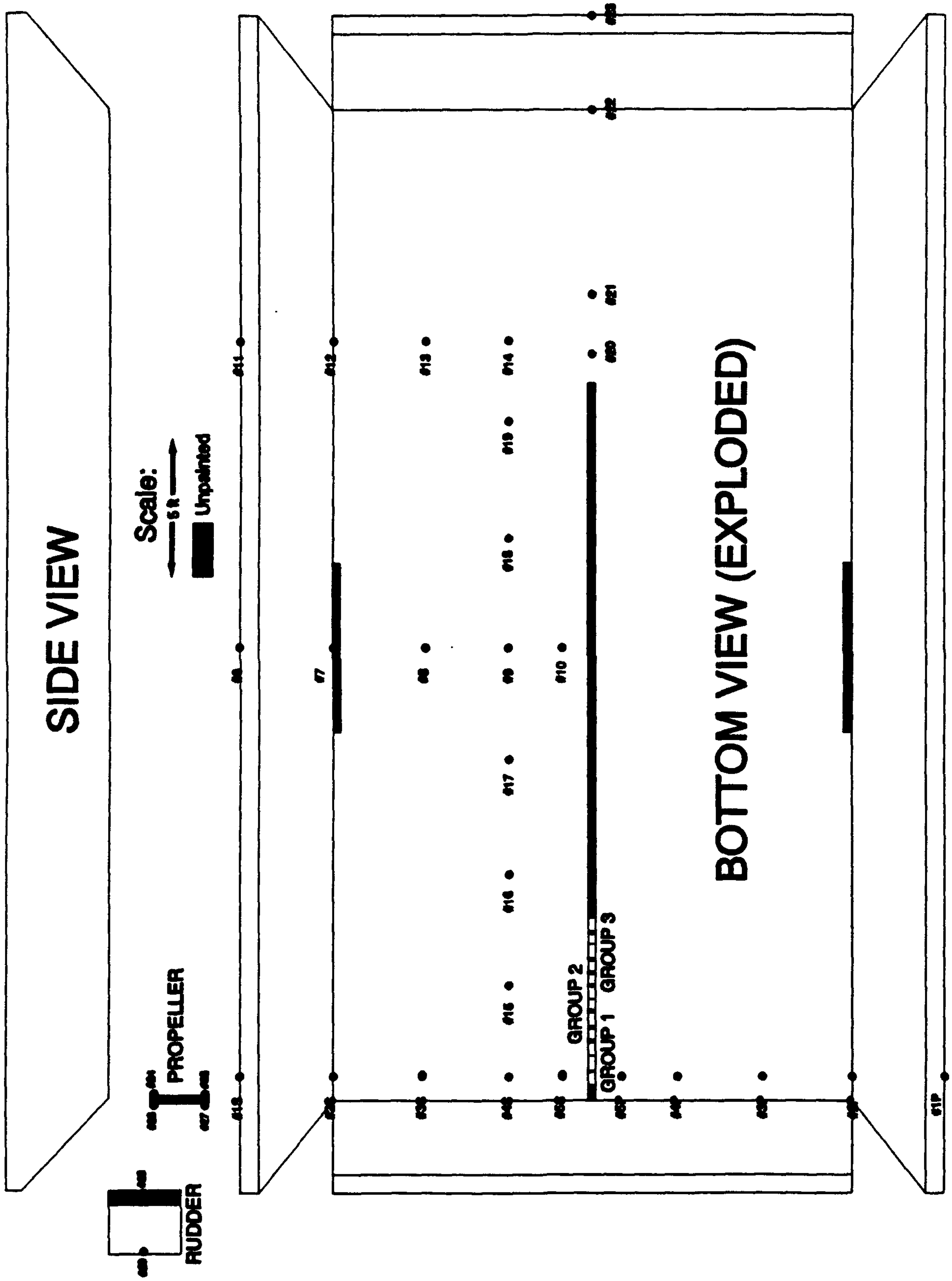

Figure 3. Anode and reference cell locations—coated barge.

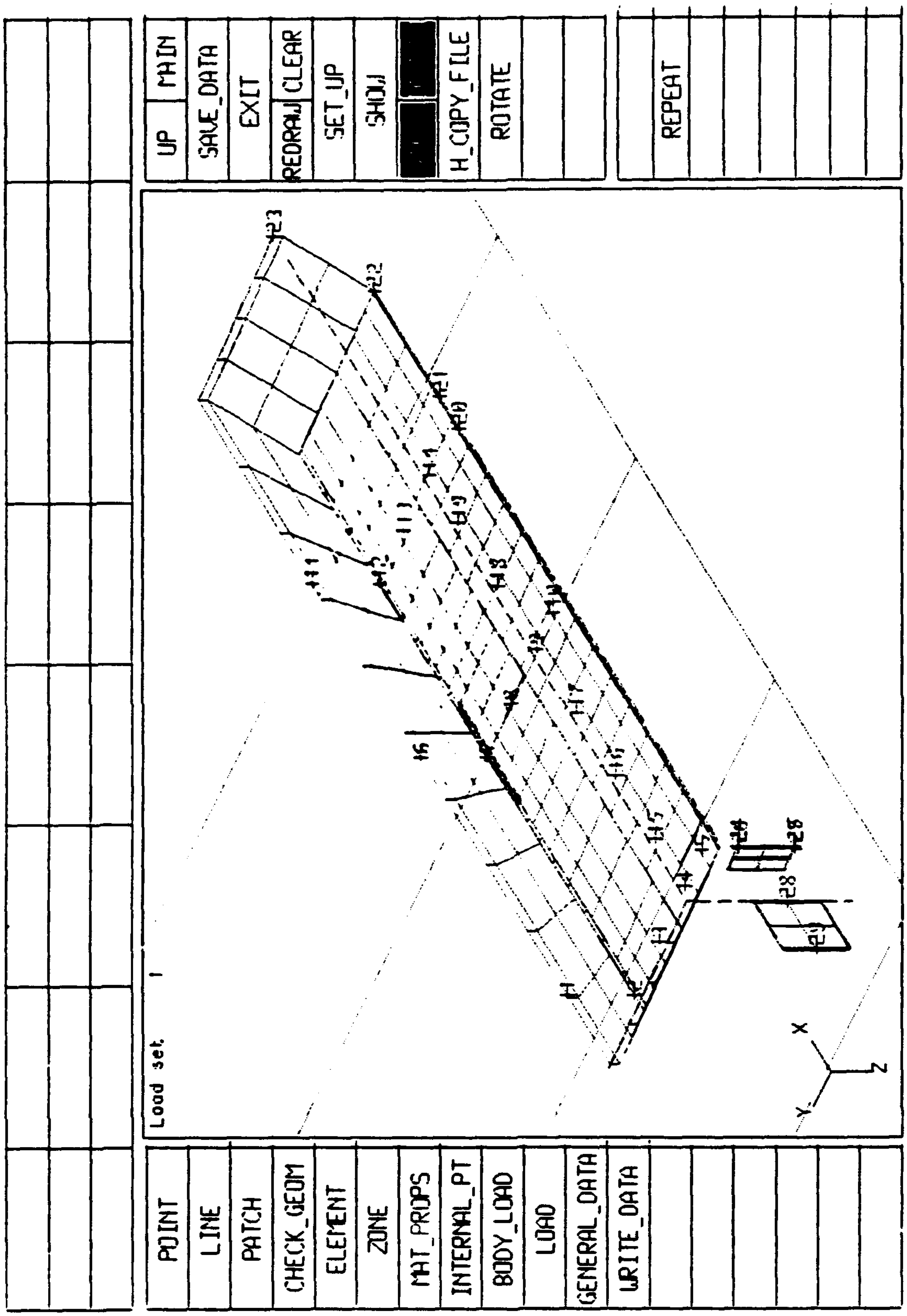

Figure 4. Boundary element grid for uncoated barge.

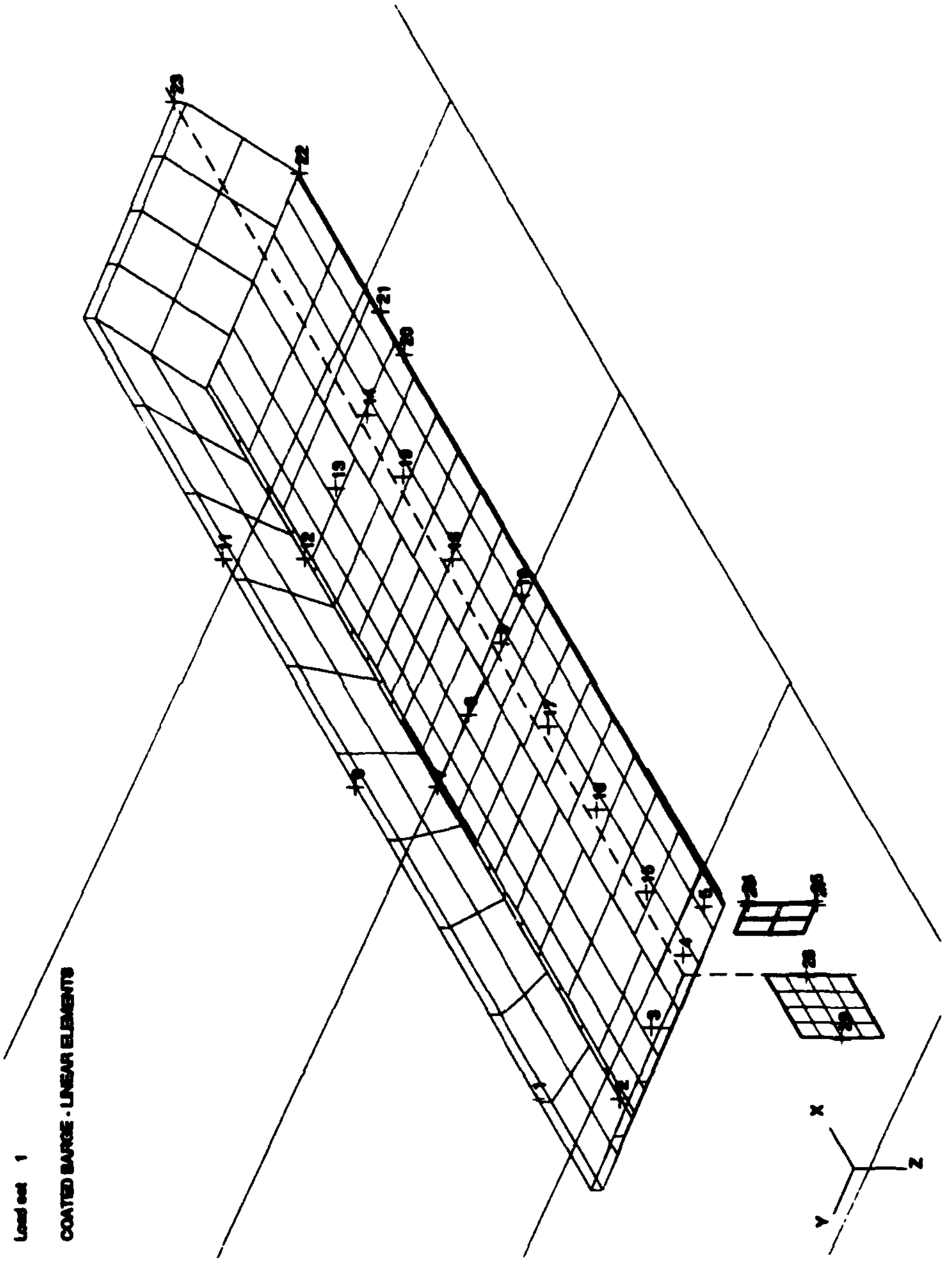

Figure 5. Boundary element grid for coated barge.

