AD-A179 823 VALIDATION OF NITRONIC 33 IN REINFORCED AND PRESTRESSED CONCRETE(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA J F JENKINS APR 87 NCEL-TN-1764 1/1

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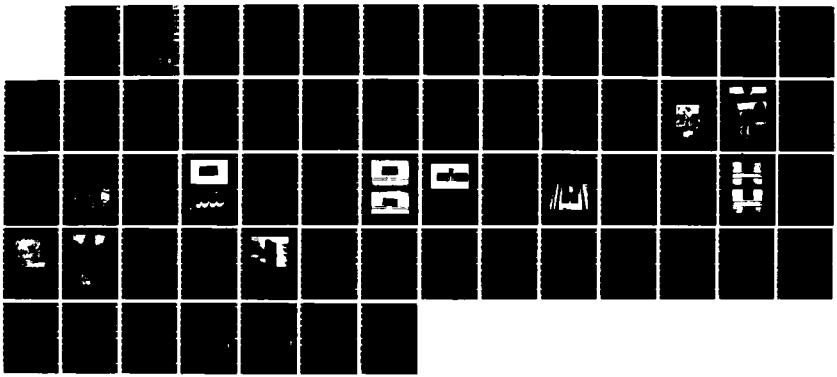

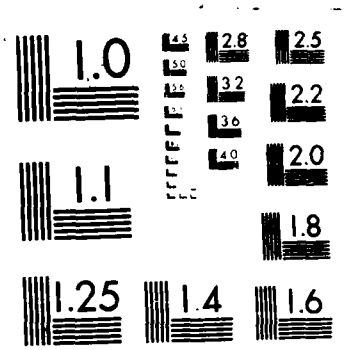

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N-1764
April 1987

NCEL
Technical Note

By James F. Jenkins

Sponsored By Naval Facilities
Engineering Command

AD-A179 823

Validation of Nitronic 33 in Reinforced and Prestressed Concrete

ABSTRACT Nitronic 33 stainless steel (~~Trademark of Armco~~ Steel Corporation) has a unique combination of high strength and nonmagnetic properties which make it an excellent candidate for use as prestressing strand for concrete waterfront structures where the magnetic properties of the carbon steel commonly used for prestressing strand are not acceptable. Before Nitronic 33 stainless steel prestressed concrete waterfront structures were constructed, it was necessary to establish the corrosion performance of the Nitronic 33 stainless steel in marine concrete. A test plan was developed where a series of tests which compared the performance of carbon steel to the Nitronic 33 stainless steel were to be performed. The time to initiation of attack was established as the critical parameter for the evaluation of the test results. In each test, corrosion of the carbon steel initiated prior to the initiation of the corrosion of the Nitronic 33 stainless steel. In addition, previously emplaced full-scale pier pilings with both carbon steel and Nitronic 33 stainless steel prestressing were inspected. The corrosion activity of the Nitronic 33 stainless steel prestressed piling was less than that of the companion carbon steel prestressed pilings.

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METRIC CONVERSION FACTORS

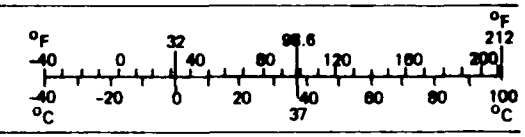
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Nitronic 33 stainless steel (Trademark of Armco Steel Corporation) has a unique combination of high strength and nonmagnetic properties which make it an excellent candidate for use as prestressing strand for concrete waterfront structures where the magnetic properties of the carbon steel commonly used for prestressing strand are not acceptable. Before Nitronic 33 stainless steel prestressed concrete waterfront structures were constructed, it was necessary to establish the corrosion performance of the Nitronic 33 stainless steel in marine

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concrete. A test plan was developed where a series of tests which compared the performance of carbon steel to the Nitronic 33 stainless steel were to be performed. The time to initiation of attack was established as the critical parameter for the evaluation of the test results. In each test, corrosion of the carbon steel initiated prior to the initiation of the corrosion of the Nitronic 33 stainless steel. In addition, previously emplaced full-scale pier pilings with both carbon steel and Nitronic 33 stainless steel prestressing were inspected. The corrosion activity of the Nitronic 33 stainless steel prestressed piling was less than that of the companion carbon steel prestressed pilings.

It was concluded that prestressed concrete waterfront structures using Nitronic 33 as prestressing strand should perform at least as well as similar structures using carbon steel prestressing. Recommendations for additional work to evaluate possible differences in inspection, maintenance, and repair techniques required for Nitronic 33 stainless steel prestressed concrete waterfront structures are presented.

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TN-1764 62 pp illus April 1987 Unclassified

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Nitronic 33 stainless steel (Trademark of Armco Steel Corporation) has a unique combination of high strength and nonmagnetic properties which make it an excellent candidate for use as prestressing strand for concrete waterfront structures where the magnetic properties of the carbon steel commonly used for prestressing strand are not acceptable. Before Nitronic 33 stainless steel prestressed concrete waterfront structures were constructed, it was necessary to establish the corrosion performance of the Nitronic 33 stainless steel in marine concrete. A test plan was developed where a series of tests which compared the performance of carbon steel to the Nitronic 33 stainless steel were to be performed. The time to initiation of attack was established as the critical parameter for the evaluation of the test results. In each test, corrosion of the carbon steel initiated prior to the initiation of the corrosion of the Nitronic 33 stainless steel. In addition, previously emplaced full-scale pier pilings with both carbon steel and Nitronic 33 stainless steel prestressing were inspected. The corrosion activity of the Nitronic 33 stainless steel prestressed piling was less than that of the companion carbon steel prestressed pilings. It was concluded that prestressed concrete waterfront structures using Nitronic 33 as prestressing strand should perform at least as well as similar structures using carbon steel prestressing.

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INTRODUCTION

The purpose of this validation was to qualify Nitronic 33 stainless steel for use as prestressing strand and reinforcement in concrete construction where the magnetic properties of carbon steel are not acceptable.

This validation was directed solely to the determination of the corrosion behavior of Nitronic 33 stainless steel in concrete under conditions that are likely to be present in a pier fabricated from prestressed and reinforced concrete. Previous evaluations by others have determined that the mechanical properties, magnetic properties, fabricability, bonding strength, and other characteristics of Nitronic 33 stainless steel were suitable for construction of the type required.

While actual long term in situ testing of any material for a new application is highly desirable, this test program was based upon tests which could be completed in a relatively short period since it was necessary to determinine if Nitronic 33 prestressed and reinforced concrete could be used in the construction of urgently required facilities. The tests were developed to determine the relative susceptability of carbon steel and Nitronic 33 stainless steel to loss of passivity under various conditions which are likely to occur in an actual marine structure, and to separately assess the amounts and types of attack which are likely to occur on both carbon steel and Nitronic 33 stainless steel when, or if, active corrosion has been initiated. As both carbon steel and Nitronic 33 stainless steel were expected to behave as passive materials in concrete, the side-by-side comparison of the two was considered to be valid. By separating the determination of the initiation and propagation behavior, and by comparing the behavior of carbon steel and Nitronic 33 stainless steel in each test, an assessment of the relative corrosion performance of carbon steel and Nitronic 33 stainless steel could be made within a relatively short period. By including evaluation of previously cast sections of actual prestressed pilings (one with carbon steel prestressing and reinforcement and one with Nitronic 33 stainless teel prestressing and Nitronic 32 stainless steel reinforcement), and by the inspection of in-place pilings of each type, the test data was further validated.

If corrosion were to initiate on the Nitronic 33 stainless steel in concrete, the type, distribution, and extent of attack on the Nitronic 33 could be different from that which occurs on carbon steel in concrete. Therefore, an assessment of the effect of possible corrosion of Nitronic 33 on structural integrity of prestressed concrete pilings and slabs was made. Also, the effect of magnetic fields of the magnitude and orientation which are likely to be encountered in the vicinity of the proposed structure was assessed in order to determine the possible effects of these fields on corrosion of the reinforcement.

The direct comparison of the behavior of carbon steel and Nitronic 33 stainless steel in this validation can be used to compare the impact of corrosion of carbon steel and of Nitronic 33 stainless steel in a marine

prestressed concrete structure. It has been well established that concrete structures, prestressed and reinforced using carbon steel, can be successfully used in marine environments. This direct comparison of corrosion behavior can be used to assess whether a structure fabricated using Nitronic 33 prestressing and reinforcing can be successfully used in similar environments.

Follow-on efforts to extend the duration of the corrosion tests performed to date and to establish criteria for construction, inspection, maintenance, and repair of structures fabricated using Nitronic 33 stainless steel are also identified and described.

DEVELOPMENT AND APPROVAL OF TEST PLAN AND PRESENTATION OF INTERIM RESULTS

Development of the test plan for this validation was initiated on 14 June 1985. A preliminary test plan was reviewed by the Naval Facilities Engineering Command (NAVFAC) Code 03, 04, 05, and 07 representatives during meetings at NAVFAC on 20 June 1985. A revised test plan was reviewed by NAVFAC Code 04 representatives during a meeting at the Naval Civil Engineering Laboratory (NCEL) on 26 June 1985. The test plan was forwarded to NAVFAC by NCEL ltr Ser L52/968 of 3 July 1985 for approval. NAVFAC ltr 3902 Ser 032F/3906 of 20 August 1985 gave final approval of the test plan and directed NCEL to proceed with the validation. On 17 September 1985 a briefing on preliminary results of the validation was presented to NAVFAC. The results of the tests to that date were encouraging and it was determined that the tests should proceed as planned. A briefing was presented at NAVFAC on 17 December 1985 to present final test results and to serve as a basis for the decision to proceed with construction.

PREPARATION OF TEST SPECIMENS

All test specimens were cast from the same batch of concrete to reduce the effects of variation of concrete on the corrosion behavior of the embedded metal specimens. The mix design for the concrete was developed by Mr. Doug Burke of NCEL with consultation from Mr. Bob LaFraugh of ABAM Consulting Engineers, Tacoma, WA. The mix design was developed to represent high quality concrete of the type to be specified for construction of the deperming facilities in San Diego and Kings Bay. The mix design was as follows:

Cement - Type II	8.4 bags/yd
Water (W/C ratio = 0.40)	37.9 gal/yd
Sand (San Gabriel)	1113.0 lb/yd
Coarse aggregate (San Gabriel) 3/8 in maximum	1526.4 lb/yd

Admixture (Sika Mix 126)	200.5 fl oz/yd

Slump before admixture = 4 in
Slump after admixture = 0 in

The Nitronic 33 material was furnished by ARMCO Steel Corporation. All specimens were cut from the same coil of material. The wire diameter was 0.1875 inch. The chemical composition of the material, as determined by ARMCO, was as follows:

Composition of Nitronic 33 Test Wire

Element	%
Chromium	17.69
Manganese	12.23
Nickel	3.48
Silicon	.50
Nitrogen	.30
Molybdenum	.10
Carbon	.039
Phosphorous	.028
Sulphur	.002

The mechanical properties of the Nitronic 33 stainless steel wire, as determined by ARMCO, were as follows:

Ultimate tensile strength	136,000 psi
Yield strength	116,000 psi
Elongation	33.3%
Reduction of area	70.3%
Hardness	26 R_c

The stainless steel test material met the composition and strength requirements of ASTM Specification A580, Grade XM-29. This specification can be used for procurement of wire for prestressing strand with the additional requirement that the carbon content of the wire should be below .048% to insure adequate weldability.

The carbon steel wire specimens were center wires from prestressing strand meeting ASTM Specification A416. This is the standard specification for prestressing strand.

Both the stainless steel and carbon steel wire specimens were cut to a length of 22 inches and straightened as necessary. The specimens were degreased using mineral spirits to remove the bulk of the drawing compound on the wire and rinsed with acetone to remove any remaining surface contamination. Pairs of strands of the same materials were joined into dual strand specimens using an epoxy potting compound to be cast into 4- by 4- by 24-inch concrete prisms as shown in Figure 1.

Wires for other size test specimens were cut to the appropriate length, degreased in mineral spirits, and then in acetone. All of the molds for the test specimens were prepared in advance of casting. The dual strand specimens were placed in gang molds for the 4- by 4- by 24-inch prisms as shown in Figure 2.

After casting, all of the specimens were placed in a steam cabinet and steam cured for 16 hours. The 4- by 8-inch test cylinders cast and cured along with the test prisms were used to determine the strength of the concrete after steam curing and after 27 additional days of curing in 72-degree fog. The strength of the test cylinders was as follows:

Strength of 4- by 8-Inch Test Cylinders

16-hour steam cure	5914 psi
24-hour steam cure + 27-day fog cure	9380 psi

The 4- by 4- by 24-inch test prisms, which were to be cracked, were prepared by sawing a 1/2-inch-deep, 3/16-inch-wide "crack starter" notch in the upper "free" face of the specimen and then loading the specimen at three points as shown in Figure 3.

Eight test specimens were cut by sawing from two sections of piling furnished by ABAM Consulting Engineers, Seattle, WA. These sections were fabricated by Concrete Technology Inc., Tacoma, WA, and were used to compare the stress relaxation characteristics of the Nitronic 33 stainless steel prestressing strand with those of carbon steel. The sections are octagonal and are nominally 16 inches wide and 10 feet long. The section prestressed using Nitronic 33 stainless steel has 12 prestressing strands where the section prestressed using carbon steel has 11 prestressing strands. The section prestressed with Nitronic 33 has Nitronic 32 stainless steel spiral reinforcement. Each of the specimens cut from the Nitronic 33 prestressed section has two strands. Two of the specimens cut from the carbon steel prestressed section have one strand each and the other two specimens have two strands each. This variation in number of strands in the specimens was necessary due to the different spacing and the different number of wires in the piling sections. The test specimens and remaining sections are shown in Figure 4.

PERFORMANCE OF TESTS AND TEST RESULTS

Test Series No. 1 - Electrochemical Behavior in Mortar Extracts

Purpose of Test. To determine the chemical conditions, representative of those in marine concrete structures, which result in passivity of both carbon steel and Nitronic 33 stainless steel and to evaluate the relative stability of the passive films where they are present.

Test Specimens.

- Carbon Steel
- Carbon Steel w/crevice
- Nitronic 33
- Nitronic 33 w/crevice

Test Setup. Potentiostatic polarization per ASTM G61.

Test Measurements.

