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LABORATORY TESTING AND MONITORING OF STRAY CURRENT CORROSION OF PRESTRESSED CONCRETE IN SEA WATER

by

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Abstract

Stray current corrosion of prestressed concrete beams was investigated in the laboratory by exposing 40 specimens 6.4 x 6.4 x 122 cm, prestressed by a central high strength steel wire to 1.86×10^9 N/m^2, in sea water. The steel wire was made anodic to a copper cathode, with steel current densities maintained at fixed values between 27 and 915 mA/m^2 (2.5 and 85 mA/ft^2).

Monitoring was done by measuring steel potential relative to a silver-silver chloride reference electrode with current on, weekly, and with current off, bi-weekly. Beams were examined visually biweekly; presence of rust spots and longitudinal cracks were noted, and lengths of cracks were measured, for exposures which ranged between 8 and 83 weeks. After exposure, the prestressing wire was tensioned to failure.

Reductions in breaking strength of 70% were observed in 25 weeks exposure at 915 mA/m^2 (85 mA/ft^2), with lesser reductions in strength for shorter exposures and lower current densities.

Ampere-hours did not correlate satisfactorily with the reduction in breaking strength of the wire. Potentials measured with current on or off indicated

(Cornet; R/E-12)

that corrosion was occurring, but gave no quantitative indication of the reduction in breaking strength. Resistance measurements of the electrochemical circuit did not relate to the extent of corrosion damage. Time to change in potential of the prestressing steel did correlate with time for initiation of steel corrosion. Existence and length of longitudinal cracks in the concrete beam did not correlate quantitatively with the reduction in breaking strength of the prestressing steel.

After the tension test, beams were notched lengthwise with a saw and opened. The prestressing wire was then examined to determine the distribution and extent of corrosion. Quantitative estimates of the corroded length were made. Qualitatively, where there was considerable localized corrosion attack, there was great reduction in breaking strength for a given number of ampere hours exposure. Where the corrosion attack was well distributed, an equal number of ampere hours gave less reduction in fracture strength.

Stray electrical currents can cause serious deterioration in the strength of prestressed concrete structures, as measured by testing to destruction. However, none of the methods of monitoring used in this investigation can predict the extent of the damage quantitatively.

Key Words

Laboratory Testing, Monitoring,Stray Current Corrosion, Prestressed Concrete in Sea Water.

Introduction

Steel under tension in concrete in sea water is susceptible to corrosion by stray anodic electric currents.

The passivity of steel in an alkaline environment is well known. Concrete provides such an environment for embedded steel. Breakdown of passivity can occur due to a lowering of the pH under the action of stray electrical current(1) in sea water.

Steel starts to corrode when the pH is less than 11.5 with oxygen and water present(2).

The critical chloride concentration for steel to start to corrode depends on various factors. As low as 700 ppm of chloride in concrete(3) in the presence of oxygen can start corrosion. In the absence of oxygen, the threshold chloride content is about four times higher at a potential of about -0.4 to -0.5 volt relative to a saturated calomel electrode(4). This would suggest that the specification of the pH and the chloride concentration to corrosion should be supplemented by the specification of the steel potential as a relation may exist among the three quantities involved. The critical level of chloride was also found to be a function of the cement factor and the water/cement ratio (W/C)(5).

The presence of chloride itself does not affect markedly the pH of the concrete(6).

The mechanism of steel corrosion in concrete is reasonably well understood. Oxygen is needed at the cathodic area for the reaction $2H_2O + O_2 + 4e^- \rightarrow 4\ OH^-$ to go, and a minimum content of the aggressive ions, i.e., chloride ions, is required to break down the passive film with the resulting dissolution of iron $Fe \rightarrow Fe^{++} + 2e^-$, at the anode.

Diffusivities of dissolved oxygen through concrete pores have been measured(7) but these values will be affected by the degree of oxygen saturation of concrete.

Chloride ions will move into concrete by two transport mechanisms, diffusion and convection or moisture motion. The reaction between chloride ion and tetracalcium aluminate in concrete(8) renders the analysis of chloride diffusion more complicated.