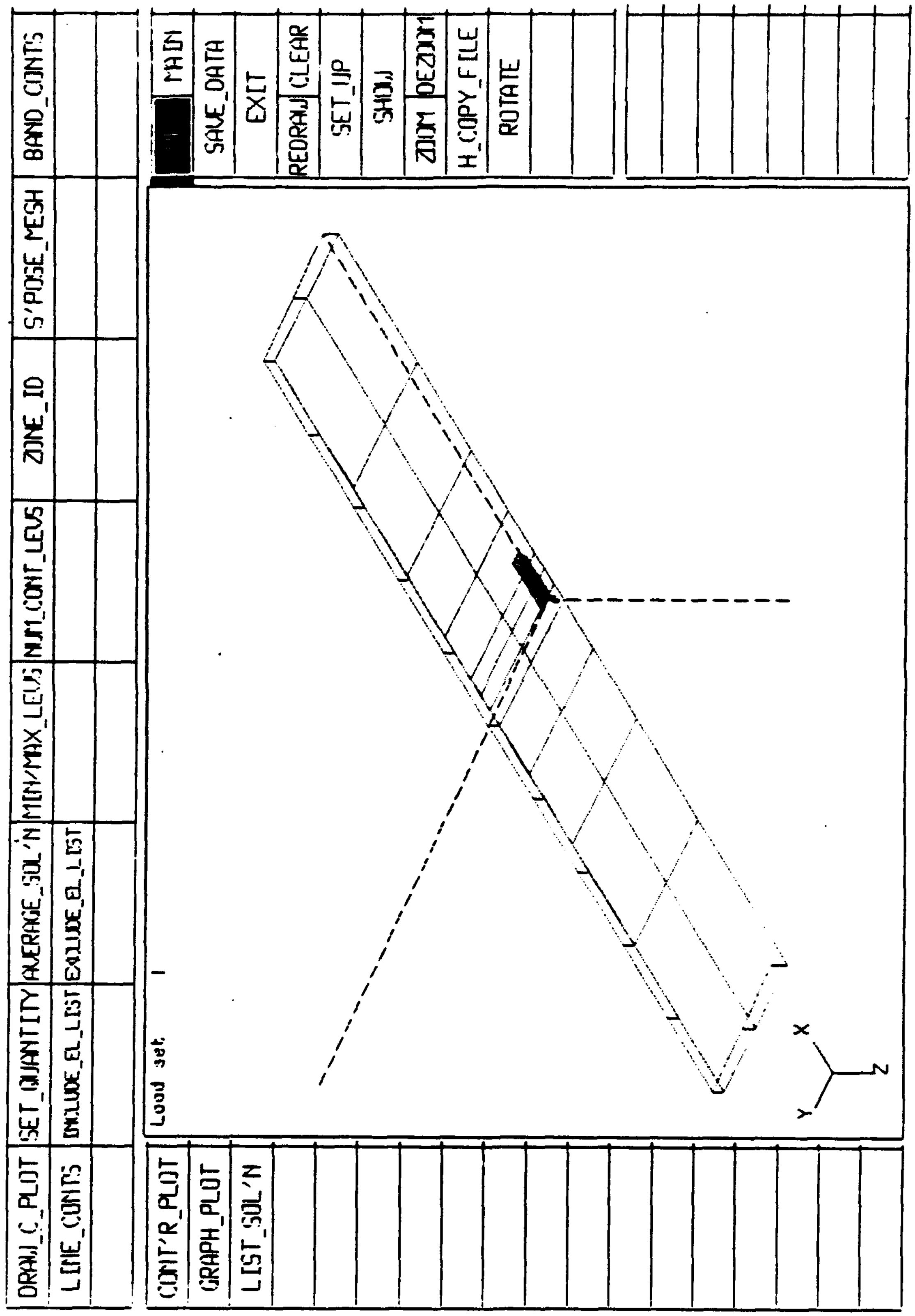

Figure 6. Boundary element grid for non-conducting surfaces.

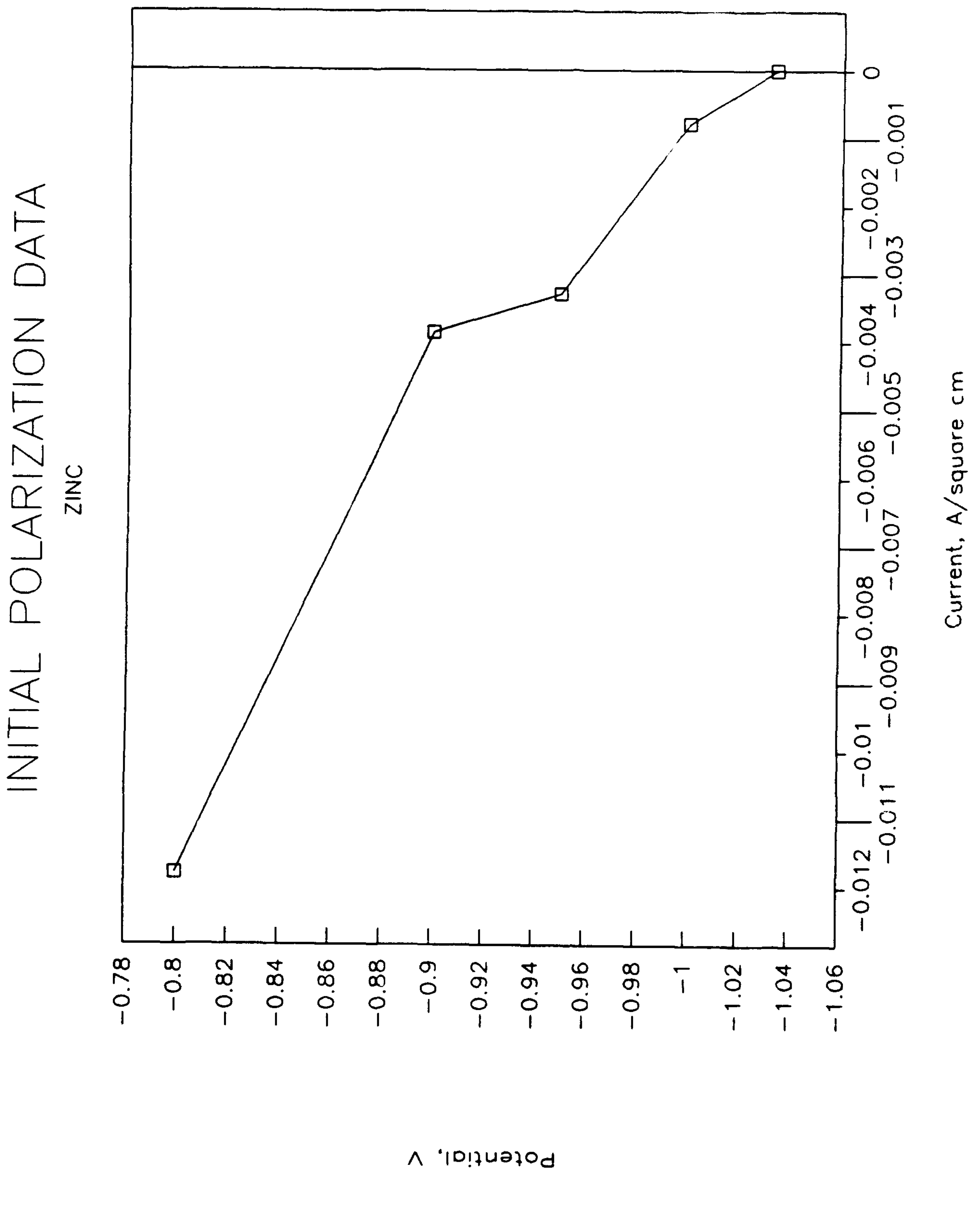

Figure 7. Zinc polarization data.

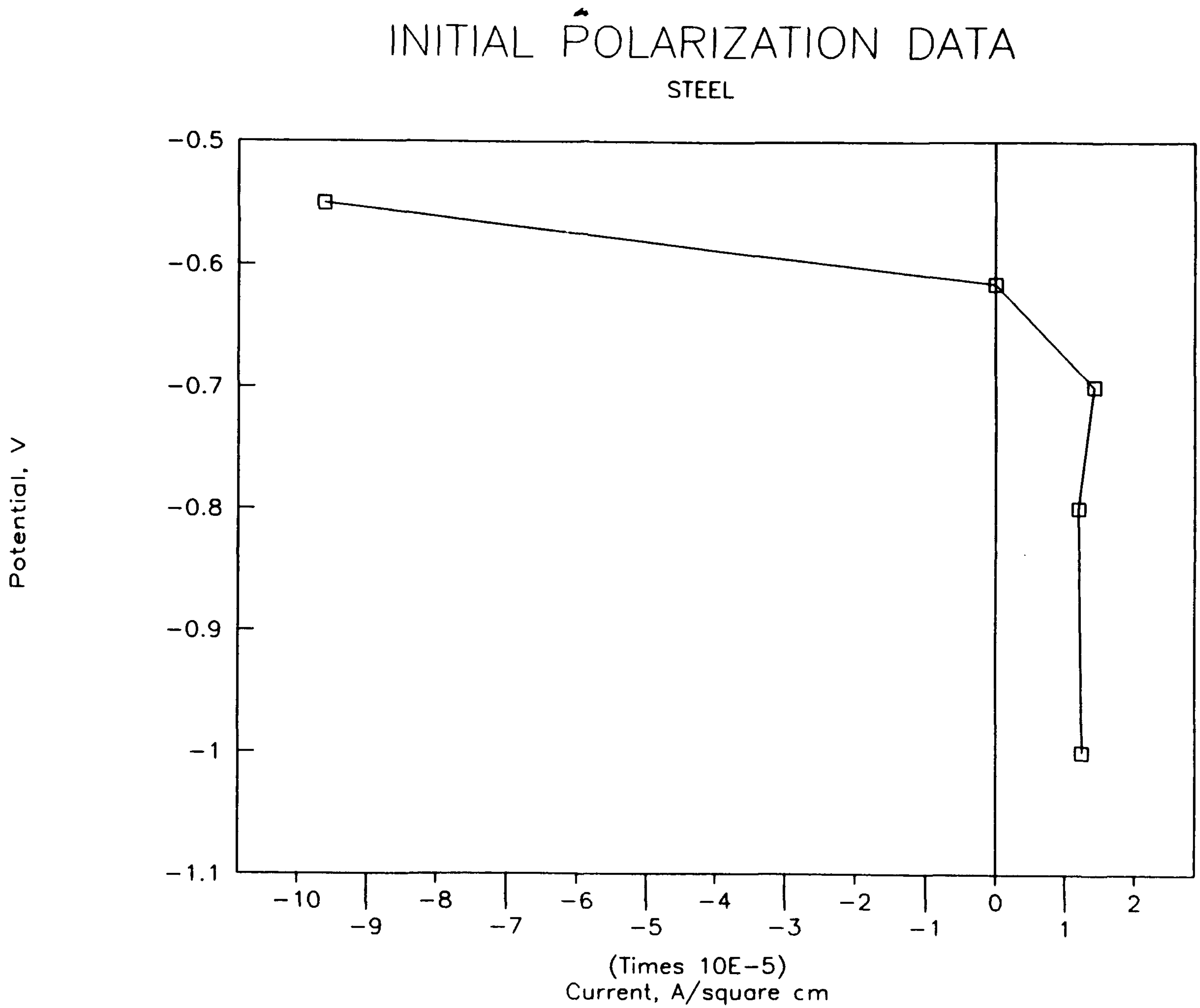

Figure 8. Steel polarization data.