- Breakdown potential
- Repassivation potential

Test Condition Matrix.

Chloride PPM	pH (by dilution) 12.1	11.6	11.2	10.0
0				
40				
400				
4000				

Chloride was from seawater. Duplicate runs were made on each test specimen type for each condition.

Total Specimens.

Carbon steel	32
Carbon steel w/crevice	32
Nitronic 33	32
Nitronic 33 w/crevice	32
Total	128

Test Results. The electrochemical tests showed that the tolerance of Nitronic 33 stainless steel to both an increase in chloride ion and a decrease of pH was substantially greater than the tolerance of carbon steel. The electrochemical behavior for the specimens with crevices and those without crevices was essentially identical for both the carbon steel and Nitronic 33 stainless steel. Typical passive behavior for both the carbon steel and Nitronic 33 stainless steel as exhibited at pH 12.2 and 0 chloride are shown in Figures 5 and 6.

As the pH was lowered and/or the level of chloride increased, a point was reached where the passivity of each alloy was reduced. In the case of the carbon steel, the alloy exhibited essentially nonpassive behavior. As shown in Figures 7 and 8, the passivity of the carbon steel was reduced considerably at pH 11.6 and 200 ppm chloride and nonpassive behavior was exhibited at pH 10.0 and 200 ppm chloride. As shown in Figure 9, the level of passivity of Nitronic 33 stainless steel retained at a pH of 10.0 and 6000 ppm chloride was substantial.

Tables 1 and 2 summarize the results of the electrochemical tests. Fully passive behavior is indicated in the tables by a P. Marginal passivity is indicated by a M where passivity breaks down near the highest potential used in the tests. Lower levels of passivity are indicated by rupture potentials at increasingly negative potentials. Nonpassive behavior is indicated by a N.

Table 1. Electrochemical Behavior of Carbon Steel

Chloride (ppm)	Potential (MV) at pH (by Dilution) of--			
	12.1	11.6	11.2	10.0
0	P	P	P	P
20	P	M	+100	0
200	P	+100	-100	-200
2000	0	-100	-400	N
6000	-200	N	N	N

Table 2. Electrochemical Behavior of Nitronic 33 Stainless Steel

Chloride (ppm)	Potential (MV) at pH (by Dilution) of--			
	12.1	11.6	11.2	10.0
0	P	P	P	P
20	P	P	P	P
200	P	P	P	P
2000	P	P	P	P
6000	P	P	P	+100

Test Series No. 2 - Ion Tolerance Tests

Purpose of Test. To determine the relative tolerance of carbon steel and Nitronic 33 embedded in concrete to increased ionic content resulting from forced migration of seawater through the concrete.

Test Specimens.

- Carbon steel
- Nitronic 33

Test Setup. The apparatus used to determine the resistance of specimens embedded in concrete to accelerated ion migration is shown in Figure 10.

The voltage impressed across the test cell to drive the ions by electrophoresis was adjusted to give a voltage gradient of 1 V/in across the test specimen. Each test specimen contained one probe of Nitronic 33 stainless steel and one probe of carbon steel in order to eliminate any effects of concrete variability.

Test Measurements. Relative time (ion increase is proportional to time when applied voltage is present) for depassivation of the embedded probes.

Test Conditions.

1. Time to depassivation with diffusion potential on.

2. Run stainless steel specimen for time needed to depassivate carbon steel, then hold in seawater without diffusion voltage for 30 days to determine if delayed depassivation occurs. Duplicate runs were made for each test condition and material.

Total Specimens.

	Probes	Blocks
Carbon steel	4	2
Nitronic 33 w/crevice	8	4
Total	12	6

Test Results. The tolerance of Nitronic 33 stainless steel to ion migration was substantially greater than that of carbon steel. Figure 11 shows a typical potential versus time curve for an ion migration test run. After approximately 200 hours with voltage applied across the cell the carbon steel became active as indicated by an decrease in potential. The Nitronic 33 stainless steel remained passive for 1000 hours.

After 1600 hours of testing with the potential applied, the tests were terminated and the probes were removed from the concrete blocks by crushing the blocks. The Nitronic 33 specimens showed no evidence of attack. As shown in Figure 12, the carbon steel showed considerable attack and the Nitronic 33 stainless steel showed no attack.

Test Series No. 3 - Propagation Rates

Purpose of Test. To determine the relative rates of propagation of corrosion of carbon steel and Nitronic 33 embedded in concrete under conditions which will cause corrosion to initiate.

Test Specimens.

- Carbon steel
- Nitronic 33

Test Setup. The test setup for the determination of corrosion propagation rates is shown in Figure 13. The concrete cylinders were cut with a 1/16-inch-wide saw to a depth which exposed one of the two test probes.

Test Measurements. Corrosion current versus time measured with a zero resistance ammeter. Corrosion potential versus time.

Test Conditions. Seawater immersion. Duplicate specimens for each material.

Total Specimens.

	Probes	Blocks
Carbon Steel	4	2
Nitronic 33	4	2
Total	8	4

Test Results. The corrosion current for the carbon steel increased rapidly at the start of the test but fell to approximately 40 microamps after 50 hours. The Nitronic 33 stainless steel remained fully passive after 1000 hours with no measureable current flow. Figures 14 and 15 show the potential and current versus time for the carbon steel and Nitronic 33 stainless steel specimens.

The test probes were removed from the test blocks after 1600 hours of test exposure. The Nitronic 33 stainless steel test probes were not attacked. The carbon steel test probes showed considerable surface attack. Figure 16 shows the condition of the carbon steel and Nitronic 33 stainless steel probes after 1600 hours of exposure in the propagation rate tests.

Test Series No. 4 - Depassivation at Closed Cracks

Purpose of Test. To determine the relative susceptibility of carbon steel and Nitronic 33 embedded in concrete to depassivation in the presence of a crack in the concrete which has opened and reclosed.

Test Specimens.

- Carbon steel w/crevice
- Nitronic 33 w/crevice

Test Setup. The test setup for evaluation of depassivation at closed cracks is shown in Figure 17.

Test Measurements. Corrosion potential versus time.

Test Conditions. Seawater exposure. Duplicate specimens for each material.

Total Specimens.

	Probes	Blocks
Carbon steel w/crevice	4	2
Nitronic 33 w/crevice	4	2
Total	8	4

Test Results. Neither the carbon steel nor the Nitronic 33 stainless steel depassivated at closed cracks during the duration of this test. The corrosion potential versus time for the carbon steel is shown in Figure 18 and the corrosion potential for the Nitronic 33 stainless steel versus time is shown in Figure 19.

The test bars in these specimens were removed from the test blocks after 1200 hours of exposure in the depassivation at closed crack tests. Neither the carbon steel nor the Nitronic 33 stainless steel specimens showed any attack.

Test Series No. 5 - Ion Diffusion Tolerance at Closed Cracks

Purpose of Test. To determine the relative tolerance of carbon steel and Nitronic 33 embedded in concrete to increased ionic content resulting from forced diffusion of seawater into the concrete in the presence of a closed crack.

Test Specimens.

- Carbon steel w/crevice
- Nitronic 33 w/crevice

Test Setup. The test setup for the determination of ion diffusion tolerance at closed cracks was similar to the test setup for the determination of depassivation at closed cracks ecxept that the inner bars were used as a counter electrode to produce a potential gradient within the specimen.

Test Measurements. Corrosion potential versus time.

Test Conditions. Seawater immersion.

1. Time to depassivation with diffusion potential on.

2. Run stainless steel specimen for time needed to depassivate carbon steel, then hold in seawater without diffusion voltage for 30 days to determine if delayed depassivation occurs. Duplicate runs were made on each material.

Total Specimens.

	Probes	Blocks
Carbon steel w/crevice	4	2
Nitronic 33 w/crevice	4	2
Total	8	4

Test Results. The carbon steel specimens depassivated after an average of 32 hours of applied current. The Nitronic 33 stainless steel remained passive after 1600 hours of applied current.

The test bars in these specimens were removed from the test blocks to determine their surface condition. The Nitronic 33 stainless steel specimens showed no attack. The carbon steel test specimens showed considerable surface attack in the area of the crack.

Test Series No. 6 - Repassivation at Closed Cracks

Purpose of Test. To determine the relative ability of carbon steel and Nitronic 33 embedded in concrete to repassivate in the presence of a closed crack if corrosion initiates when the crack is open.

Test Specimens.

- Carbon steel w/crevice
- Nitronic 33 w/crevice

Test Setup. The test setup for this series is identical to that shown for depassivation at open cracks (Figure 17).

Test Measurements. Corrosion potential versus time.

Test Conditions. Open crack until corrosion initiates. Measure time to achieve repassivation. Duplicate runs were made for test condition and material.

Total Specimens.

	Probes	Blocks
Carbon steel w/crevice	4	2
Nitronic 33 w/crevice	8	4
Total	12	6

Test Results. As the Nitronic 33 stainless steel did not depassivate at open cracks over the duration of the test in Series No. 7, it was not possible to make a comparison between the carbon steel and Nitronic No. 3 stainless steel for the ability to repassivate. The carbon steel repassivated within 35 hours of closing the crack as shown in Figure 20.

Test Series No. 7 - Depassivation at Open Cracks

Purpose of Test. To determine the relative susceptibility of carbon steel and Nitronic 33 embedded in concrete to depassivation in the presence of cracks in the concrete cover of various widths.

Test Specimens.

- Carbon steel w/crevice
- Nitronic 33 w/crevice

Test Setup. The test setup for determination of depassivation at open cracks is shown in Figure 21.

Crack Widths.

- 1/64 inch
- 1/32 inch
- 1/16 inch
- 1/8 inch

Test Measurements. Corrosion potential versus time.

Test Conditions. Seawater immersion. Duplicate specimens for each material and crack width.

Total Specimens.

	Probes	Blocks
Carbon steel w/crevice	16	8
Nitronic 33 w/crevice	16	8
Total	32	16

Test Results. None of the Nitronic stainless steel specimens showed depassivation during the duration of these tests. The carbon steel bars with 1-inch cover showed depassivation upon immersion for the 1/8-inch-wide crack, 50 hours for the 1/16-inch crack, 150 hours for the 1/32-inch crack, and 180 hours for the 1/64-inch crack. The carbon steel bars with 2-1/4-inch cover show depassivation immediately upon immersion for the 1/8-inch-wide crack but continued passive behavior for the 1/16-inch and tighter cracks. Figures 22 and 23 show the potential of the inner (2-1/4-inch cover) and outer (1-inch cover) bars versus time.

The test bars in these specimens were removed from test blocks to determine their surface condition. As shown in Figures 24 and 25, the Nitronic 33 stainless steel specimens were not attacked, but the carbon steel specimens showed considerable attack.

Test Series No. 8 - Corrosion Product Volume

Purpose of Test. To determine the relative volume of corrosion products produced in the corrosion of carbon steel and Nitronic 33 when embedded in concrete.

Test Specimens.

- Carbon steel
- Nitronic 33

Test Setup. The test setup for the determination of corrosion product volume is shown in Figure 26.

Test Measurements.

- Change in cylinder diameter
- Visual inspection of metal-concrete interface at end of test
- Weight loss of probes

Test Conditions.

- Seawater immersion
- Anodic current from propogation rate test
- Triplicate specimens for each material

Total Specimens.

Carbon steel	3
Nitronic 33	3
Total	6

Test Results. As corrosion of the Nitronic 33 stainless steel did not initiate in the propagation rate tests it was not possible to perform the tests for the Nitronic 33 stainless steel in this series as appropriate corrosion currents could not be established.

There were no instances in the tests performed for this validation that resulted in the generation of sufficient volumes of corrosion products to establish any conclusions regarding the effects of corrosion product volume on corrosion.

Test Series No. 9 - Evaluation of Prestressed Pile Specimens

Purpose of Test. To determine the susceptibility of Nitronic 33 and carbon steel strand embedded in concrete to depassivation using specimens cut from a prestressed test piling section with cracks in the concrete cover. Original plans to test the specimens from the piling without cracks were not performed as the resistance to corrosion initiation of both the carbon steel and Nitronic 33 stainless steel in specimens without cracks was likely to be longer than the time available for these tests. Original plans to test each strand in the sections cut from the pilings were changed since it was determined that the strands were electrically connected through the spiral wrap. It was also determined after the original plans for this test that the spiral reinforcements in the Nitronic 33 stainless steel prestressed piling were Nitronic 32 stainless steel.

Test Specimens. Cut from test piling prestressed with Nitronic 33 strand and carbon steel strand.

Test Setup. The test setup for the determination of the susceptibility of carbon steel and Nitronic 33 stainless steel strand in specimens cut from test pilings is shown in Figure 27. The faces and ends of the test sections were sealed with paraffin prior to filling the reservoir with seawater.

Test Measurements. Corrosion potential versus time.

Test Conditions.

- Seawater immersion
- Crack widths - 1/8 and 1/16 inch

Total Specimens.

	Strands	Blocks
Carbon steel	2	2
Nitronic 33	2	2
Total	4	4

Test Results. The corrosion potentials versus time for the carbon steel and Nitronic 33 stainless steel piling sections showed erratic behavior. This was attributed to the more complex geometry of the specimens, the presence of the spiral reinforcement which was exposed (but coated with paraffin), and the variation of cover over the strands. The potentials indicated that there may be limited corrosion activity in both the carbon steel and Nitronic 33 stainless steel prestressed specimens.

Upon completion of the potential measurements, the strand and spiral reinforcement was removed from the test specimens. As shown in Figure 28, the carbon steel strand and spiral showed considerable surface attack in the vicinity of the cracks.

The Nitronic 32 stainless steel spiral reinforcement in the piling specimens showed several areas of incipient attack. The strand in the specimens was not attacked. The condition of the strand and spiral reinforcement is shown in Figure 29.

Test Series No. 10 - Evaluation of In-Place Pilings

Purpose of Test. To determine the short term (17-month) performance of prestressed pilings fabricated using both carbon steel and Nitronic 33 stainless steel exposed in a marine structure.

Test Specimens. Pilings in the SEA-LAND pier - Port of Tacoma.

Test Setup. The test pilings were evaluated using a developmental diver-held, surface-supported probe which measured the flow of current into or from the surface of the test pilings. The technique is described in NCEL TM 52-85-01.

Test Measurements. Corrosion currents resulting from corrosion cells on the prestressing strand or spiral reinforcement. Visual observations of surface defects on pilings.