The above corrosion process is no longer valid for steel in concrete immersed in sea water and subjected to an external DC current source. In the early stage where sea water has not penetrated into the concrete, the free calcium hydroxide in solution in the free moisture of concrete will provide most of the elements for the reactions at the anode and cathode:

$$O_2 + 2H_2O + 4e^- \underset{\text{anode}}{\overset{\text{cathode}}{\rightleftharpoons}} 4OH^-$$

Hydrogen evolution occurs at the cathode only at a potential less than -1.1 volt Ag/AgCℓ. At the same time, anions, mostly $C\ell^-$, and cations Na^+ and Ca^{++} in concrete are attracted toward the anode and cathode, respectively. In an electrolysis test(9) of concrete in sodium chloride solution, traces of calcium ion were found in the solution.

In an absence of corrosive environments, the anode steel corrodes when the hydroxyl ions are sufficiently depleted at the steel concrete interface. There exists then an induction time. Chloride ion will shorten the induction time. It was found that 300 ppm of chloride(10) is sufficient to promote corrosion. When concrete is 100% saturated with sea water, the mechanism of ion motion is more complex and needs further study.

Once corrosion starts, the dissolution of iron does not take place all along and around the steel surface and may not be the only reaction at the anode. In part this is a function of anode efficiency, as well as localized corrosion of the steel. The distribution of the corrosion will have a crucial importance in determining the strength left in the steel.

Methods of monitoring corrosion of steel in prestressed concrete are visual inspection, resistance and potential measurement. The present laboratory work was undertaken for assessing the method of monitoring and testing of stray current corrosion of prestressed concrete in sea water, seeing how well it could detect the corrosion in its different stages, and evaluating the corrosion damage to the embedded steel.

Test Specimens

Beams 2.5 x 2.5 x 48" (63.5 x 63.5 x 1219 mm) with a single prestressing wire centered within a square cross section were used. The prestressing wire was the center wire of an uncoated seven wire stress-relieved strand for prestressed concrete conforming to ASTM 416-68 grade 270 specification. The average strength was 270 ksi (1.86 x 10^9 N/m^2) and the average diameter 0.172" (4 mm).

Two wires were prestressed to 175,000 ± 5000 psi (1.2 x 10^9 N/m^2) between two reinforcing steel floor anchors prior to the day of casting. The load was applied with a hydraulic jack at one end and monitored at the other end by a transducer load cell connected to a strain gauge indicator. Six beams were made at a time in three wooden forms. After casting, they were cured with moist burlap for seven days. Then the prestress force was transferred to the concrete. Beams were cured seven more days in a fog room and fourteen additional days in dry air. During the last week of air curing, 9 inches of the beam ends were coated twice with epoxy resin "Concrete Concresive 1170" to suppress end effects. This epoxy resin was also applied to the protruding ends of wire which were further protected by encasing in vinyl tubing and sealing with a marine-type silicone sealant. Copper wire of .125" (3 mm) diameter served as a cathode installed in either diffuse (Z wrapped) or concentrated (single loop) configuration. The two geometries for the cathode were for simulating the effect of the urrent distribution (Figure 1). Concrete mix proportions and compressive strength are shown in Table 1.

Monitoring and Testing

Each beam was put into an individual tank of 6" (152 mm) ID and 60" (1524 mm) height filled with synthetic sea water of composition shown in Table 2, in a room kept at 60 ± 2 F (15.6 C). The prestressing steel was connected to the anode and the copper wire to the cathode. The maximum potential used was 3 volt. The rectified current was maintained at its set value daily during weekdays by means of resistor in series with the beam. A schematic of the electric circuit is shown in Figure 2. Potential measurements with current on were performed every week with the steel anode connected to the + of a millivoltmeter and the silver/silver chloride reference electrode (Ag/AgCl) to the - , resistance and potential measurements were made with current off, biweekly. The measured potential obtained in this way corresponds to the reduction potential in the thermodynamic sign convention. For the resistance measurement, an AC meter (Vibroground Model 293, two points method) was used. In the early part of the experiment, the resistance was taken between the copper cathode and the embedded steel. Due to the coating depositing on the cathode, a foot of steel wire similar to the anode replaces the copper cathode in later measurements. For some beams, the obtained values were compared to the one from a regular ohmeter. Results are based on the AC meter measurement.