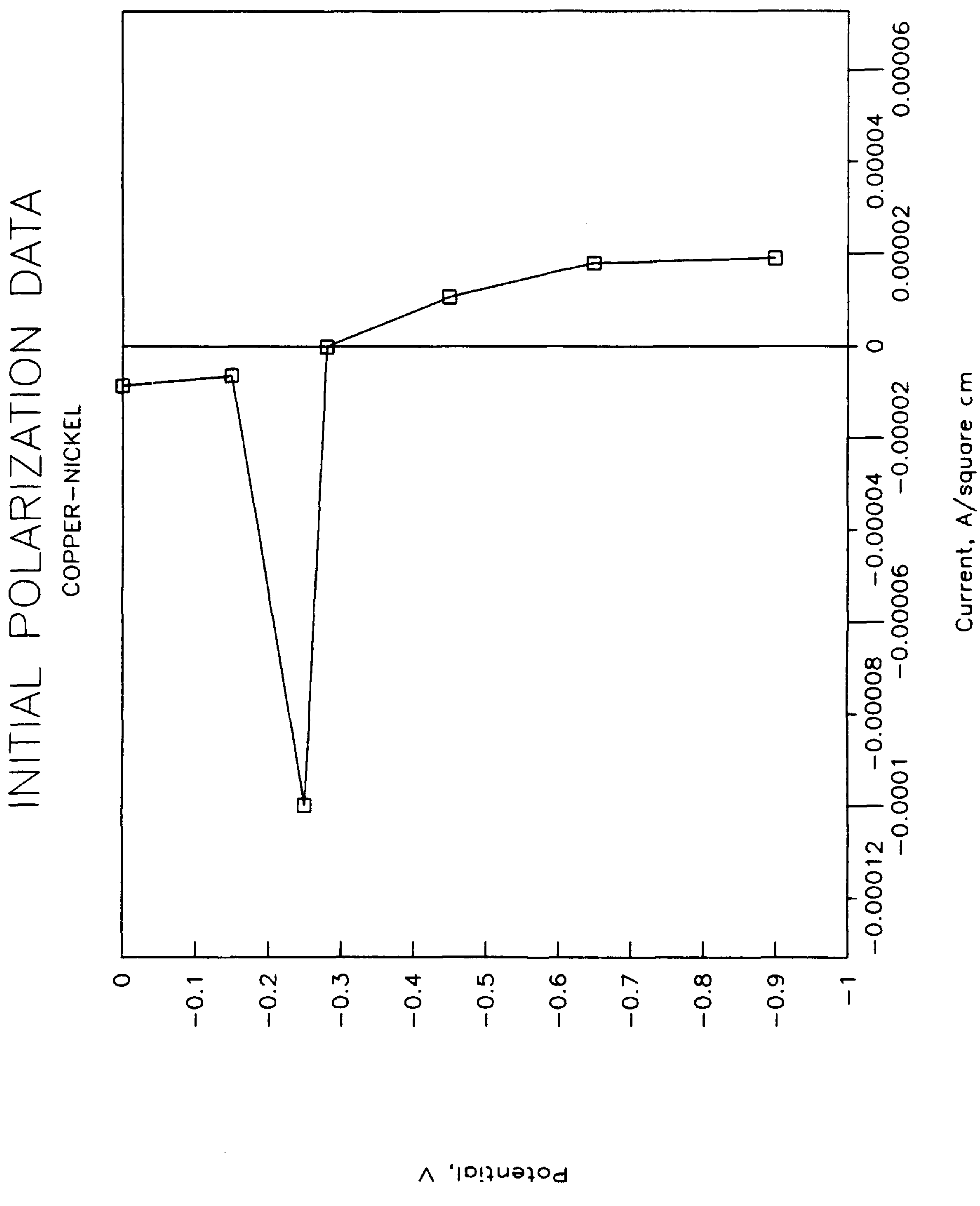

Figure 9. Copper-nickel polarization data.

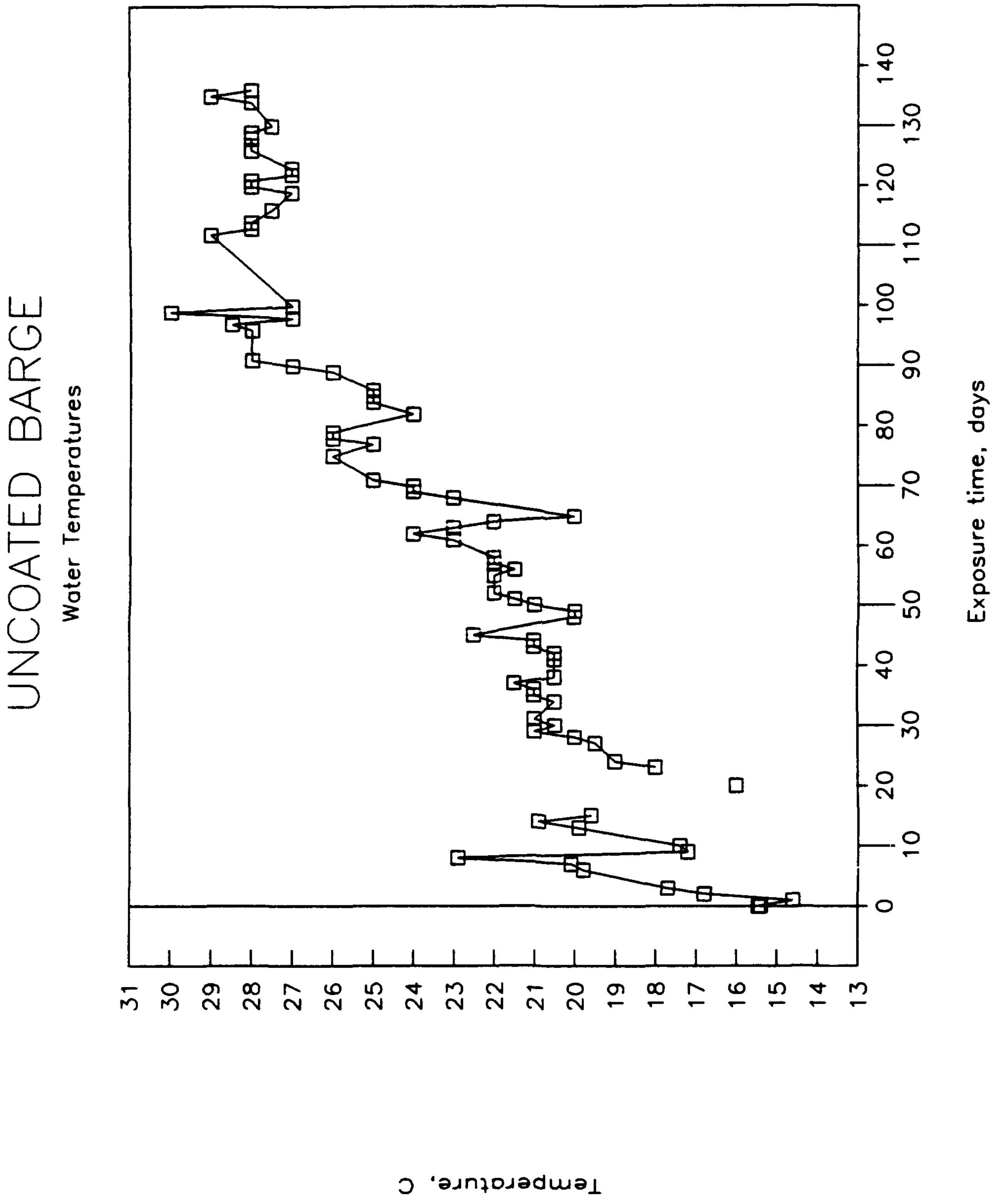

Figure 10. Water temperature—uncoated barge exposure.

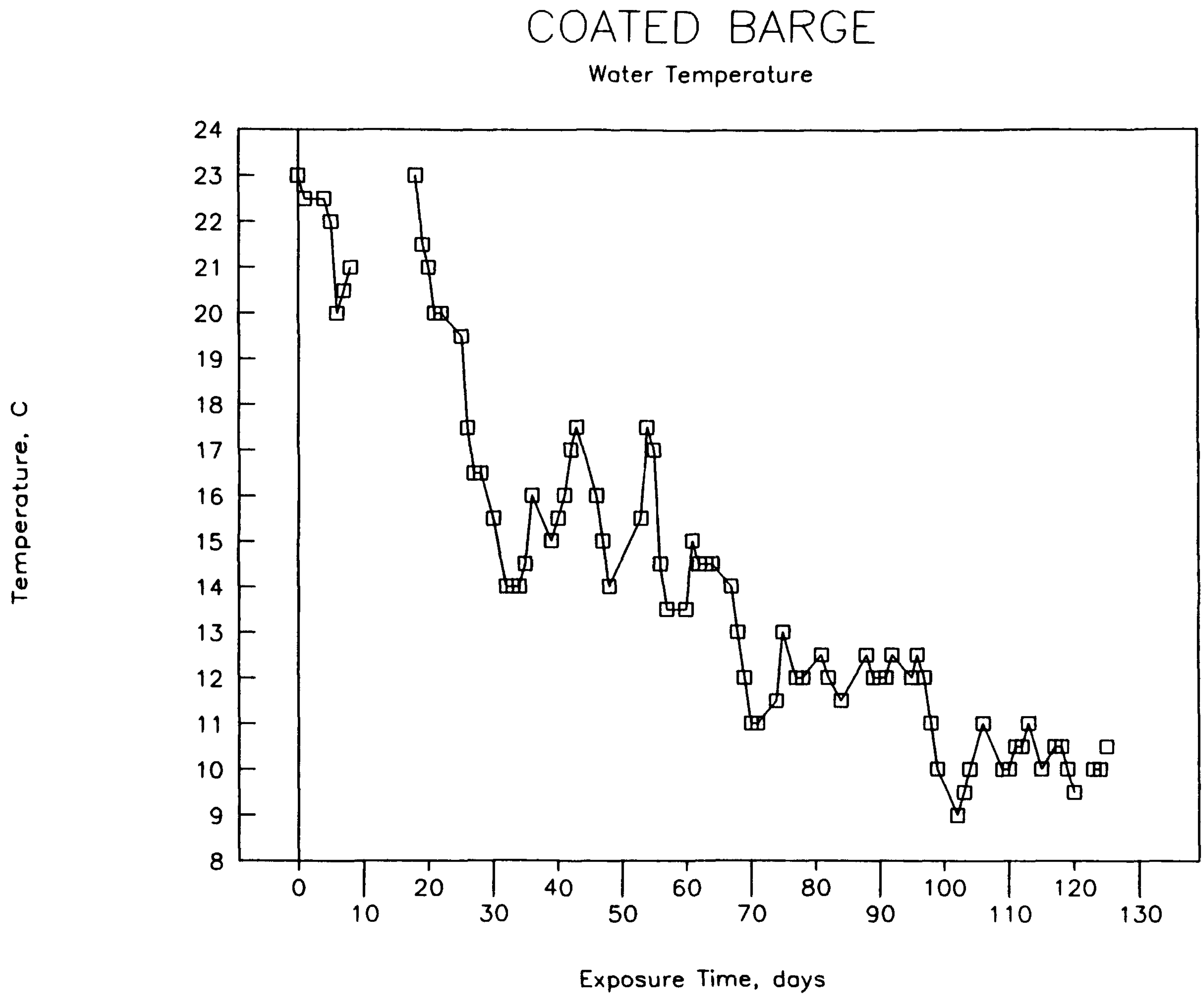

Figure 11. Water temperature—coated barge exposure.