Test Conditions. Seawater immersion of driven piling in an in-service structure.

Test Results. No significant corrosion activity was detected in either the Nitronic 33 stainless steel or the carbon steel prestressed pilings. The readings obtained on both types of pilings were statistically identical. Small locations on the Nitronic 33 stainless steel prestressed piling where limited corrosion activity was located were correlated with carbon steel "pre-ties" used in the manufacture of the test piling.

Due to instrument limitations, the readings taken during the first inspection of the test pilings on 12 September and 13 September 1985 showed no corrosion activity on either piling. The performance of the probe was substantially improved by modifying the electronics in the topside instrumentation package and the test probe. A second inspection of the pilings on 31 October 1985 and 1 November 1985 resulted in the generation of reliable and meaningful test results. The corrosion activity in the test pilings was extremely small. The maximum readings obtained were less than one-tenth of the readings typically obtained on laboratory specimens where corrosion activity was known to be occuring. Figures 30 and 31 show that the readings obtained for both the carbon steel and stainless steel were similar in the frequency of readings versus their polarity and intensity. As shown in Figure 32, which is a current profile map of the Nitronic 33 prestressed piling, there were several small sites on one surface of the piling where the majority of the corrosion activity on the pile was concentrated. The level of current was small, however the readings were reproducible and were interpreted as locations of corrosion activity. No surface indication of activity was noted by the divers at these sites or at any other location on the test pilings.

Subsequent detailed examinations of the piling sections obtained by NCEL for sectioning revealed that there were carbon steel tie wires used at some locations for securing the spiral wrap to the prestressing strand in the Nitronic 33 piling. Figure 33 shows a magnet adhering to such a tie wire. The tie wire was found on the same face of the test section where the corrosion activity was located by the test probe. The majority of the tie wires in this specimen were, however, nonmagnetic austenitic stainless steel.

Discussions with Mr. Philip Birkeland of ABAM Consulting Engineers regarding the manufacture of the test piling sections revealed that the carbon steel tie wire located on the test piling section and the corrosion activity located by the test probe were at locations where the spiral wrap was "pre-tied" to the strands. These "pre-ties" are spaced at approximately 4-foot intervals and are located along the face of the piling identified as 3.0 in Figure 32. This is identical to the spacing and location of corrosion activity on the test piling. While the use of carbon steel wires was neither intended nor confirmed by ABAM, their use

was considered possible, particularly as their presence was confirmed in Figure 33 which shows a small bar magnet being suspended from the tie wire.

The presence of the limited number of small carbon steel ties in the exposed pilings is not considered to be significant from the standpoint of the lifetime of the pilings, however, the use of such tie wires should be avoided in future construction so that inspection using current probes can be more readily interpreted. In fact, confirmation of the ability of the test probe to detect such small sites of limited activity was considered to be a positive aspect of the presence of the carbon steel ties in the Nitronic 33 test pilings.

IMPACT OF CORROSION ON STRUCTURAL INTEGRITY

Purpose of Effort

The purpose of this effort is to assess the impact of the type and extent of corrosion which is likely to occur on Nitronic 33 stainless steel in concrete on the structural integrity of prestressed and reinforced concrete structures. As the distribution, type, and extent of corrosion of Nitronic 33 is likely to be substantially different from that of the carbon steel commonly used, the structural impact of the corrosion which is likely to occur on the Nitronic 33 may also be substantially different.

Results of Assessment

The results of this assessment are included in this report as Appendix A. This assessment was performed by Dr. George Warren of NCEL. The assessment showed that the structural impact of distributed localized attack of the type anticipated for the Nitronic 33 prestressed piling, should it occur, would be less serious than the more general attack which would be likely to occur on carbon steel prestressed structures of similar design.

ASSESSMENT OF INDUCED ELECTRICAL CURRENTS

Purpose of Effort

The purpose of this effort is to determine the magnitude and likely paths of electrical currents which may be induced in prestressed concrete structures by pulsating magnetic fields. It is possible that electrical currents which are induced can flow from the reinforcement into an electrolyte and induce corrosion.

Results of Assessment

This assessment was performed by Mr. Jim Brooks of NCEL. The results of this assessment are given in Appendix B. The assessment showed that the worst case currents are less than 1 ampere. This level

is substantially below that required to cause significant corrosion activity, and can be reduced substantially by increasing the resistance of the current path by not allowing the prestressing strand to protrude from the bottom of the pilings. As this will be required to prevent direct contact between the strands and seawater or bottom sediments, the currents in an actual structure will be insignificant from the standpoint of corrosion.

REVIEW OF TEST RESULTS

This review of test results is based upon the electrochemical tests and the actual condition of the test bars removed from the test specimens except for the evaluation of the in-place pilings.

Test Series	Results
#1	Nitronic 33 more resistant to lower pH and increased chloride.
#2	Nitronic 33 more resistant to ion migration.
#3	Carbon steel became active; Nitronic 33 remained passive.
#4	Neither alloy became active.
#5	Nitronic 33 more resistant.
#6	Carbon steel repassivated; Nitronic 33 did not depassivate.
#7	Carbon steel depassivated; Nitronic 33 did not depassivate.
#8	Carbon steel depassivated; Nitronic 33 did not depassivate. Corrosion product volume insufficient to cause measurable changes.
#9	Carbon steel corroded; Nitronic 33 did not corrode. Nitronic 32 showed incipient corrosion.
#10	No significant difference between pilings. Carbon steel in Nitronic 33 piling had become active, otherwise, no significant activity in either piling.

Test Series	Results
Structural Integrity	The type of attack expected on the Nitronic 33, should it occur, would have less impact than that of the typical corrosion of carbon steel.
Induced Currents	The effect of induced electrical currents will be insignificant and may be easily reduced further.

CONCLUSIONS

Based upon the results of all of the tests performed in this validation, it is concluded that the resistance of Nitronic 33 stainless steel to corrosion in environments representative of those found in a prestressed or reinforced structure is superior to the corrosion resistance of carbon steel.

The type of local attack which may occur if corrosion of the Nitronic 33 stainless steel is initiated will have less effect than the distributed corrosion which occurs on carbon steel prestressing.

Electrical currents induced by the operational magnetic fields associated with degaussing facilities will not result in accelerarted attack of the Nitronic 33 stainless steel.

NEED FOR ADDITIONAL EFFORTS

Construction Criteria

As the properties and performance of Nitronic 33 stainless steel have been found to be substantially different from the commonly used carbon steel, it is necessary to develop different criteria for the construction and construction inspection of structures using Nitronic 33 stainless steel. This has already been accomplished for the design of Nitronic 33 prestressed and reinforced structures where such differences in strength, elasticity, stress relaxation, bond strength, and weldability were assessed and changes to the design and fabrication of the structural elements were modified as necessary. This must also be done for the differences in corrosion behavior. The most critical factors related to corrosion performance are likely to be the tolerable limits for cracking in the cover over prestressing strand and reinforcing bars, and the method for repairing such cracks and encapsulating the exposed ends of the prestressing strands.

Maintenance, Repair Methods, and Criteria

As for construction criteria, it will be necessary to develop different methods and criteria for the in-service inspection of structures using Nitronic 33. The most critical factors related to corrosion performance are likely to be the detection of corrosion activity and the location of the position of the prestressing strands. The test probe

used experimentally in this validation should be developed into a field unit which can be used for the inspection of Nitronic 33 prestressed structures and for carbon steel prestressed and reinforced structures as well.

As for construction criteria, it will be necessary to develop different methods and criteria for the in-service maintenance and repair of structures using Nitronic 33. The most critical factors related to corrosion performance are likely to be the methods for repair of in-service cracking in the cover over prestressing strand and reinforcing bars, and the the methods for spalled elements.

Continuation of Test Exposures

Long term exposure is the most reliable method of determining actual performance of any material. The tests performed in this validation were designed to determine the relative performance of Nitronic 33 stainless steel and carbon steel under artifically produced conditions and in small samples. While the results of such tests can be used to compare performance, they should not be used to predict the lifetime of the materials tested when they are in use in full-scale structures.

Selected test exposures of Nitronic 33 should be continued to both support the recommended methods and criteria efforts and to serve as a basis for the prediction of the long term performance of Nitronic 33 stainless steel in full-scale structures.

RECOMMENDATIONS

1. The design and construction of the depermiag facilities should proceed.

2. The design drawings should be carefully reviewed to insure that adequate cover is provided over all of the Nitronic 33 stainless steel.

3. Construction and construction inspection criteria should be developed for the facilities constructed using Nitronic 33 stainless steel.

4. In-service inspection methods and criteria should be developed for facilities constructed using Nitronic 33 stainless steel.

5. Maintenance and repair methods and criteria should be developed for facilities constructed using Nitronic 33 stainless steel.

6. Selected test exposures of Nitronic 33 should be continued to support the recommended methods and criteria efforts and to obtain long term performance data on Nitronic 33 stainless steel.

Figure 1. Dual strand prestressing wire specimens.

Figure 2. Gang molds for 4- by 4- by 24-inch prisms.

Figure 5. Cracking of 4- by 4- by 24-inch prisms.

Figure 6. [illegible]

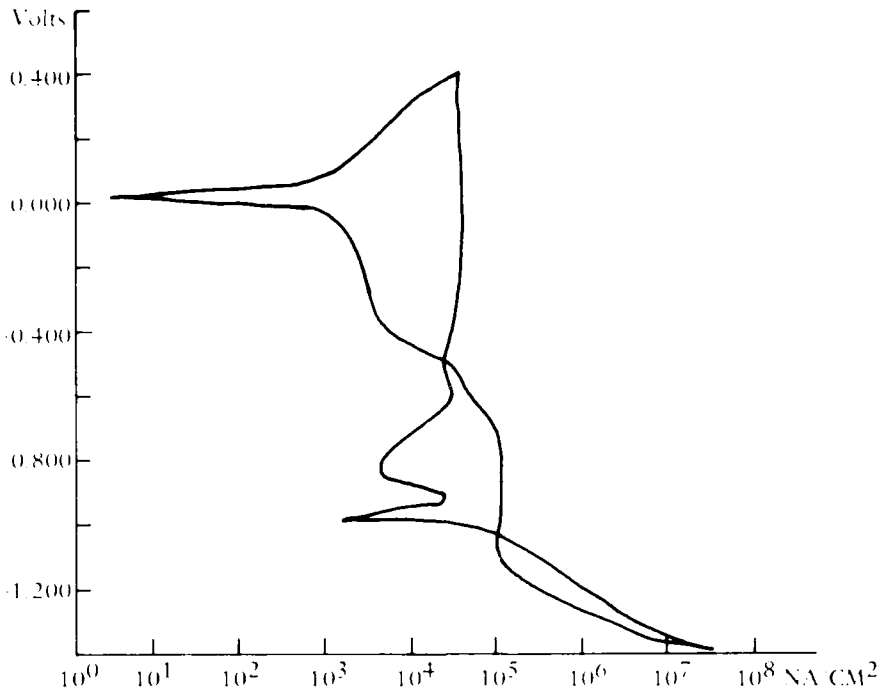


Figure 5. Polarization behavior of Nitronic 33 stainless steel - pH = 12.1, Cl^- = 0.

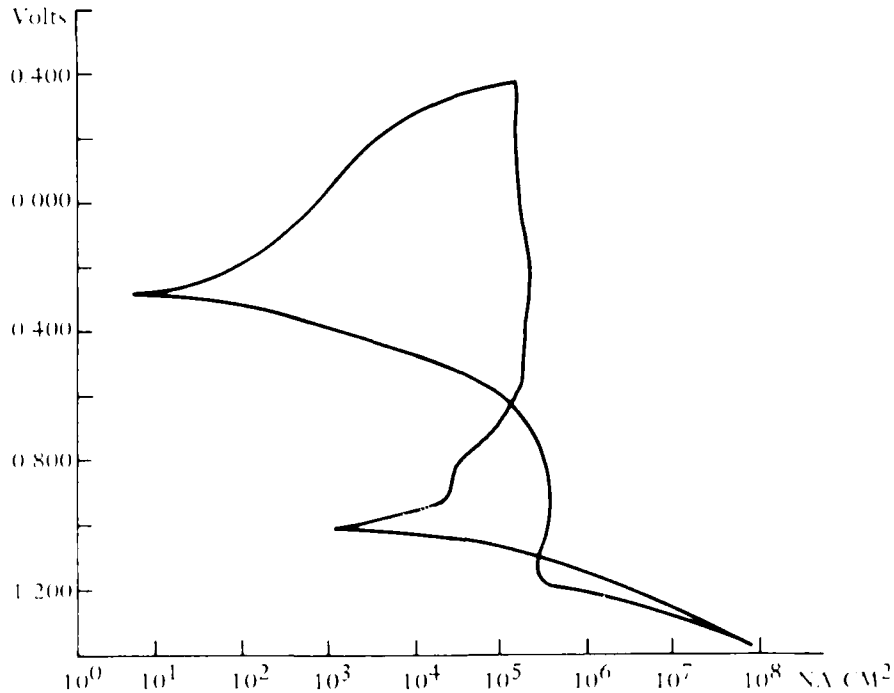


Figure 6. Polarization behavior of carbon steel - pH = 12.1, Cl^- = 0.

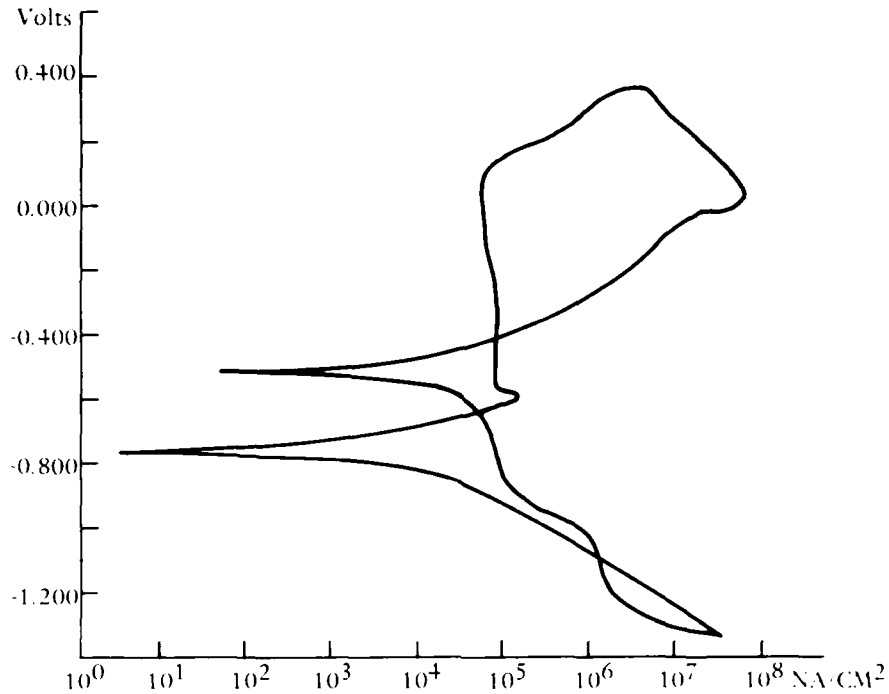


Figure 7. Carbon steel - pH = 11.6, Cl^- = 200 ppm.