After a specified time of exposure, beams that had shown visible signs of corrosion were subjected to testing in tension to failure. The test required almost the same equipment as for prestressing wire. A transducer load cell was connected to the X axis of an Esterline Angus XY plotter and a time scale generator to the Y axis. Data were obtained when the beam cracked transversely and when the wire broke. After the test, the beams were sectioned longitudinally, and the wire examined.

Results

Visual inspection has been widely used for detecting steel corrosion in concrete. It is not too practical for entirely submerged structures. Corrosion products larger in volume than the volume of the steel replaced cause cracks which may precede or follow rust staining. If the buildup of internal pressure exceeds the breaking strength before rust reaches the concrete surface, cracks precede rust stains. Sometimes rust stains appeared before cracks; sometimes cracks and rust could be seen at the same time. An example of the crack and rust propagation is shown in Figure 3. The presence of a crack or rust spot indicates that steel has been corroding, but will not indicate for how long steel has been corroding and the extent of corrosion damage. A small rust spot or crack may be associated with an early stage of corrosion, but a small crack with many ampere hours will lead to a localized attack and a great reduction in breaking strength. When the steel is removed from the concrete, in the early stage of corrosion, only a sector of the steel surface varying from 1/4 to 1/2 on the circumference is corroded. As the ampere hours increase, the rusted sector covers more and more surface and finally encircles the whole circumference. The same tendency is true for the corroded length, short for small ampere hours and more distributed for large ampere hours. Due to the wide variation in size and depth of pits, no quantitative criterion has been established. The steel under the portion of the insulated concrete remained bright. This suggests covering the concrete structure by coatings, but this may not be too practical, and any defects in the cover may shorten the life of the structure prematurely due to a localized attack.

Table 3 and Figure 4 give an example of the variation of the resistance values with exposure time. The decrease of resistance in the early minutes of exposure is associated with the larger surface area of the concrete in contact with sea water and lasts from one to two weeks for beams with applied current.

For beams without applied current, the decrease in resistance persists up to four weeks before a rise in resistance is noted. After the first or second week's drop in resistance, the electrified beams showed a steady increase in resistance until the time to first sign of corrosion, followed by a slow decrease afterwards. It is appropriate at this stage to look at the various factors affecting resistance in a porous media. Experiments(11) have shown that a homogeneous mixture of conductive solid and electrolyte can be treated as a mixture of two electrolytes with their resistivities weighted respectively with their volume fractions.

For a more complete analysis, one has to include the ionic conduction through the saturating bulk fluid, and through the surface or electrical double layer(12). It can be readily seen that the assumption of the current conduction by parallel paths through the conducting solid and the interstitial electrolyte is not at all adequate. The conducting media are not everywhere continuous and at many places interconnected. The resistivity of porous rock is then only a fraction of the resistivity of the mixture. From a purely empirical point of view, the resistivity of porous media may be expressed as(13):

$$r_{por} = \left(\frac{1}{S_w}\right)^2 r_o P^{-m}$$

where S_w is the water saturation, r_o the resistivity of the rock 100%

saturated with an electrolyte, P the porosity of the rock, m a constant depending on the rock.

A similar relation may hold for concrete. If the measurement is taken between two electrodes with the concrete immersed in a neutral electrolyte of low resistivity, $R_{concrete} = (\frac{1}{S_w})^2 \, r_o \, P^{-m} \frac{\ell}{A}$, ℓ the actual length and A the actual cross section area of the current path. With other variables constant, $R_{concrete}$ decreases as the water saturation increases. When concrete is cast against one of the electrodes, the resistance measurement will include the effect of the oxidation or reduction of ions at the steel concrete interface(14). Below a critical voltage, the resistance appears to be high and varies with the applied voltage. Above it, the ratio voltage/current is essentially constant. The increase of the concrete resistance with exposure time has been explained as a result of the formation of film due to the passage of current at the interface steel/concrete(9) or as a result of the hydration process which reduces the pore systems in the concrete, pore systems which may give room for the transport of ions(15). From the above relation it is seen that the $R_{concrete}$ is a function of S_w , P , m , ℓ , A . The degree of saturation S_w is a factor which may have a large influence in the early stage of exposure. With longer time exposure, the reduction in the pore system will have a stronger effect, assuming that m , ℓ , A do not vary markedly. The concrete resistance then increases. The decrease in resistance after beams have reached the time to visible sign of corrosion is associated with a shorter path of the electric current through the sea water electrolyte to the steel surface.