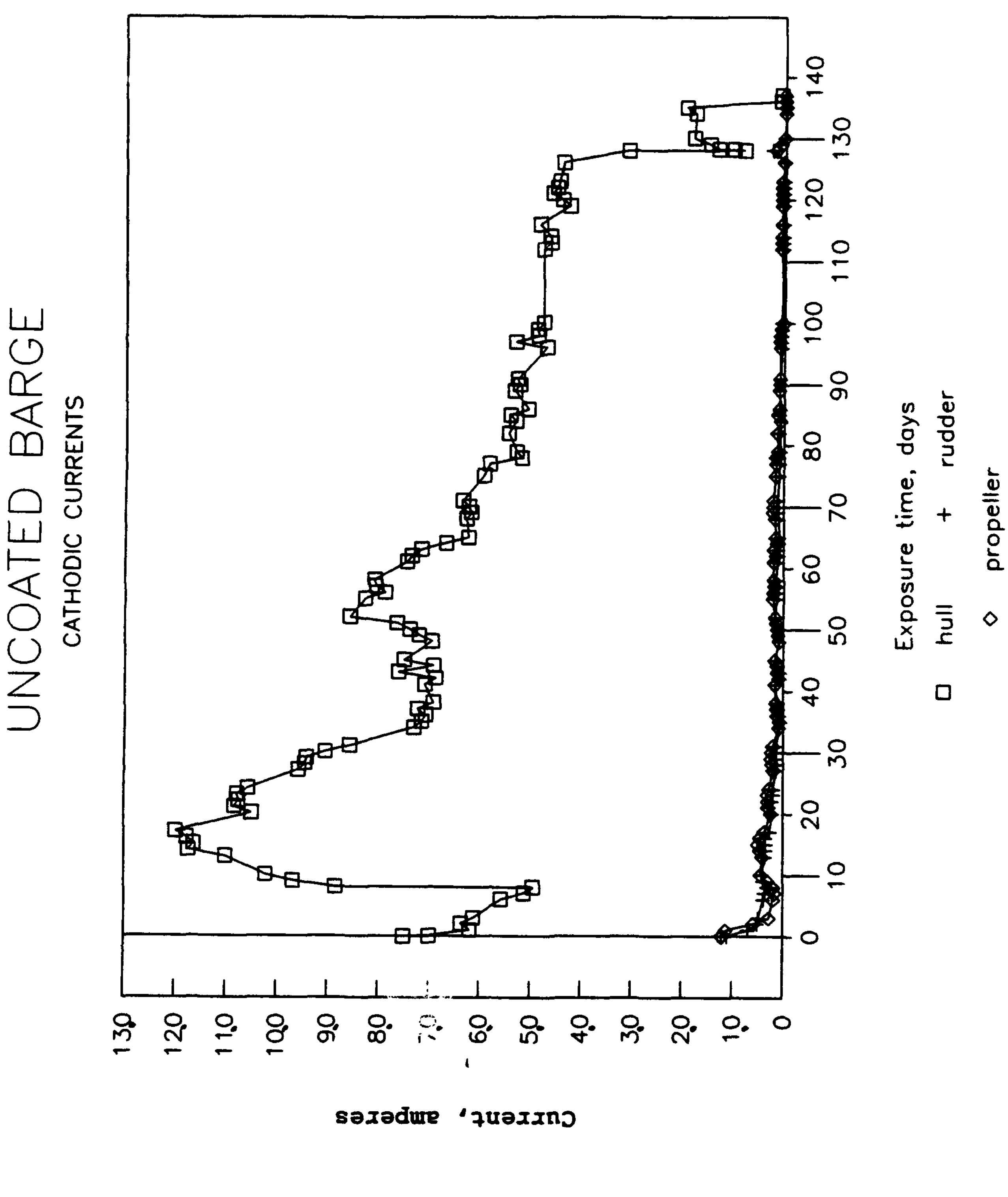

Figure 12. Cathode currents—uncoated barge.

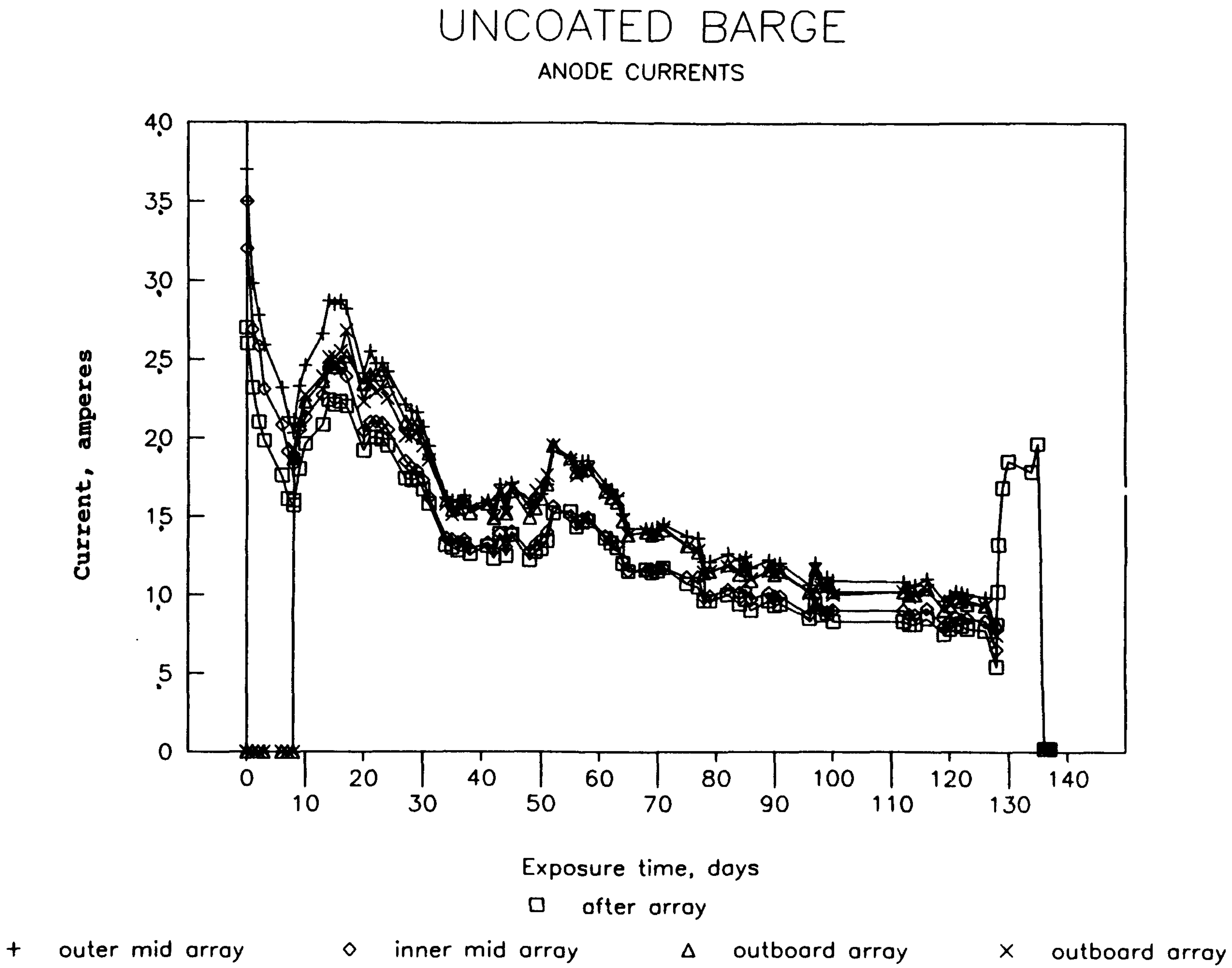

Figure 13. Anode currents—uncoated barge.

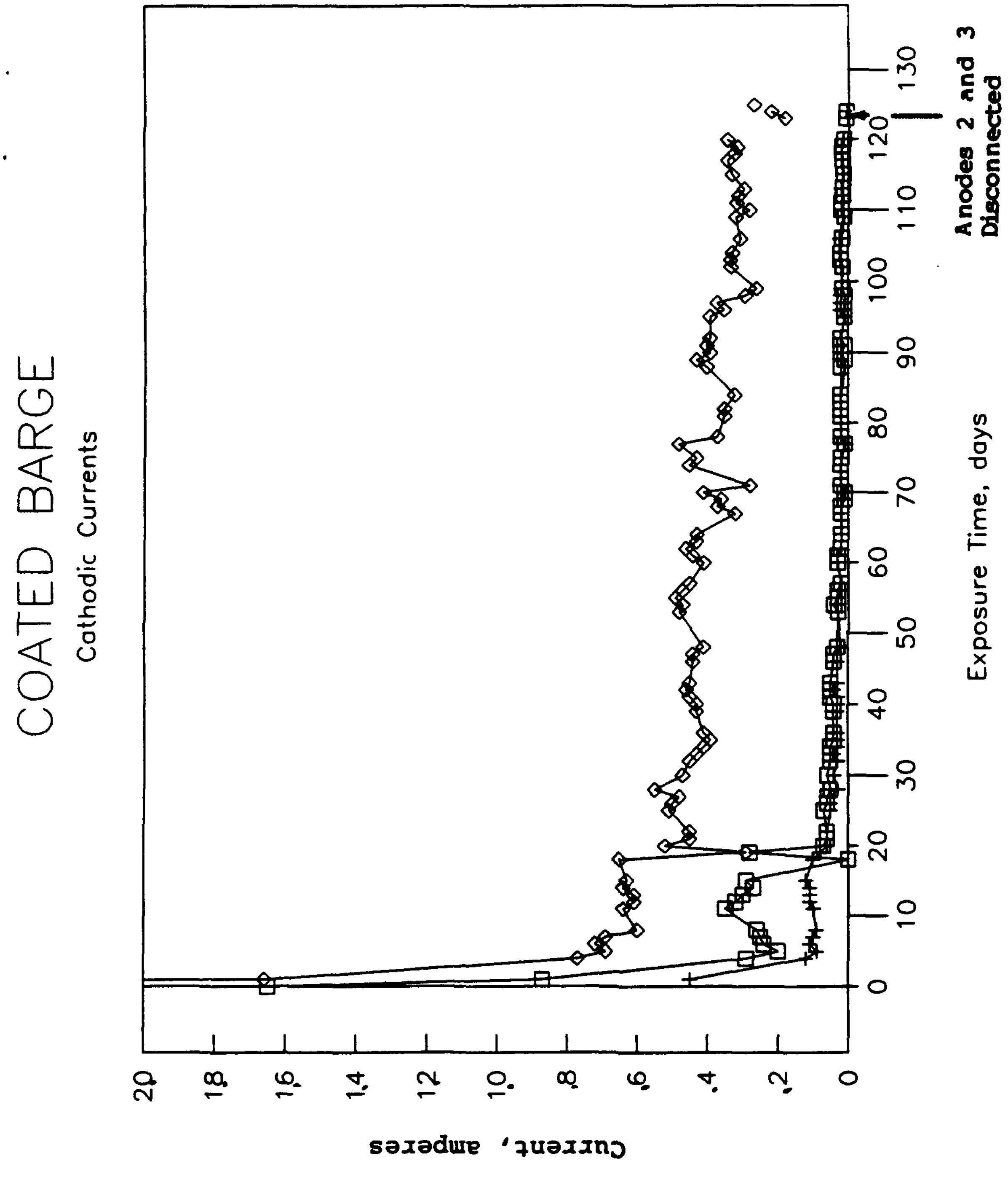

Figure 14. Cathode currents—coated barge.

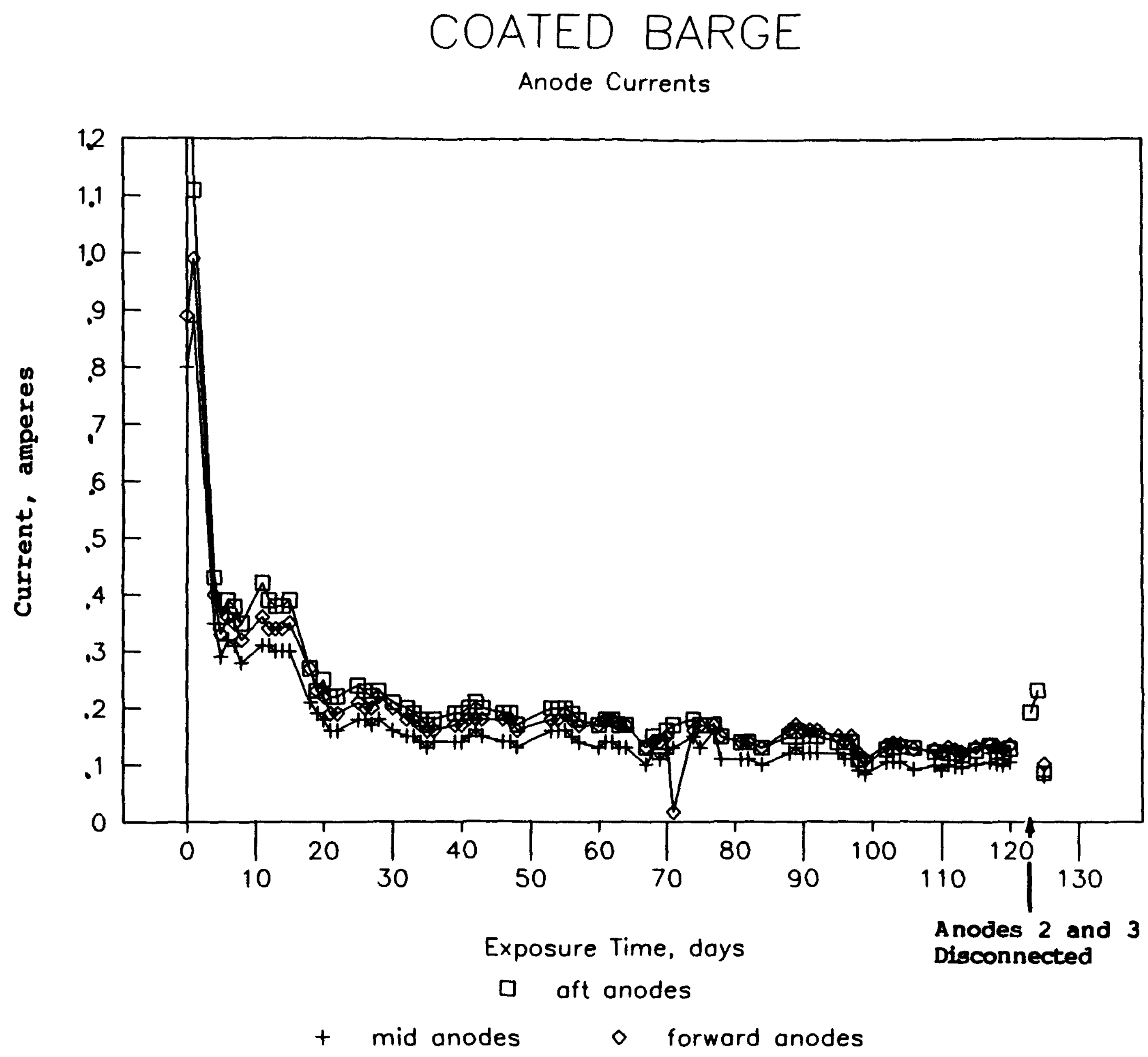

Figure 15. Anode currents—coated barge.