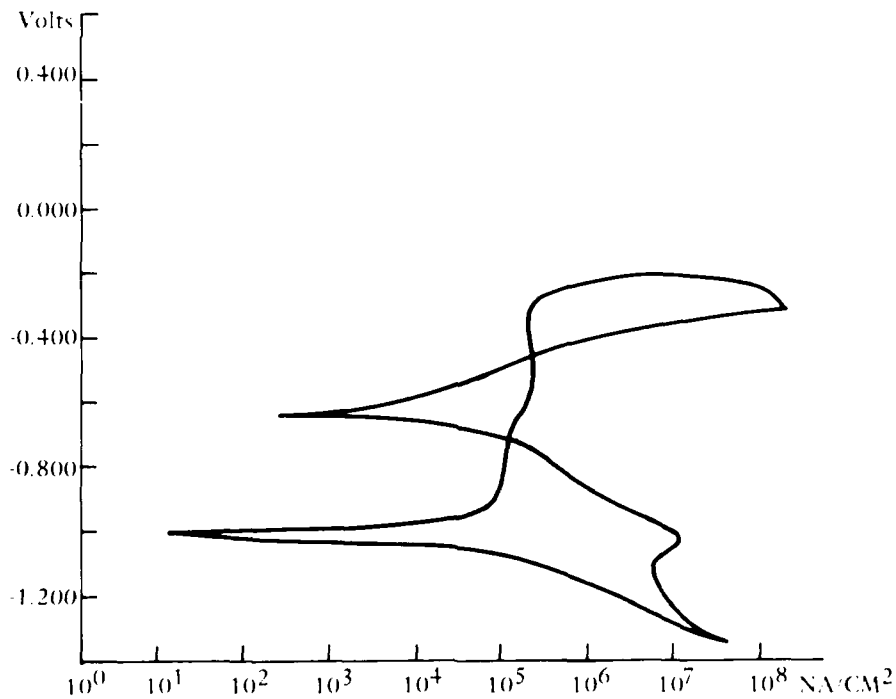


Figure 8. Carbon steel - pH = 10.0, Cl^- = 200 ppm.

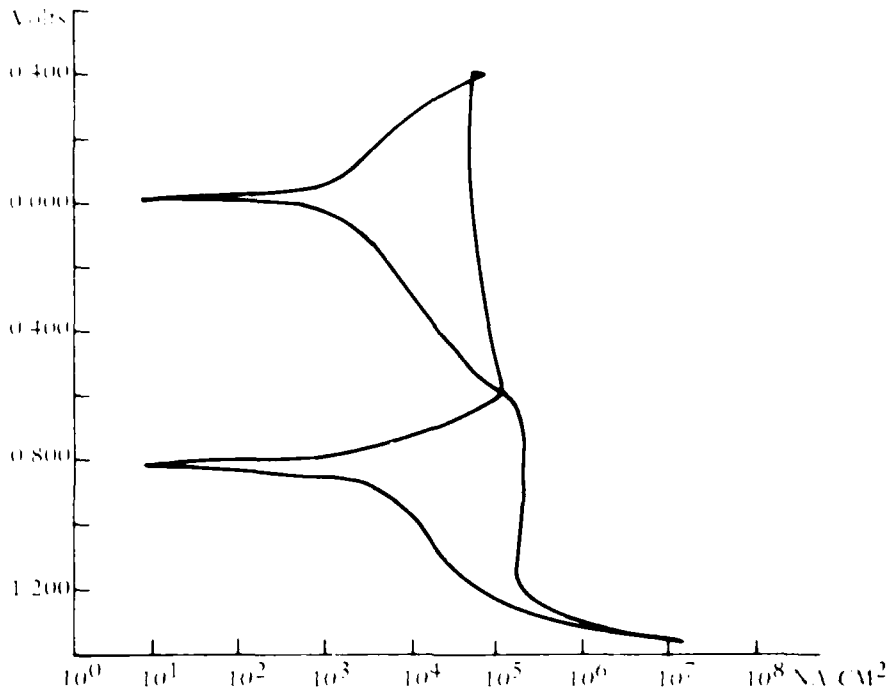


Figure 9. Nitronic 33 stainless steel - pH = 10.0, Cl^- = 6,000 ppm.

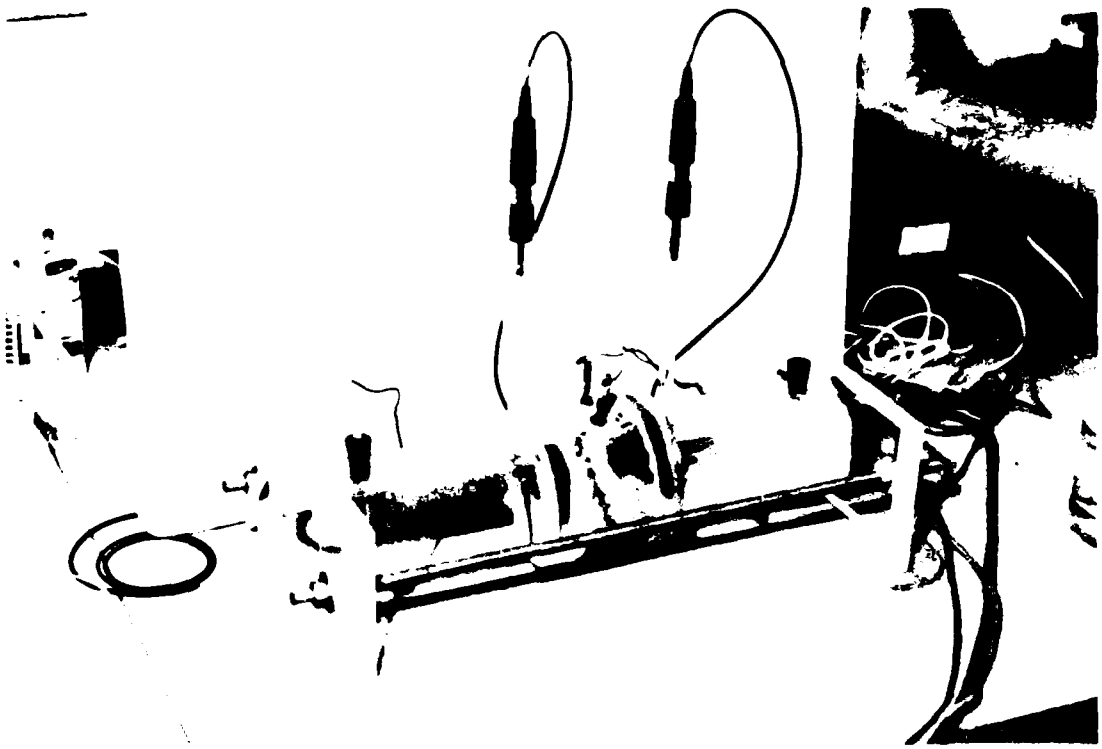


Figure 10. Apparatus for determining resistance to ion migration.

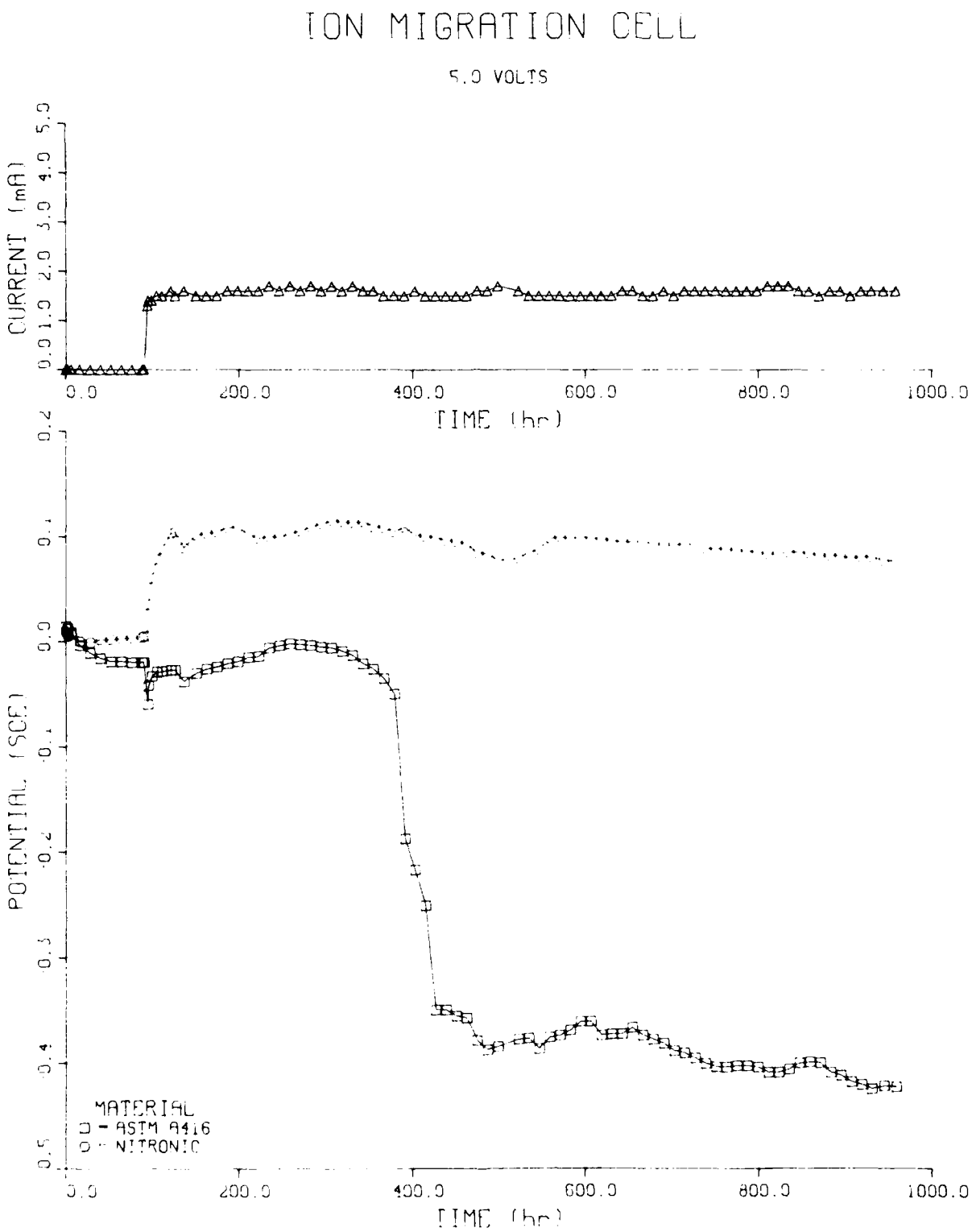


Figure 11. Tolerance of Nitronic 33 stainless steel and carbon steel to ion migration.

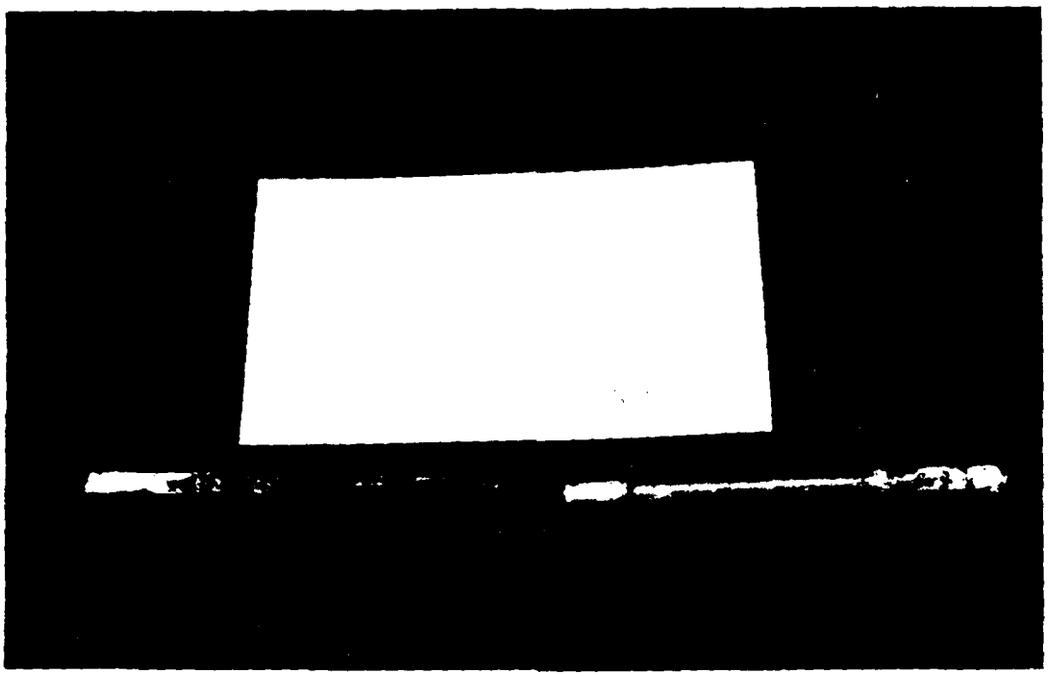


Figure 12. Condition of carbon steel and Nitronic 33 stainless steel after 1600 hours of exposure in ion tolerance test.

Figure 13. Setup for propagation rate test.