Unless the resistance of the immersed concrete structure is taken periodically from the first day of immersion, the chance of detecting the corrosion activity of steel in concrete is low, and even with a continuous monitoring, the method may not be reliable. Potential measurements are a lot safer. Several investigators (3, 6, 16, 17) had shown that the half cell potential of steel with respect to a reference electrode is a good indication of the corrosion activity of steel in concrete. Measurement of half cell potential (16) has identified steel as non-corroding when a measured value is more positive than -.23 volt (Ag/AgCℓ in sea water) measured with current off.

The steel potential with current on in this experiment is at first positive to the Ag/AgCℓ in sea water (Figure 5). Comparison with potential off and visual inspection shows that a continuous decrease in value of the potential with current on, from positive to negative value, is an indication that steel is corroding, and the time of the depassivation of the steel is picked at the first week of the drop in value of the potential on and called the time to corrosion. With a few beams, especially those at high current density, this time coincides with the time to visible corrosion (crack and/or rust spot) (Figure 6). Some beams show a sharp drop of the potential with current on, while for others, the decrease in potential follows a smoother path. One of the explanations of the significant drop in potential with current on is that probably oxidation of hydroxyl ions and iron dissolution occur simultaneously for some time before the latter predominates.

The potential off at the time to corrosion varies from beam to beam, with current density, but drops to a value less than - 0.3 volt vs. Ag/AgCℓ in sea water about a week after the time to corrosion. There exists a large variation of the levelling off value of the potential on. The levelling of the potential with current off is around -0.5 volt vs. Ag/AgCℓ in sea water. The maximum reported value of half cell potential off is -0.6 volt. The highest value obtained in this experiment is -0.54 volt. When steel in concrete is first submerged in sea water the steel potential is around -0.1 volt, the potential of a bare steel in sea water is -0.43 volt vs. Ag/AgCℓ.

Beams that have passed the time to corrosion will show visible signs of corrosion a few weeks later; the lower the current, the longer the time between the change in potential on and the appearance of a crack and/or rust spot (Fig. 7). For both Figs. 6 and 7, a straight line fit is drawn between the current densities 85 and 2.5 mA/ft^2. Beyond these two limits, a straight line fit may not be correct. The latest data for two beams without impressed current show that a change in steel potential has occurred after 53 weeks of exposure in sea water.

As the potential measurement does not indicate the extent of corrosion damage, beams with visible signs of corrosion were subjected to tension testing to failure after a specified time of exposure. The reduction in breaking strength is shown against the ampere hours of corrosion in Figure 8. Each point corresponds to a theoretical corroded length, assuming that corrosion is limited to only a portion of the wire and that the only reaction which has taken place is the iron dissolution. An attempt to compare calculated and real corroded length has been made. The real corroded length is obtained from visual evaluation by estimating the length of pits and the general attack portion. Quantitative conclusions cannot be drawn due to the uneven distribution of the corrosion along the wire. Two lines are shown on Fig. 8, the upper one representing the situation in which corrosion is distributed over 30" of the wire (total length of the test section), the lower one the reduction in breaking strength with only 1" of the wire corroded.

Figure 8 may be replotted as fraction of the original breaking strength versus time of corrosion divided by total time. This plot is suggested by the fact that the longer the time of exposure, the longer the corroded length, the less is the reduction in breaking strength for the same ampere hours of corrosion (Fig. 9). Two curves are drawn for cases where beams are subjected to a current density of 5 mA/ft^2 with a corroded length of one inch and thirty inches.

Conclusions

- Stray electric current can cause serious deterioration of the strength of prestressed concrete structures.

- Reduction in breaking strength of 70% were observed in 25 weeks of exposure at 85 mA/ft^2.

- Potential measurement with current on can be used to detect the time to corrosion.

- When the potential with current off is less than -0.3 volt Ag/AgCℓ in sea water, steel is corroding.

- Circuit resistance measurements are not suitable indicators of corrosion in the steel reinforcement.

- None of the monitoring methods used in this laboratory investigation tell the extent of corrosion damage. Only tension testing to failure measured the damage quantitatively.