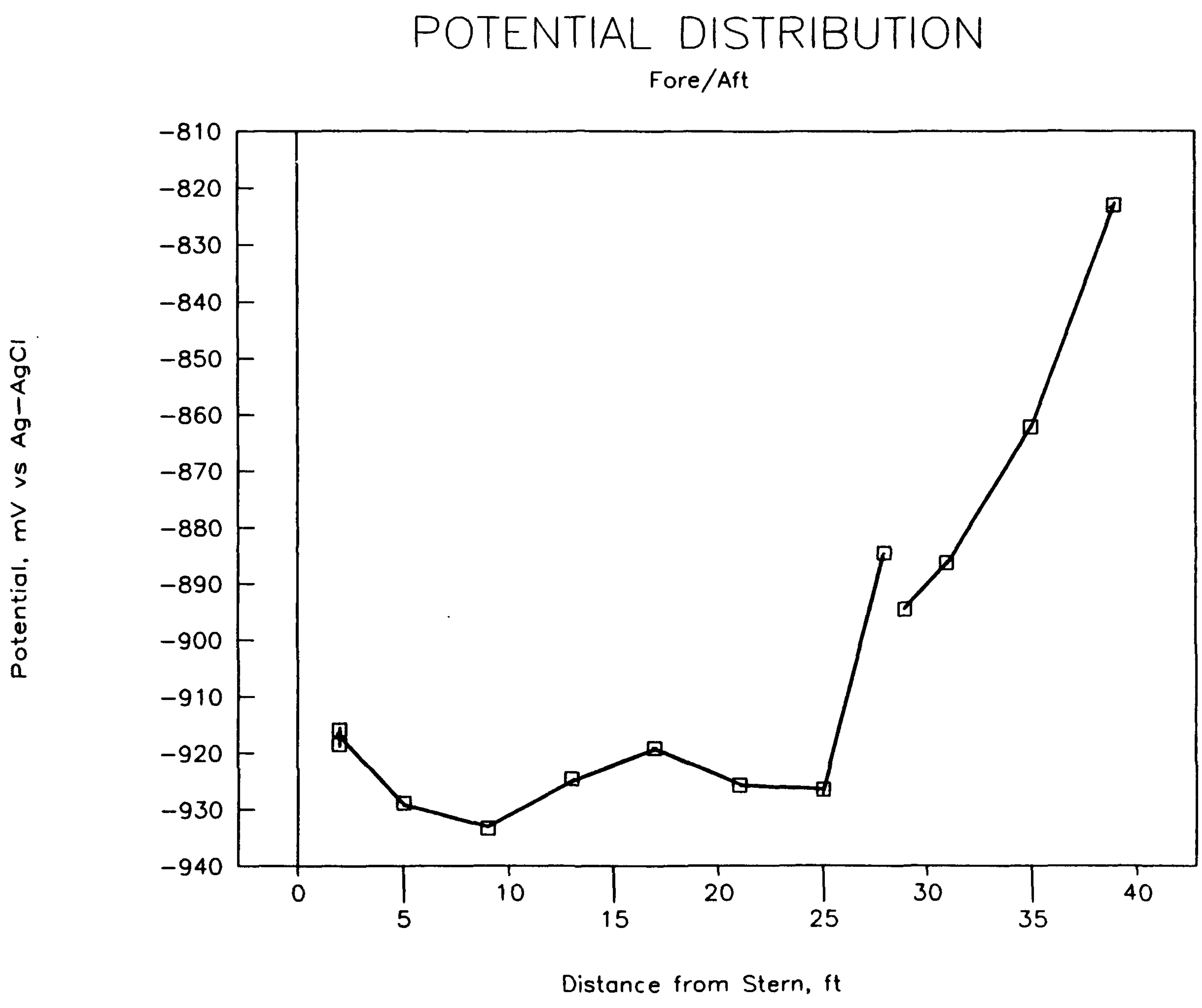

Figure 16. Measured longitudinal potential gradients—uncoated barge.

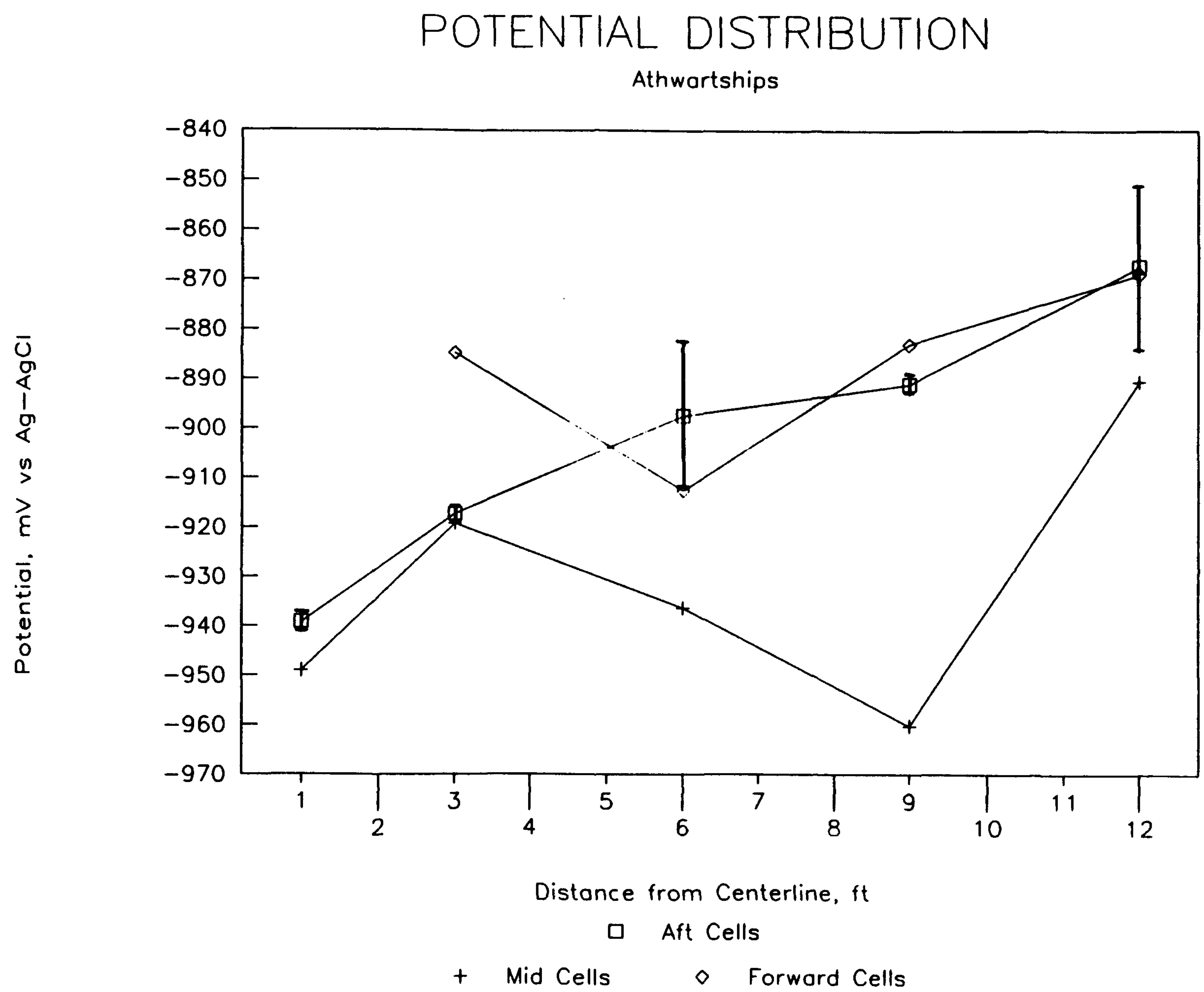

Figure 17. Measured transverse potential gradients—uncoated barge.

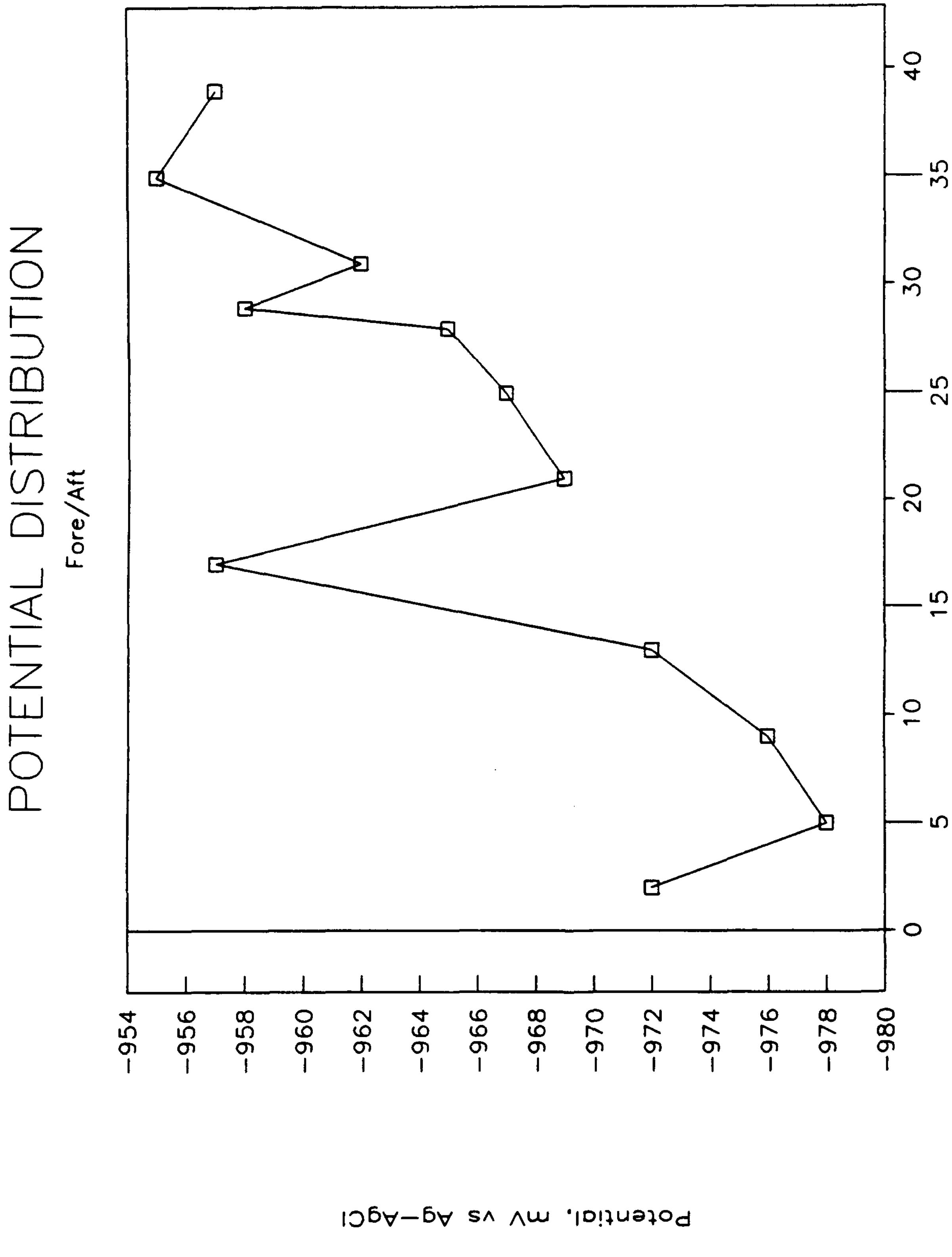

Figure 18. Measured longitudinal potential gradients—coated barge.