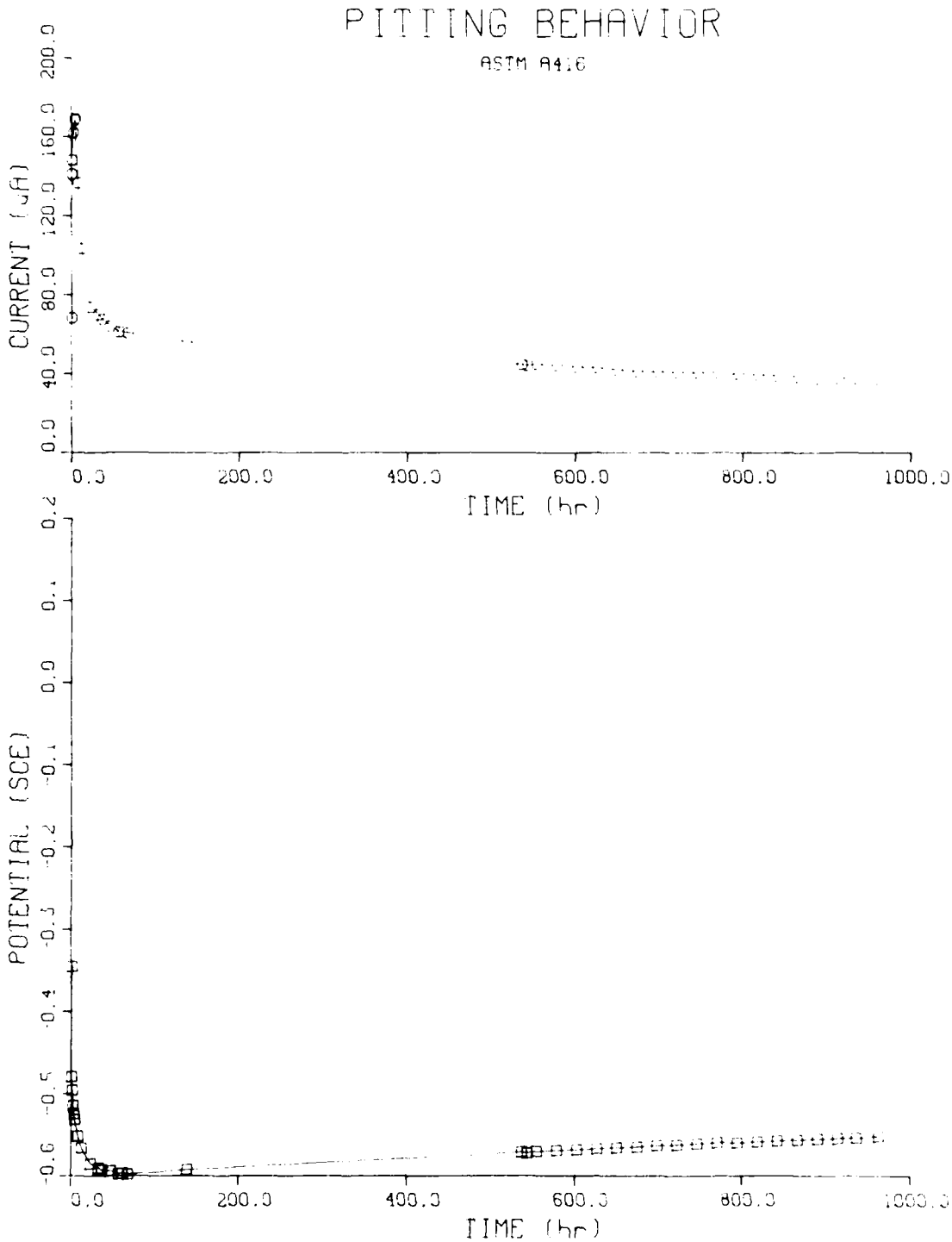


Figure 14. Corrosion current and potential versus time for carbon steel.

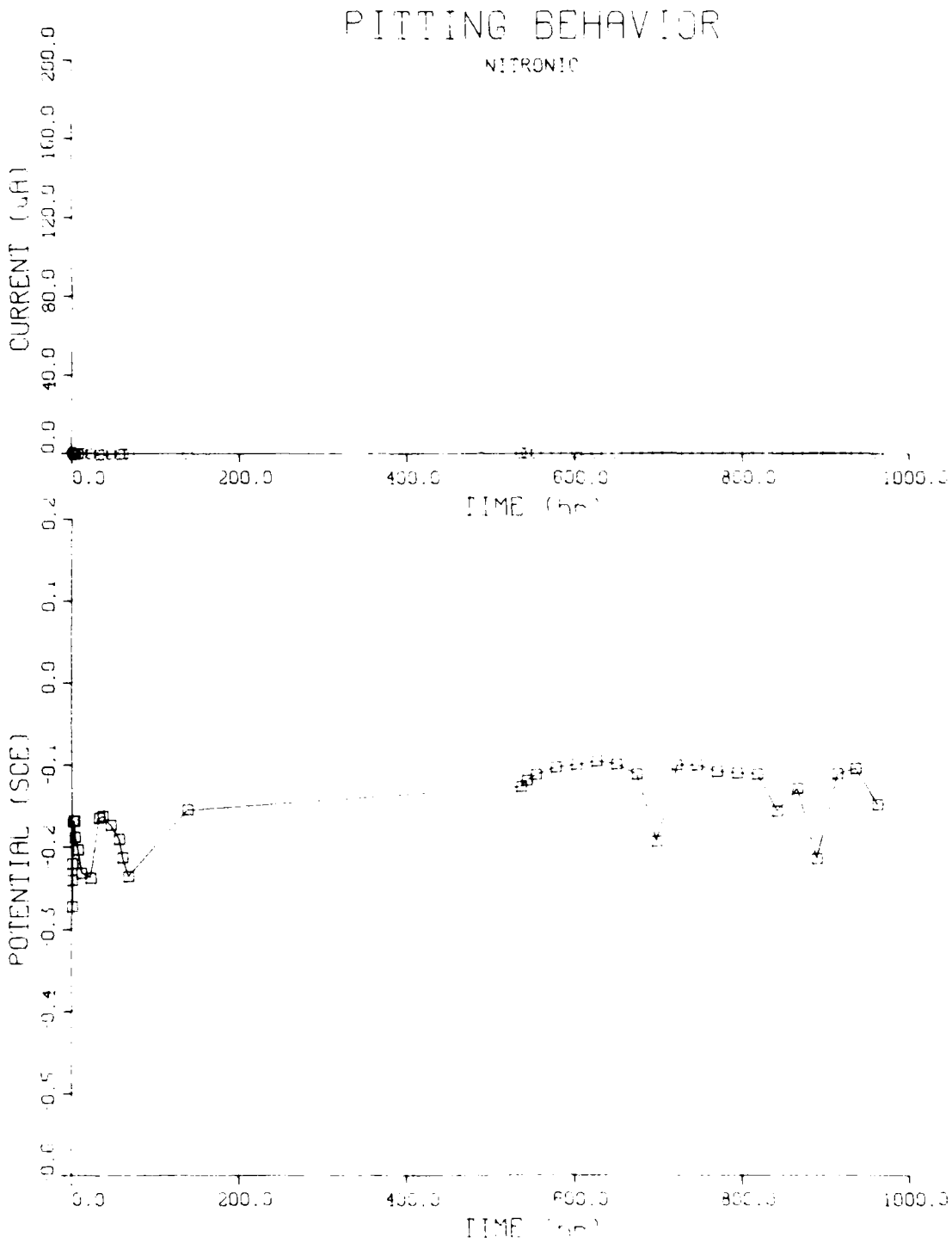


Figure 15. Corrosion current and potential versus time for Nitronic 33 stainless steel.

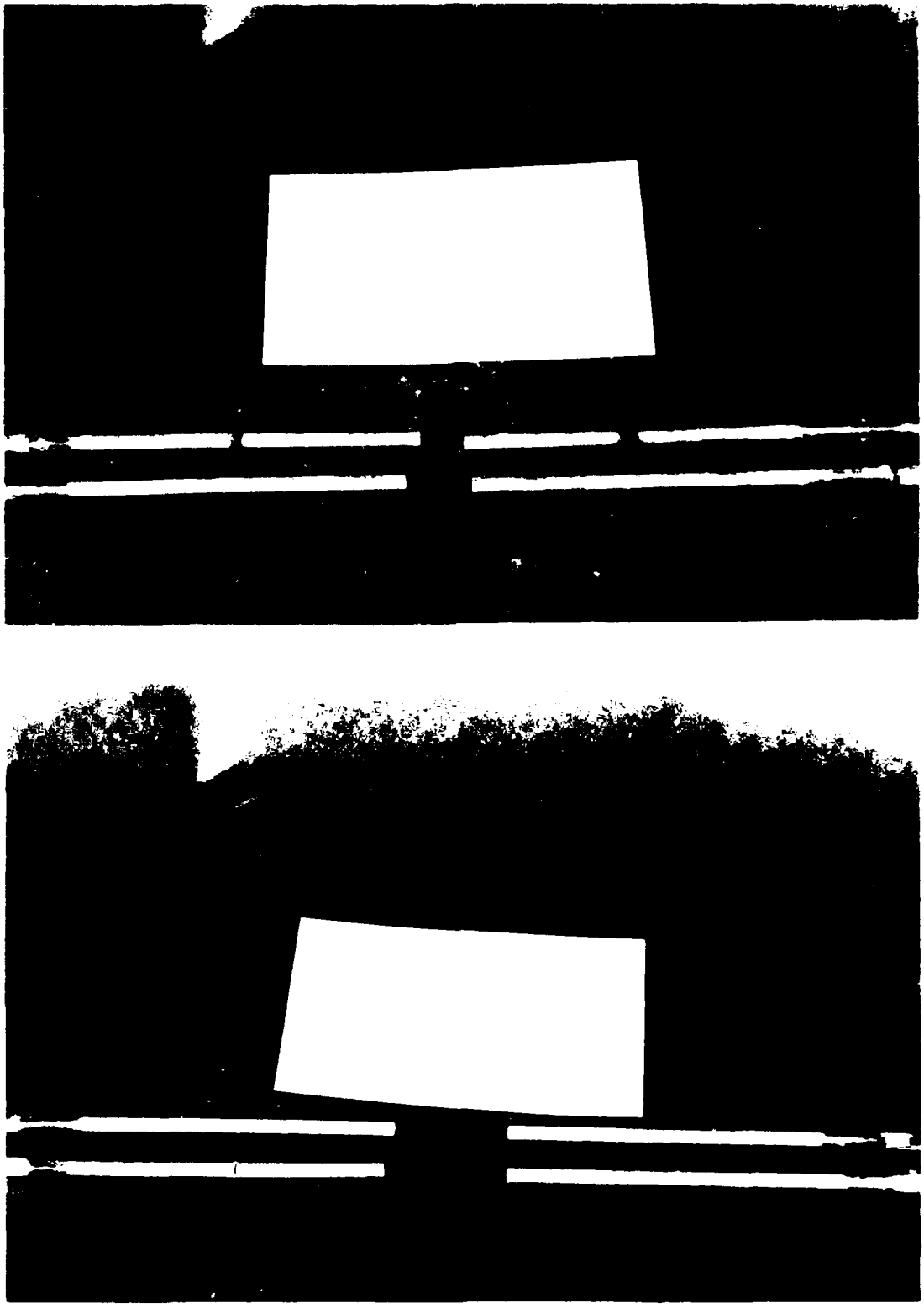


Figure 16. Condition of carbon steel and Nitronic 33 stainless steel test probes after 1600 hours of exposure in propagation rate tests.

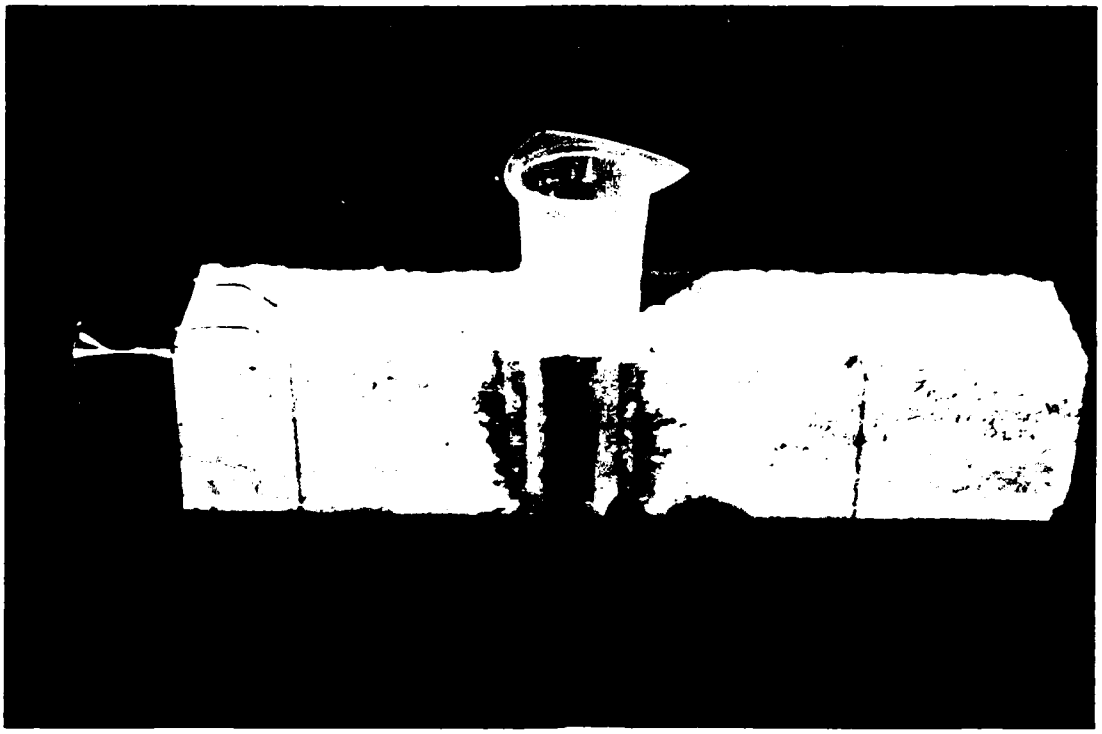


Figure 17. Test setup for depassivation at closed cracks.

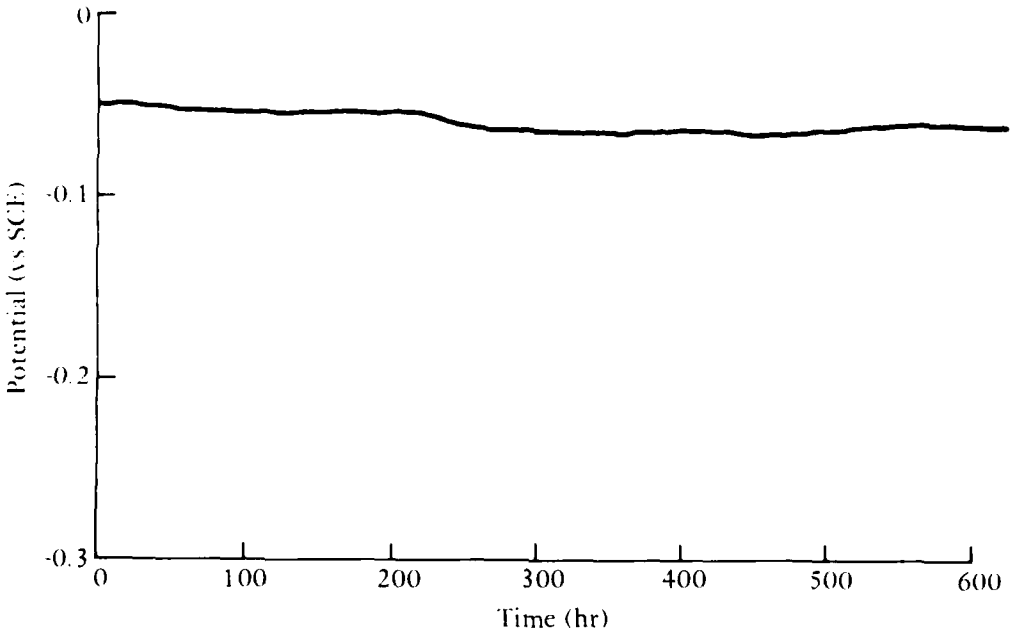


Figure 18. Corrosion potential versus time for carbon steel at a closed crack.

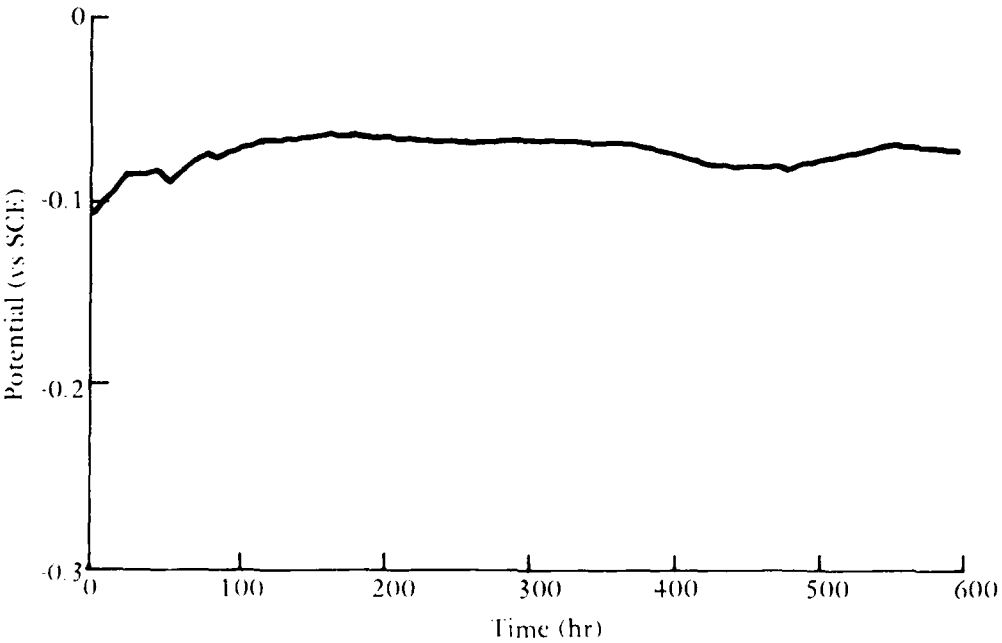


Figure 19. Corrosion potential versus time for Nitronic 33 stainless steel at a closed crack.

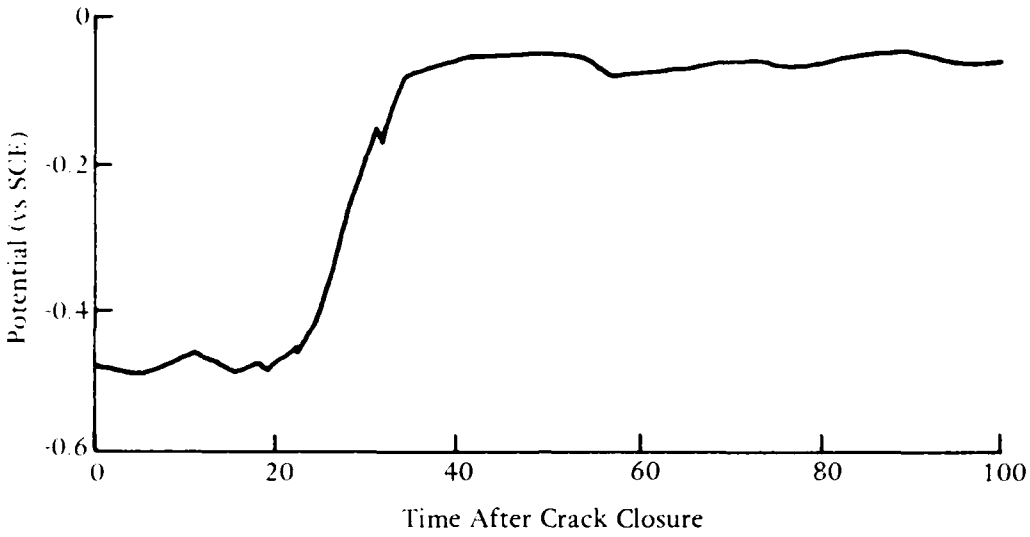


Figure 20. Repassivation of carbon steel after initiation of corrosion.

Figure 21. Setup for determination of depassivation at open cracks.

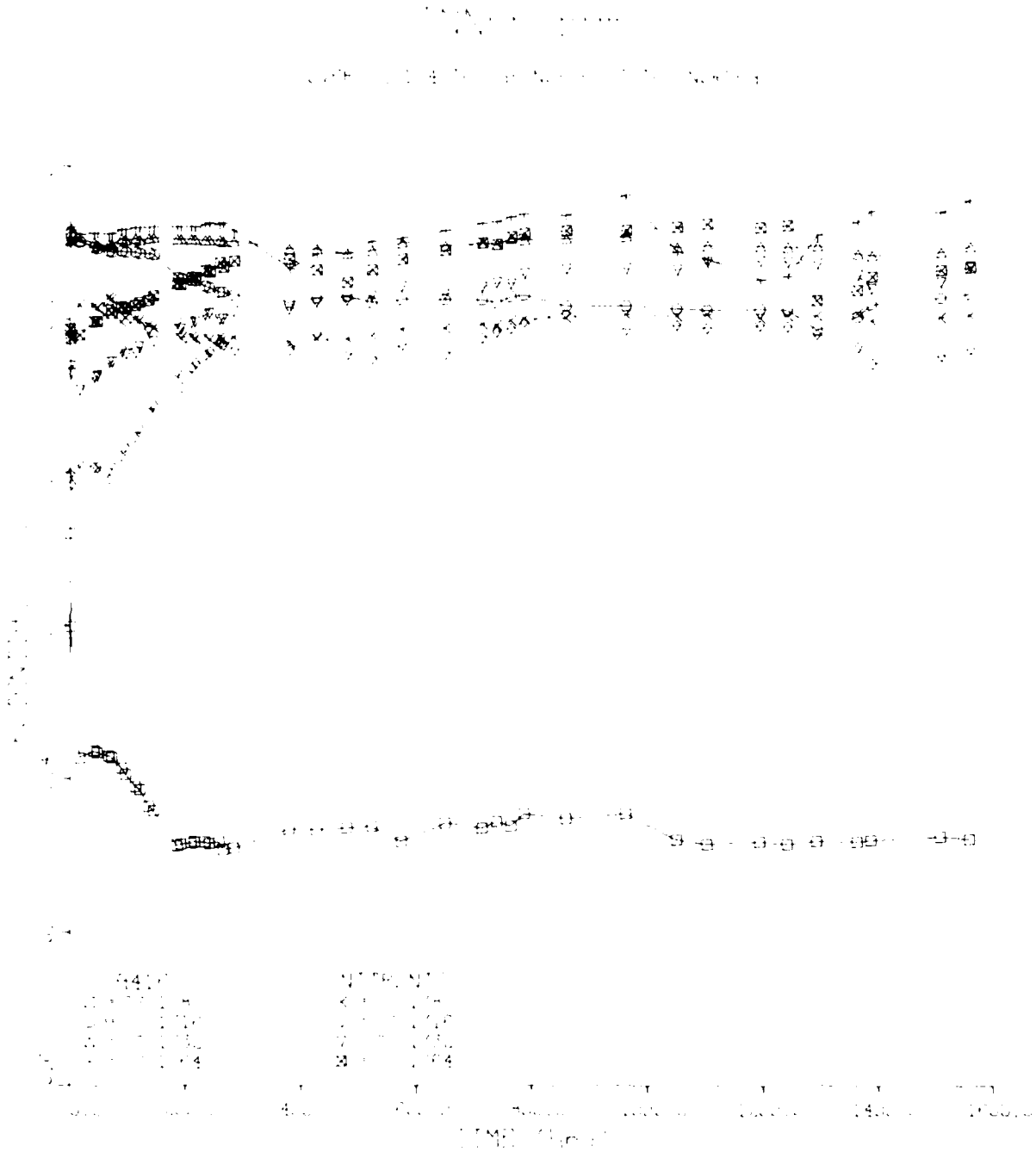


Figure 22. Potential versus time for inner bars at cracks.

Cover 1 in. at Notch, 1-3/4 in. Nominal

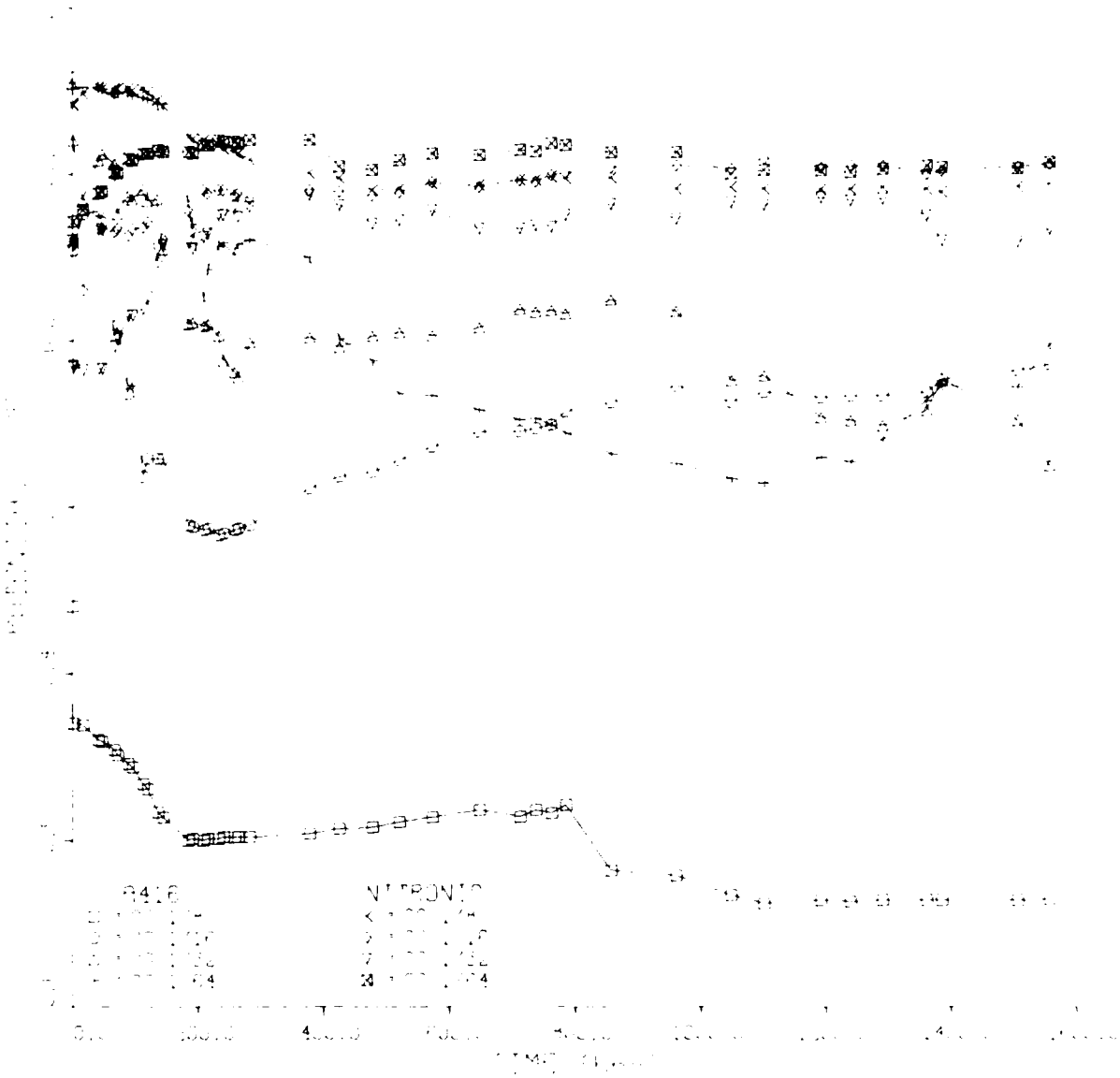
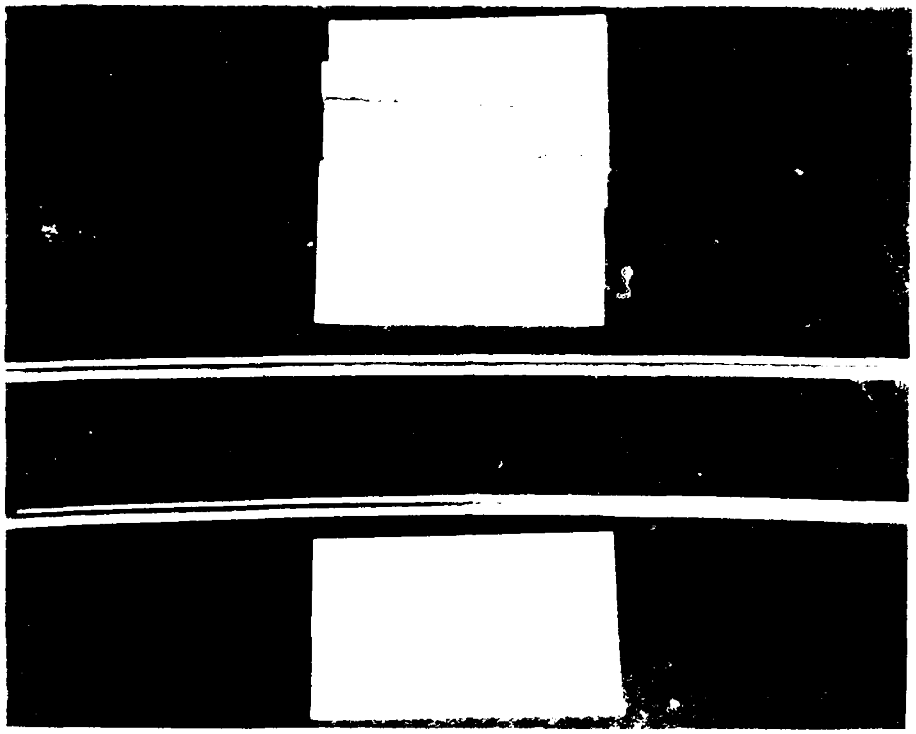
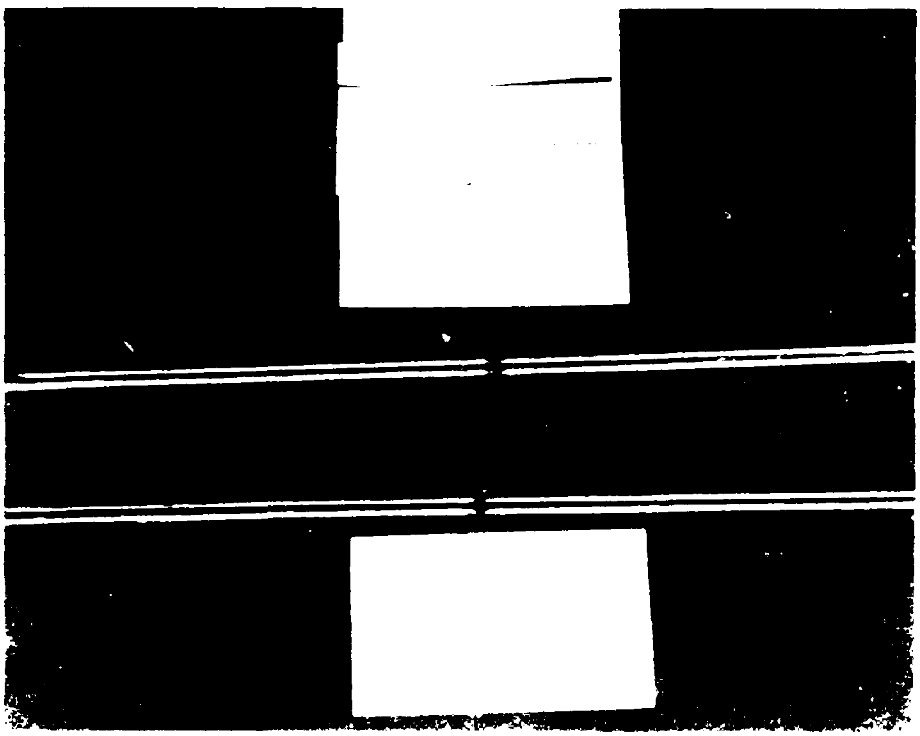