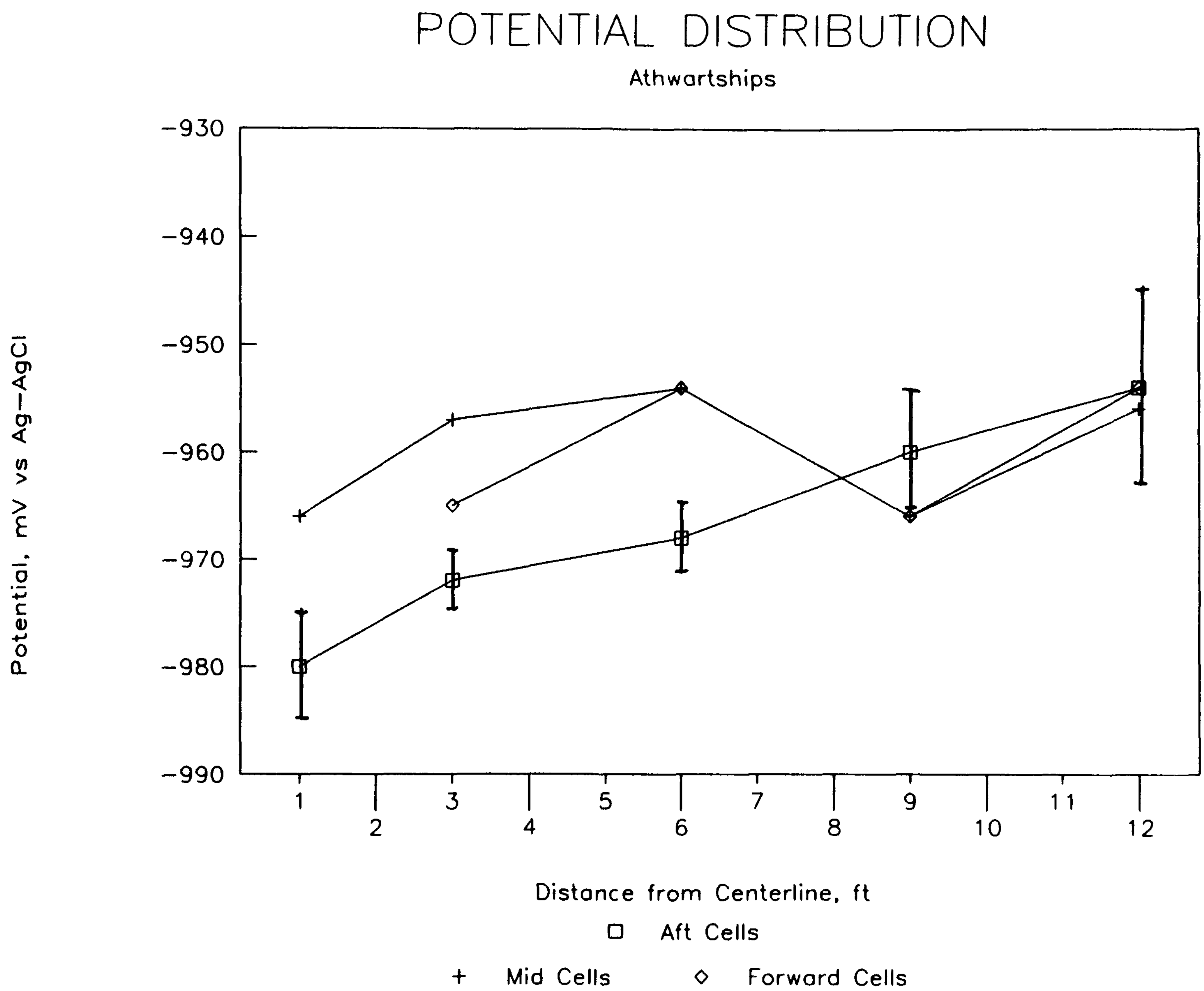

Figure 19. Measured transverse potential gradients—coated barge.

Figure 20. Fouling on hull of uncoated barge.

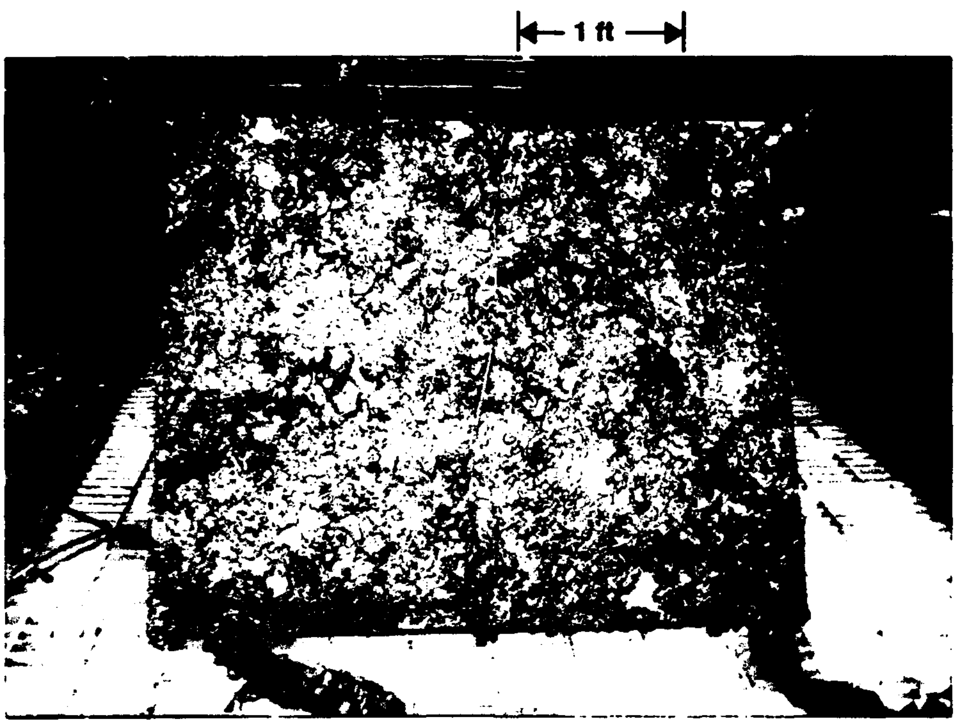

Figure 21. Fouling on rudder of uncoated barge.

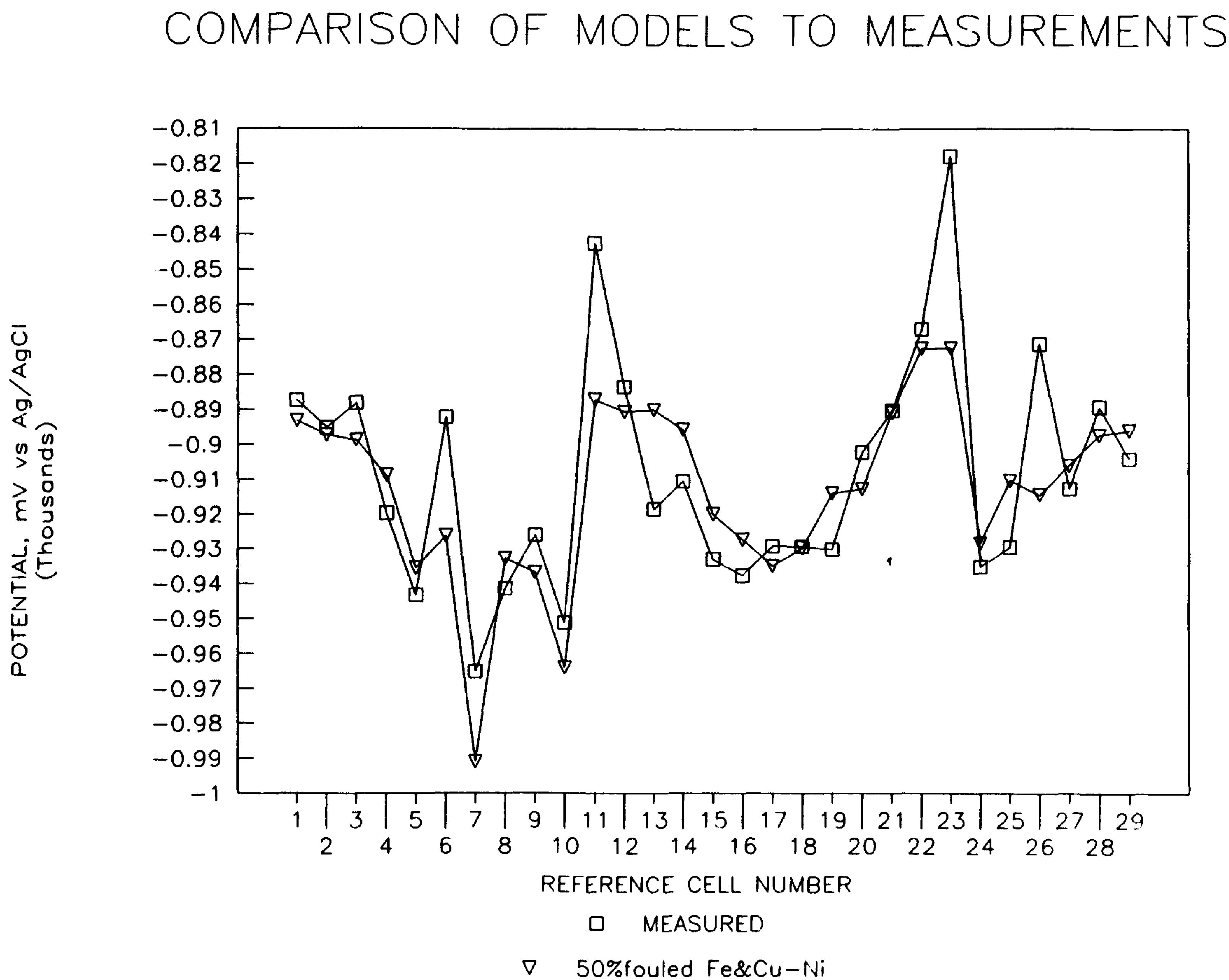

Figure 22. Comparison of model and measured potentials—uncoated barge.

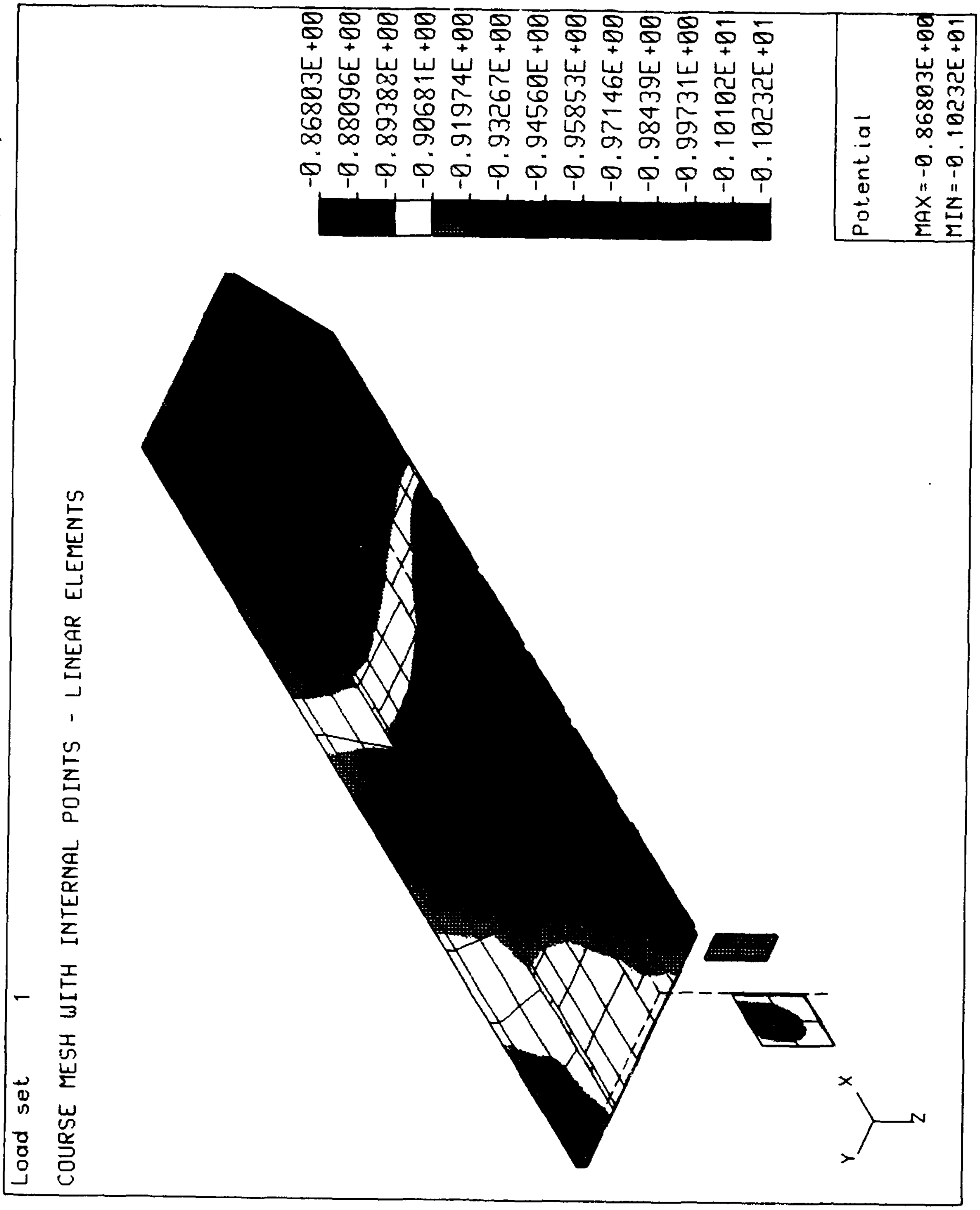

Figure 23. Modeled potential distribution—uncoated barge.

Figure 24. Lack of fouling on hull of coated barge.

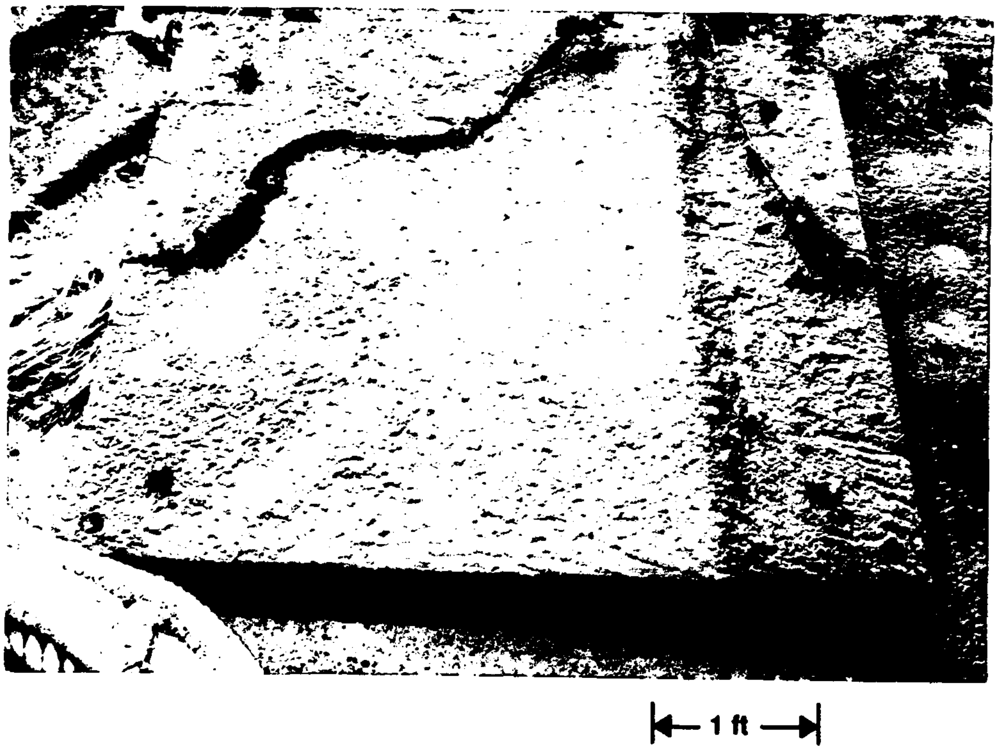

Figure 25. Lack of fouling on rudder of coated barge.

Figure 26. Soft fouling on uncoated hull areas of coated barge.

Figure 27. Soft fouling on propeller plate of coated barge.

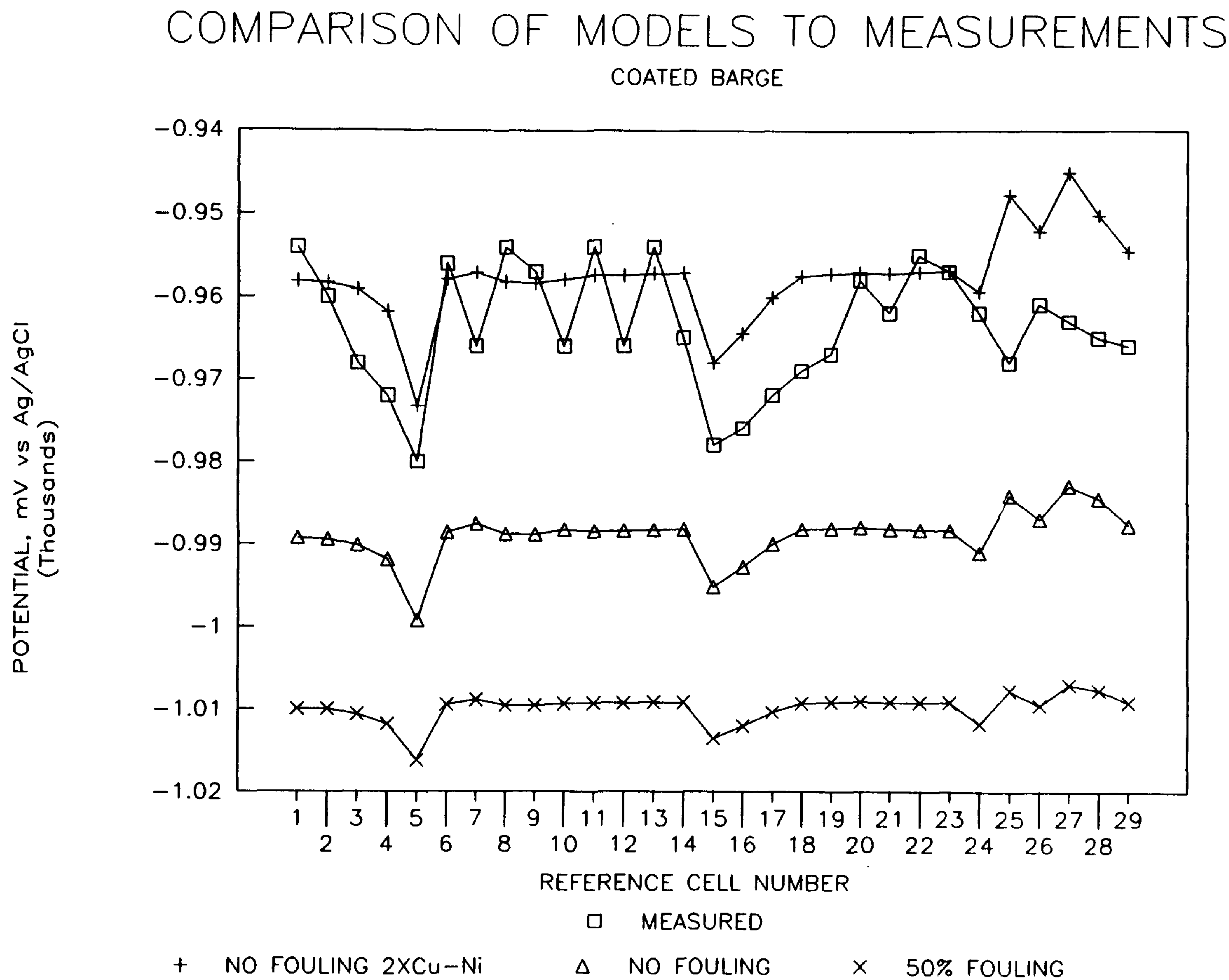

Figure 28. Comparison of model and measured potentials—coated barge.

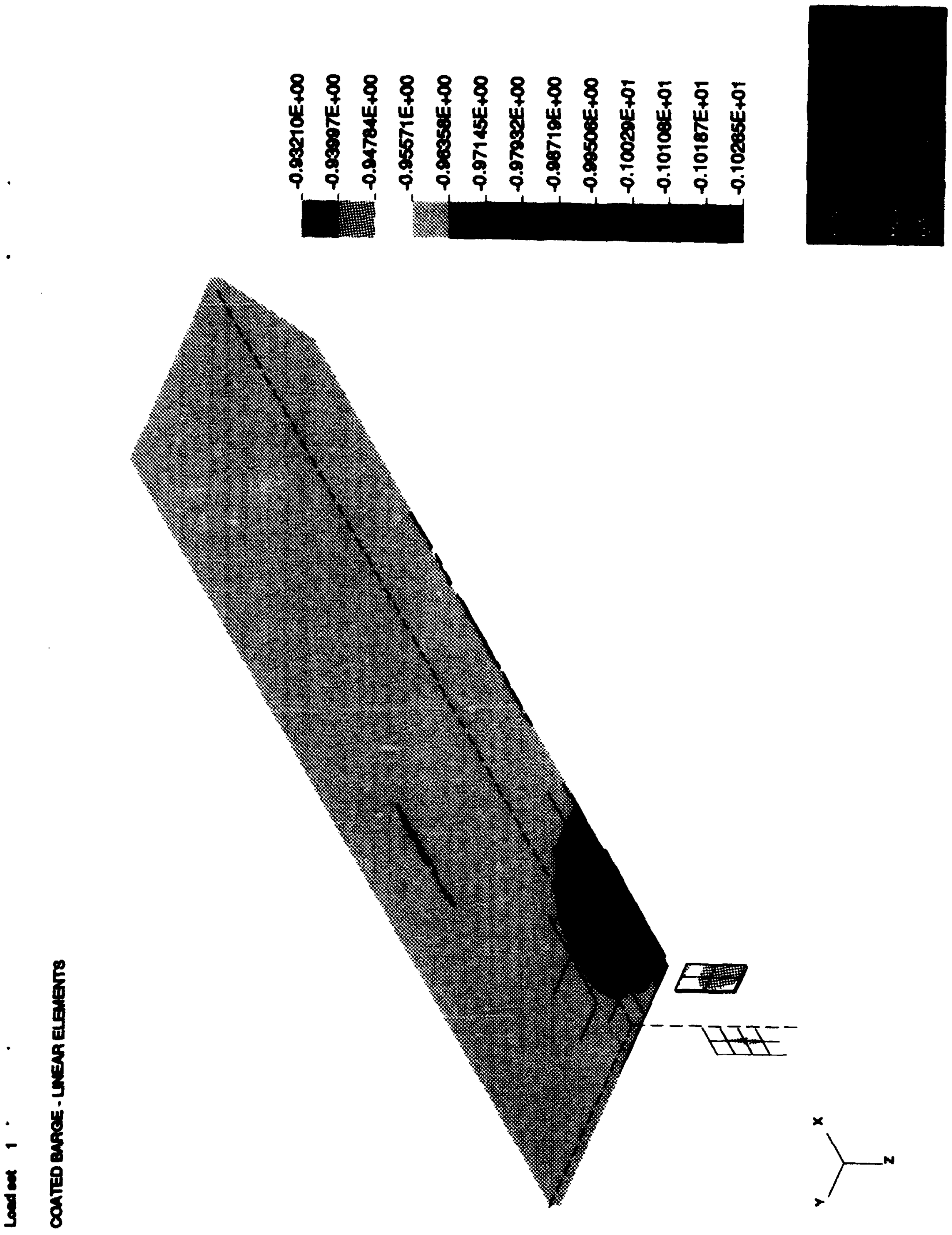

Figure 29. Modeled potential distribution—coated barge.