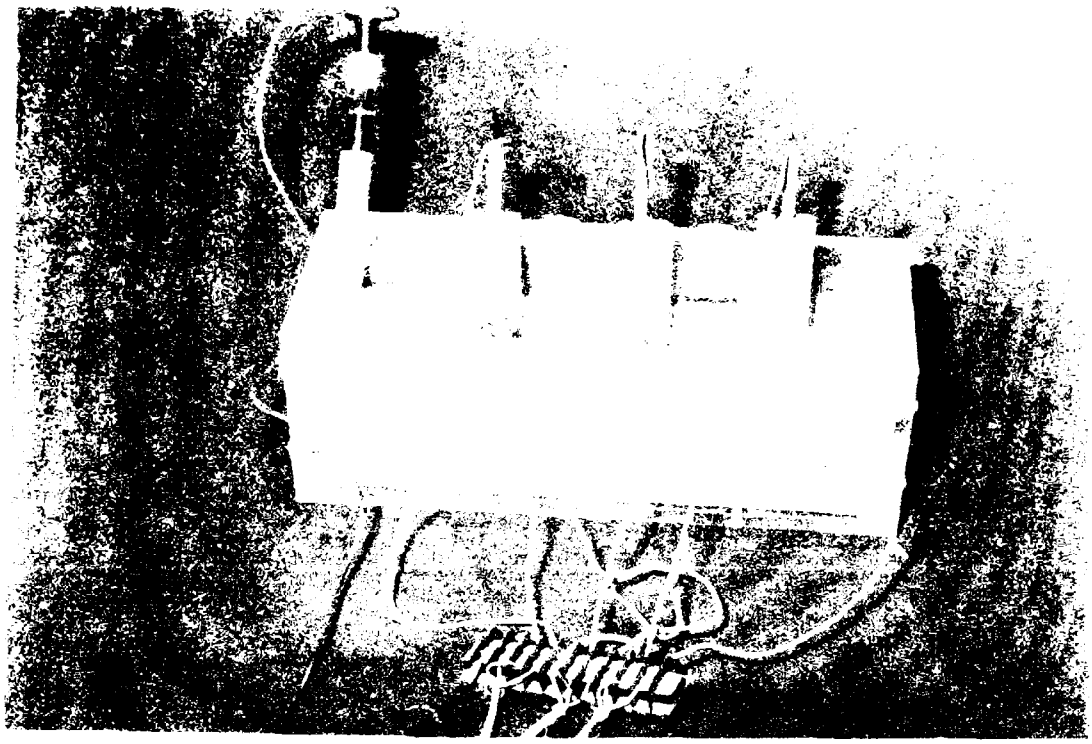
Figure 23. Potential versus time for outer bars at cracks.



[illegible] crack test.



[illegible] open crack tests



[illegible] Test setup for the determination of relative corrosion [illegible] volume.

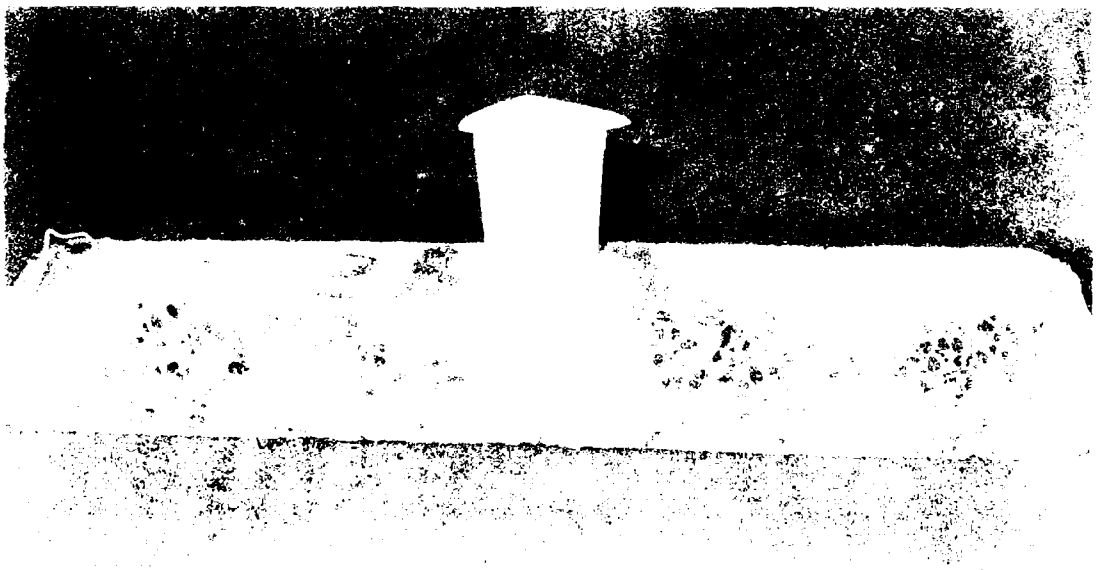


Figure 28. Carbon steel strand from piling specimen.

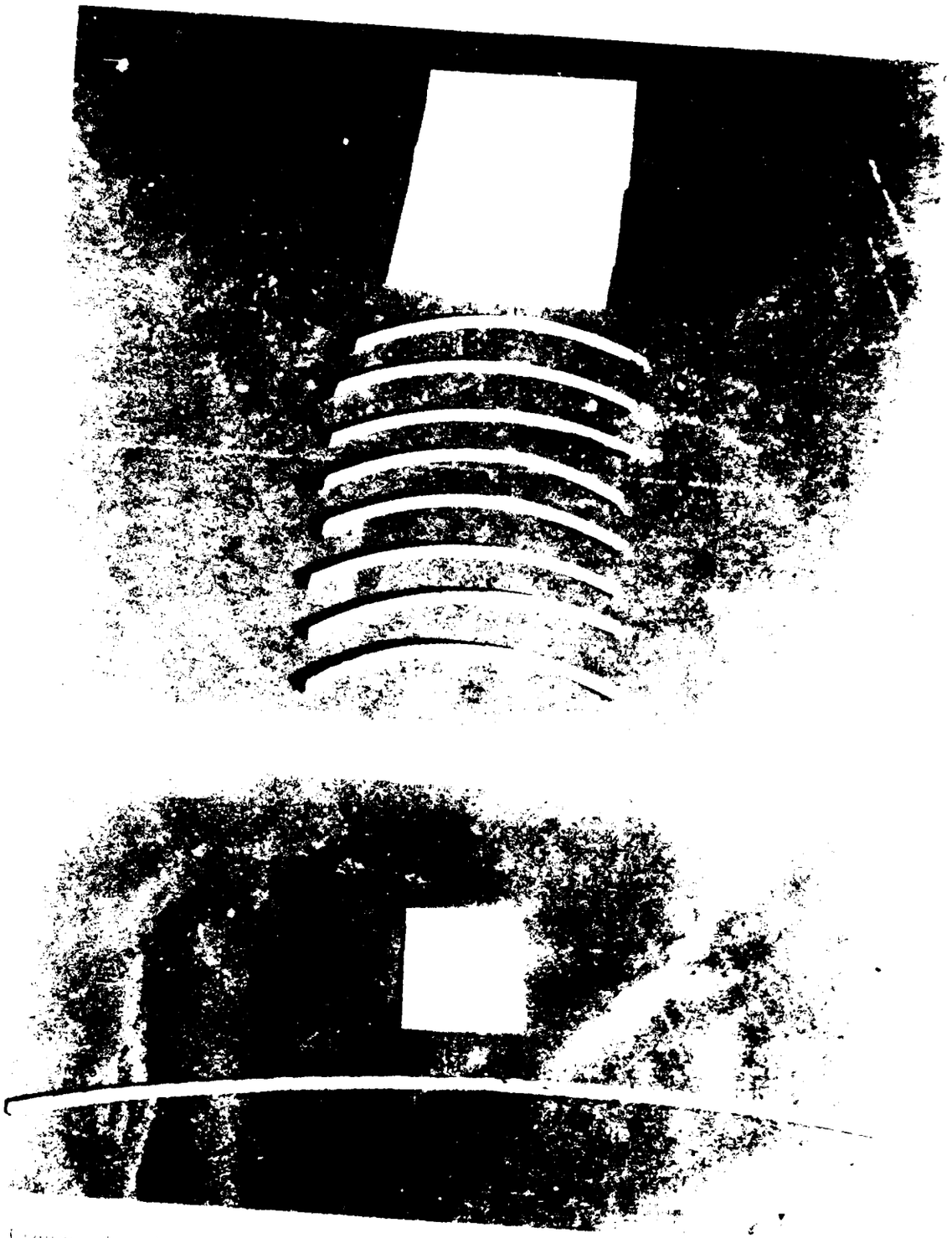


Figure 26. Vitronic 33 strand and Vitronic 32 spiral wrap from piling specimens.

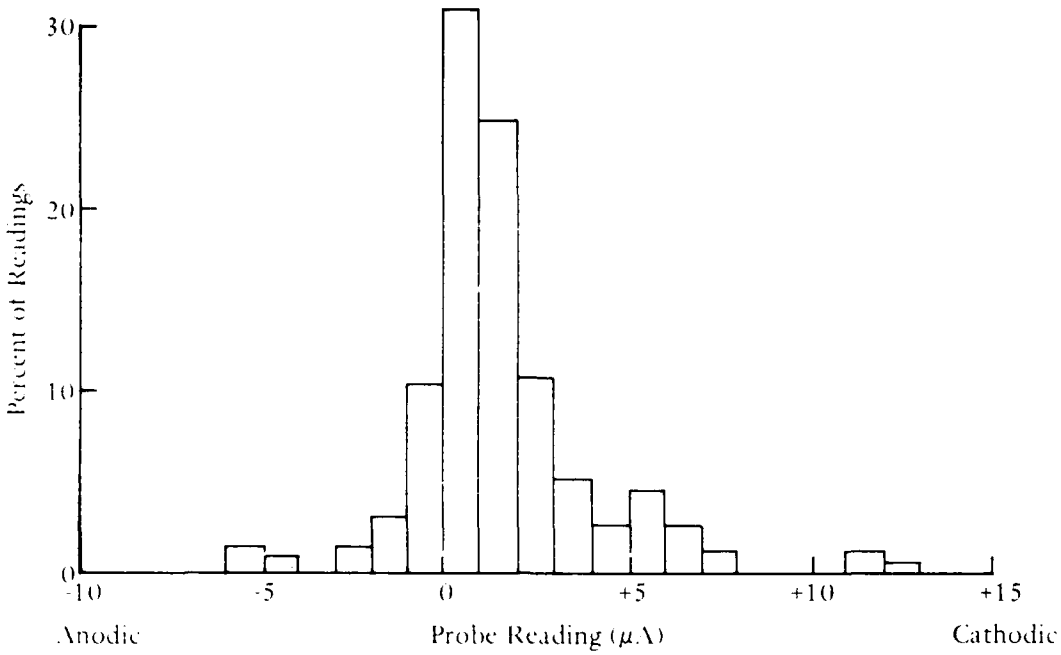


Figure 30. Frequency of readings versus values - carbon steel.