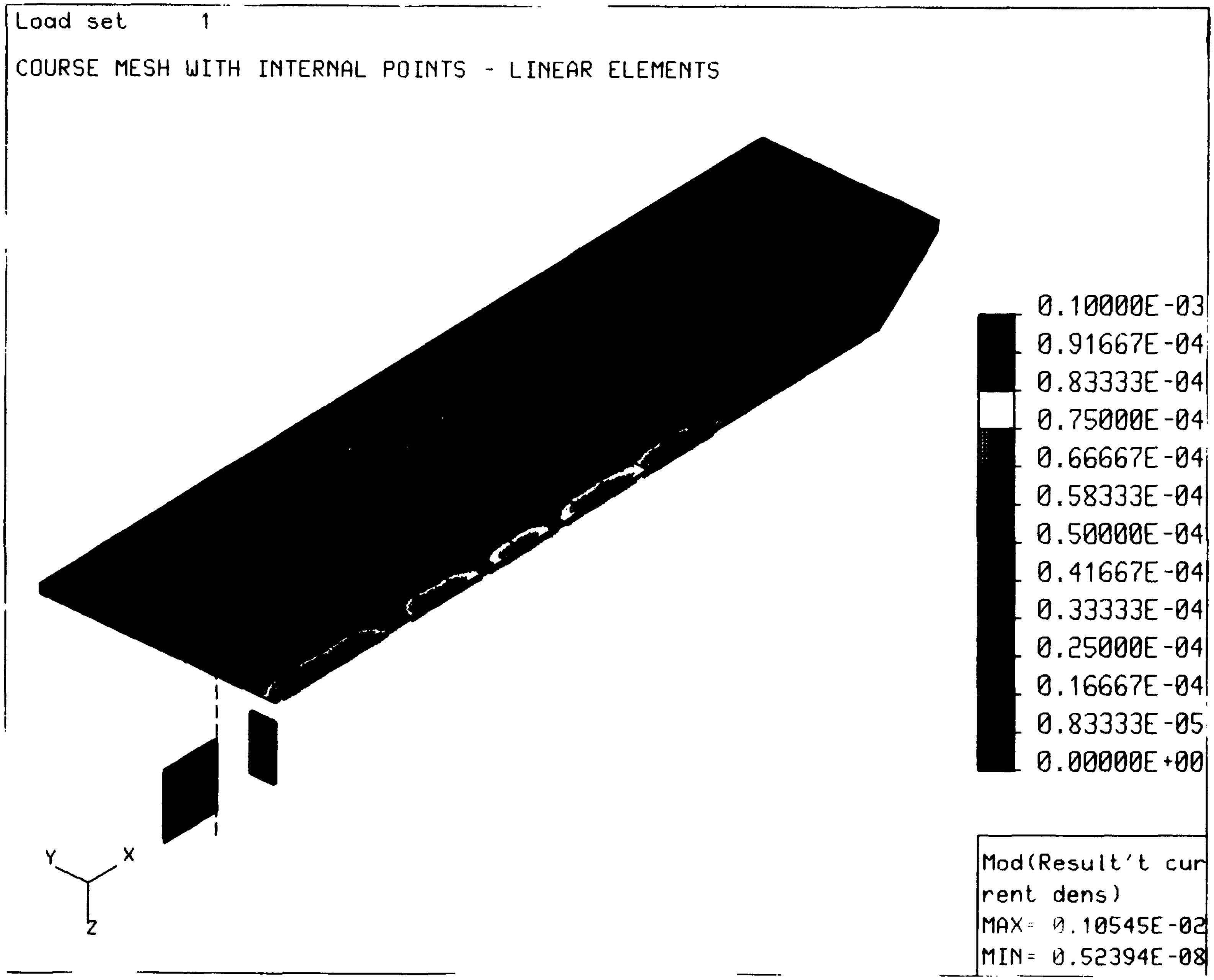

Figure 30. Modeled current distribution—uncoated barge.

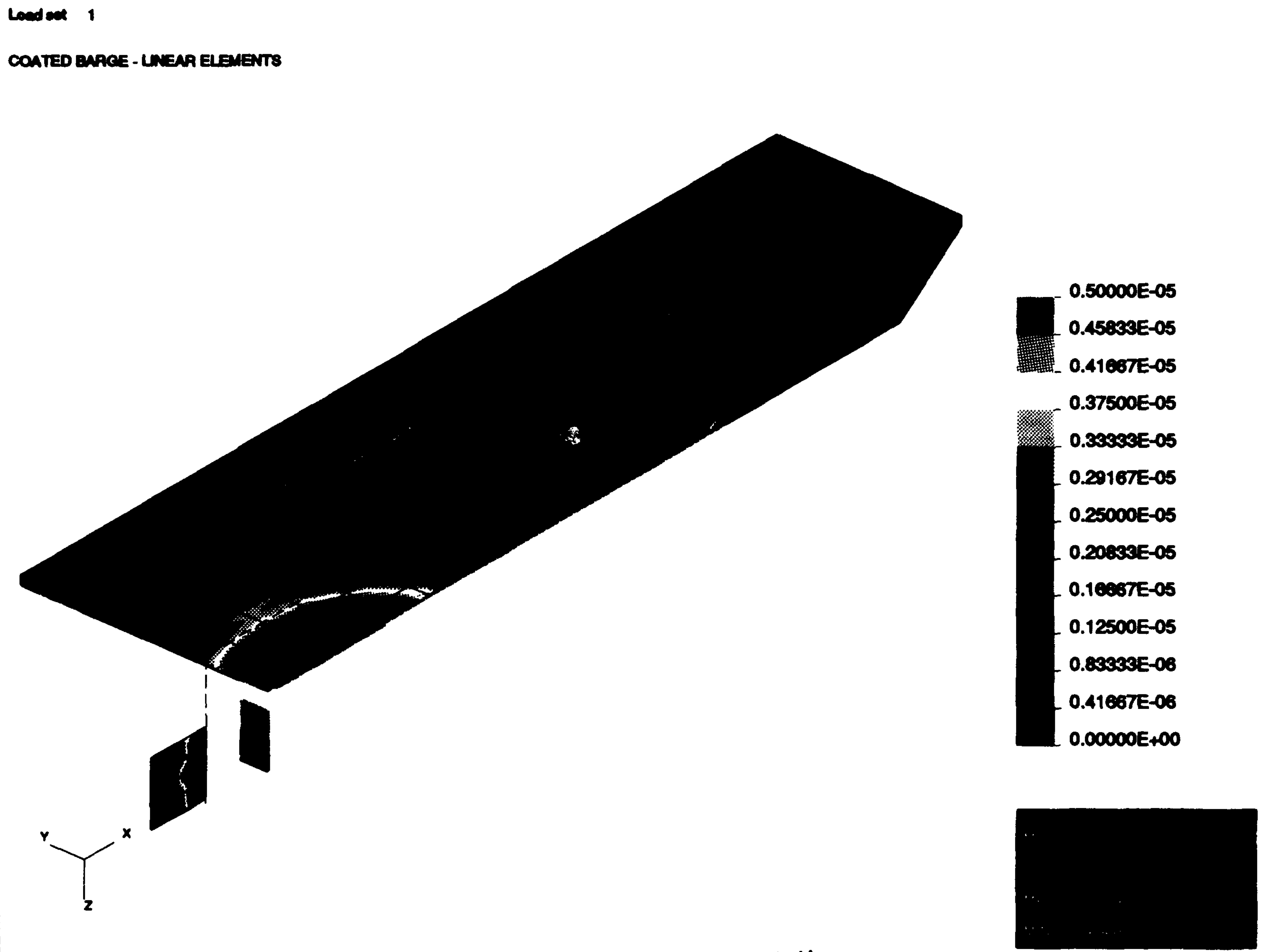

Figure 31. Modeled current distribution—coated barge.

REFERENCES

1. L. L. Shreir, Ed., *Corrosion-Volume 2-Corrosion Control*, Chapter 11, Newnes–Butterworths, Boston, MA (1976).

2. J. Tighe-Ford, J. N. McGrath, and L. Hodgkiss, "Design Improvements for a Ship's Impressed Current Cathodic Protection System Using Dimension and Conductivity Scaling (DACS)," *Corrosion Prevention and Control* (Oct 1985).

3. H. P. Hack, "Scale Modeling for Corrosion Studies," *Corrosion*, Vol. 45, No. 7 (July 1989).

4. P. Doig and P. E. J.Flewitt, "A Finite Difference Numerical Analysis of Galvanic Corrosion for Semi–Infinite Linear Coplanar Electrodes," *Journal of the Electrochemical Society* (Dec 1979) pp. 2057–2063.

5. J. W. Fu and J. S. K. Chow, "Cathodic Protection Designs Using an Integral Equation Numerical Method," *Materials Performance*, Vol. 21, No. 10 (Oct 1982).

C. A. Brebbia, Ed, *The Boundary Element Method for Engineers*, Computational Mechanics, Woburn, MA (1980).

7. M. A. Warne, "Applications of Numerical Analysis Techniques," *Proceedings of the Conference on Cathodic Protection Theory and Practice—The Present Status*, Coventry, U. K. (Apr 1982).

8. R. G. Kasper and M. G. April, "Electrogalvanic Finite Element Analysis of Partially Protected Marine Structures," *Corrosion*, Vol. 39, No. 5 (May 1983).

9. R. G. Kasper, "Theoretical and Experimental Comparisons of Nearfield Electrogalvanic Fields Due to Nonlinear Polarization Layers," NUSC Technical Report 7299 (Feb 1985).

10. J. R. Scully and H. P. Hack, "Prediction of Tube-Tubesheet Galvanic Corrosion Using Long Term Electrochemical Polarization Data," in *Galvanic Corrosion*, H. Hack, Ed., STP 978, ASTM (1988).

11. H. P. Hack and J. R. Scully, "Galvanic Corrosion Prediction Using Long and Short Term Polarization Curves," *Corrosion*, Vol. 42, No. 2 (Feb 1986).

12. R. A. Adey and S. M. Niku, "Boundary Element Simulation of Galvanic Corrosion—The Story of a Major Success for Boundary Elements," *Boundary Elements X, Vol. 2: Heat Transfer, Fluid Flow and Electrical Applications*, C. A. Brebbia, Ed., Computational Mechanics Publications, Ashurst, UK (1988).

13. H. B. Dwight, "Calculations of Resistances to Ground," *AIEE Transactions*, Vol. 55 (1939) pp.1319–1328 .

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13. ABSTRACT *(Maximum 200 words)*

Boundary element computer modeling is gaining acceptance for predicting the distribution of cathodic protection potentials on large immersed structures. Much has been published on this technique, including experimental verification on a laboratory scale. However, there has been little published on experimental verification of the model predictions on large structures, especially ships. Since the accuracy of a computer model depends on the boundary conditions used for the model, experimental verification is necessary to insure that the proper polarization conditions have been chosen.

A 42–foot barge was outfitted with a "rudder", "propeller", sacrificial anodes, and an array of reference cells to measure the distribution of potential over the surface of the hull and appendages. The barge was exposed in seawater for 4 months. The computer-predicted protection distributions were compared to the measured potential distributions. Polarization curves are presented which give good agreement between model predictions and the actual measurements on the uncoated and coated barge hull under low flow conditions.

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