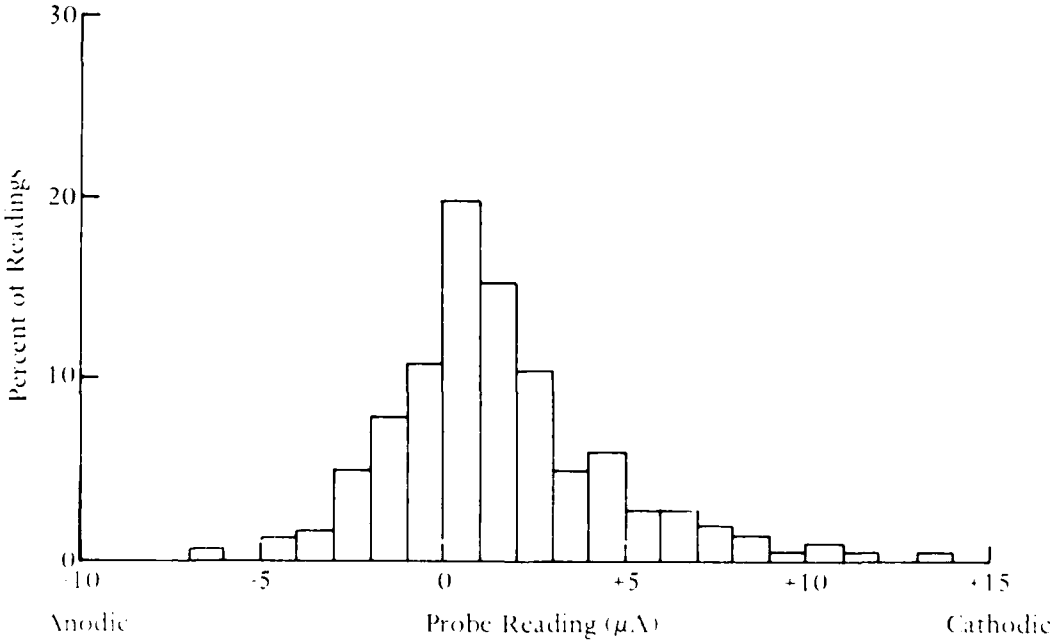


Figure 31. Frequency of readings versus values - Nitronic 33.

NITRONIC PILE

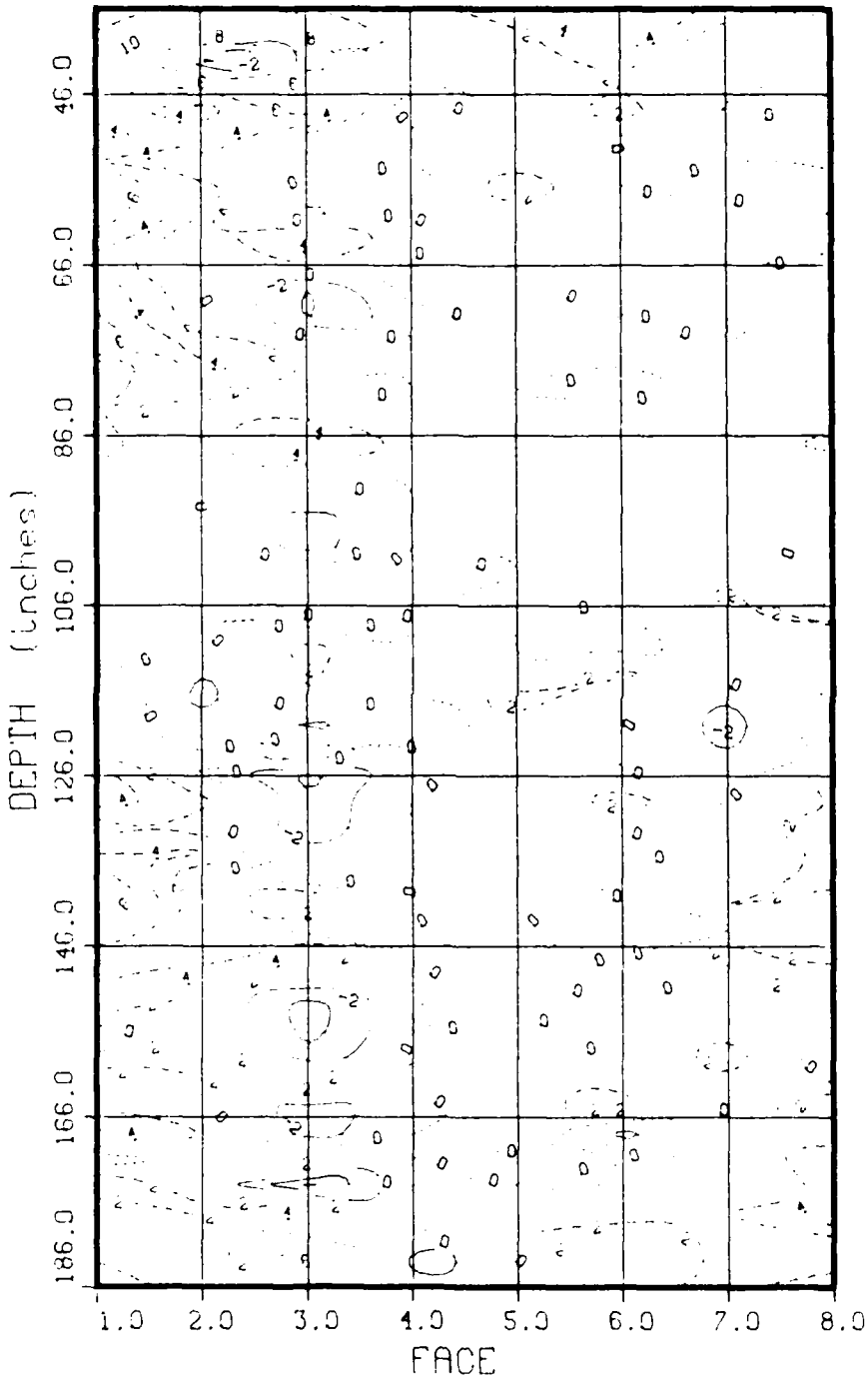


Figure 32. Current profile map - Nitronic 33 piling.

Figure 33. Carbon steel tie wire in Nitronic 33 stainless steel prestressed piling section.

Appendix A

ASSESSMENT OF IMPACT OF CORROSION ON STRUCTURAL INTEGRITY

26 November 1985

MEMORANDUM

FROM: L51/WARREN

TO: L52/JENKINS

VIA: L51
L52
L50

SUBJ: Structural analysis of deperming pier [illegible]

REF: (a) Final 35% Submittal Engineering Calculations [illegible] No2474-84-C-4194 by ABAM Consulting Engineers

(b) Final 35% Submittal Engineering Drawings [illegible] No2474-84-C-4194 by ABAM Consulting Engineers

1. This memorandum is to formalize our conversation of 11 and 26 November on the subject requested analysis.

2. The structural analysis was conducted on the deck panels subjected to critical crane loading. The objective was to determine the structural response to the loss of individual prestressing strands and reinforcing bars by corrosion. Critical loading occurs as the 20 kip wheel loads of the 30 ton portable crane are positioned near midspan of the deck (between pile bents). A review of Reference (a) showed that the pier deck was the weakest link in the structure which included the curb beam, pile caps and the piles.

3. The most sensitive mechanism in the deck panels was flexure. Critical loading will cause the prestress strands to fail at panel midspan prior to reinforcement yielding at the support (pile caps) or before any distress occurs due to shear or reactions. Critical crane loading will produce a panel maximum midspan moment of 140 ft-kips in addition to the dead load moment of the structure; moment of 115 ft-kips. Using load factors of 1.4 for dead load and 1.7 for live load, then the maximum design ultimate moment at panel midspan is 400 ft-kips.

4. A graph of the midspan flexural capacity versus loss of pre-tress strand for each deck panel is attached. The development length of the 1/2-inch diameter strand is 20 inches, so the graph reflects the ultimate capacity of the deck panel strands are sequentially corroded through at discrete points within 20 inches of midspan. The ultimate moment capacity is [illegible] ft-kips which is well above the required design strength of 400 ft-kips. Even with the loss of one strand, the capacity is still

[illegible] exist the ultimate design moment and there would [illegible] a noticeable deflection increase. After the loss [illegible] randomly placed), the panel capacity approaches the [illegible] at 255 ft kips (without load factors applied). [illegible] occurred there would be a noticeable increase [illegible] the 50 ton crane rolled over the deck.

[illegible] I will retain the calculations on file if you need them for [illegible] I shall also continue to review and checking [illegible] and the, although I doubt I will find anything to [illegible] estimates of the structural response. If you need [illegible] please contact me at ext 4765.

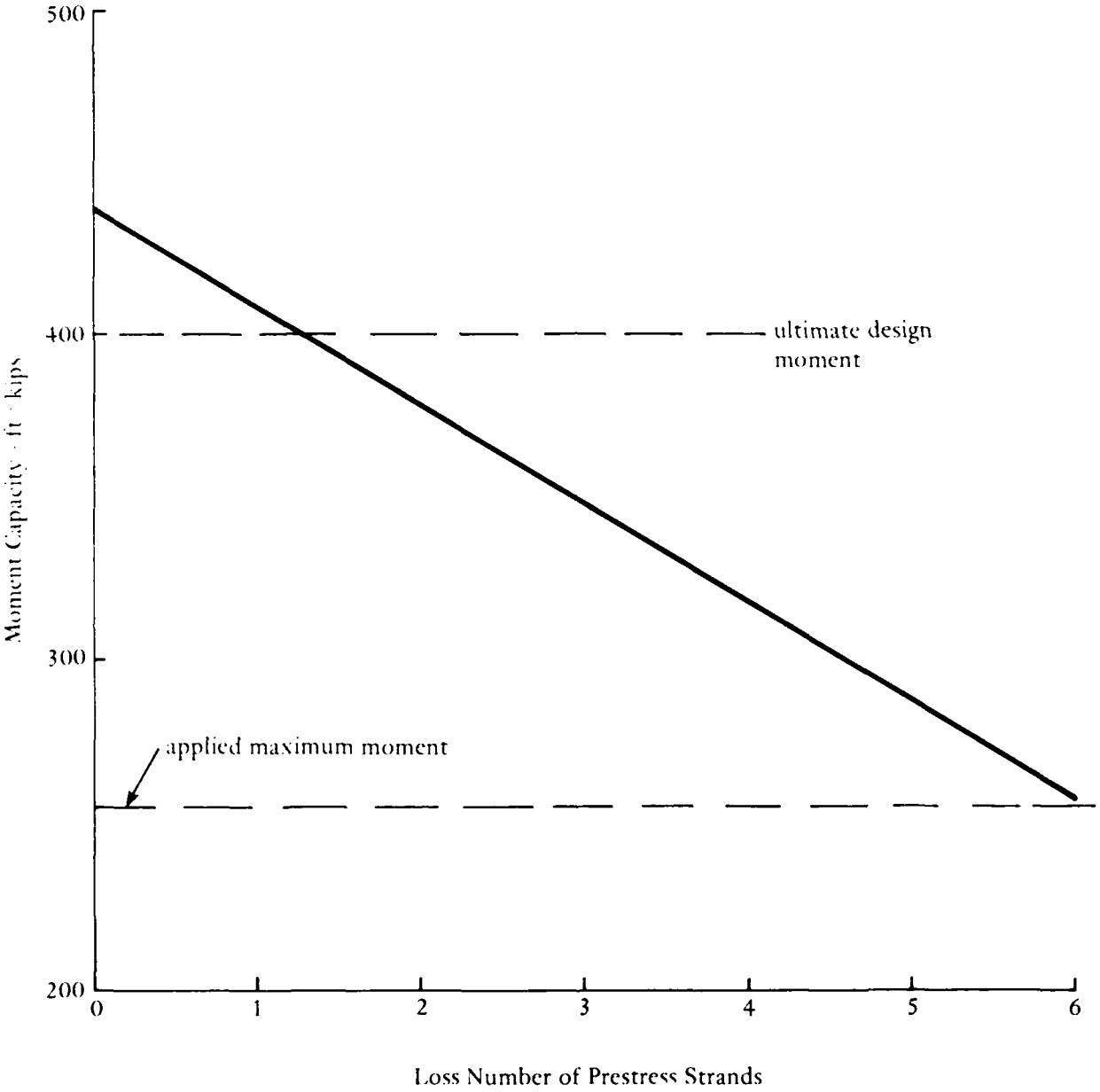


Figure A-1. Effect of prestressing strand corrosion damage on midspan flexural capacity of pier deck.

Appendix B

ASSESSMENT OF INDUCED ELECTRIC CURRENTS

L72/JLB/at
5095201
26 Nov 85

MEMORANDUM

From: L72/Brooks
To: L51/Jenkins
Via: L72
L70

Subj: CORROSION CURRENTS ASSOCIATED WITH NAVY DEPERMING PIERS

Ref: (a) L51 memo of 7 Oct 85 requesting assistance

1. As requested by reference (a), the 35% design reports of the Deperming Pier for San Diego have been reviewed. Preliminary analysis shows that the X-loops of the structure can induce currents of up to one ampere in the pier structure when the separation between loops is 10 ft. All other configurations are not expected to present a problem including the Z-loop. If currents of up to one ampere present a corrosion problem, then the following steps are recommended:

(a) Choose a configuration where the pier structure is outside the X-loops.

(b) Coat the rebar steel with a non-conducting epoxy prior to imbedding in the concrete.

(c) Do not allow the rebar steel to protrude out the bottom of the concrete piling.

(d) Do not connect the rebar steel of the piling with the rebar of the pier top structure.

JAMES L. BROOKS

Copy to:
L72/Miller

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