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Figures

Tables

Table 1 - Concrete Data

Component	lbs/cu yd	Kg/cu m
Cement SANTA CRUZ Type II	658	390.37
Water	295	175.01
Coarse aggregate Fair Oaks, 1/4 - 1/2"	1494	886.35
Fine aggregate	1612	956.36

Compressive Strength	psi	N/sq m
7 days	3850	2.654×10^7
9 days	4250	2.930×10^7
28 days	5100 - 6000	$3.516 - 4.137 \times 10^7$

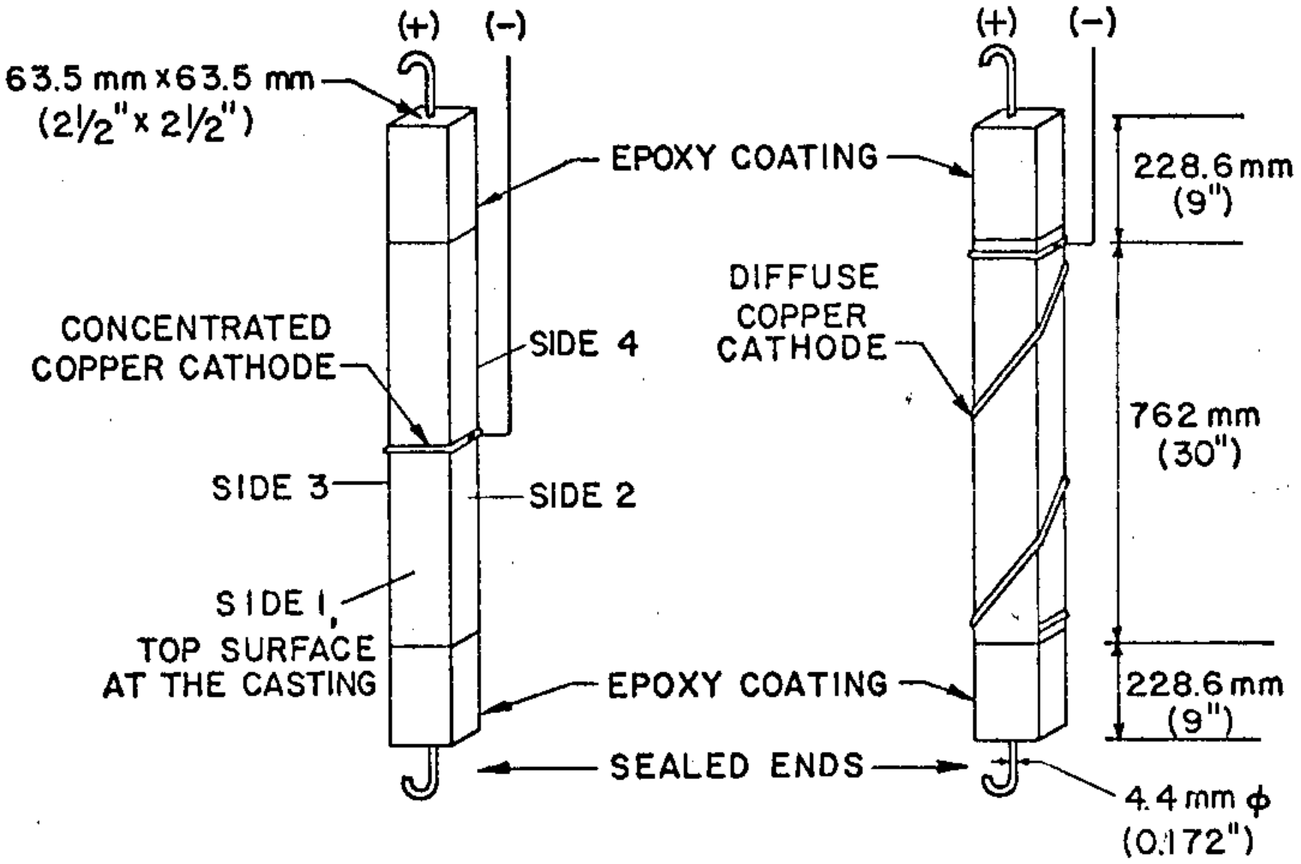
Table 2 - Composition of Synthetic Sea Water

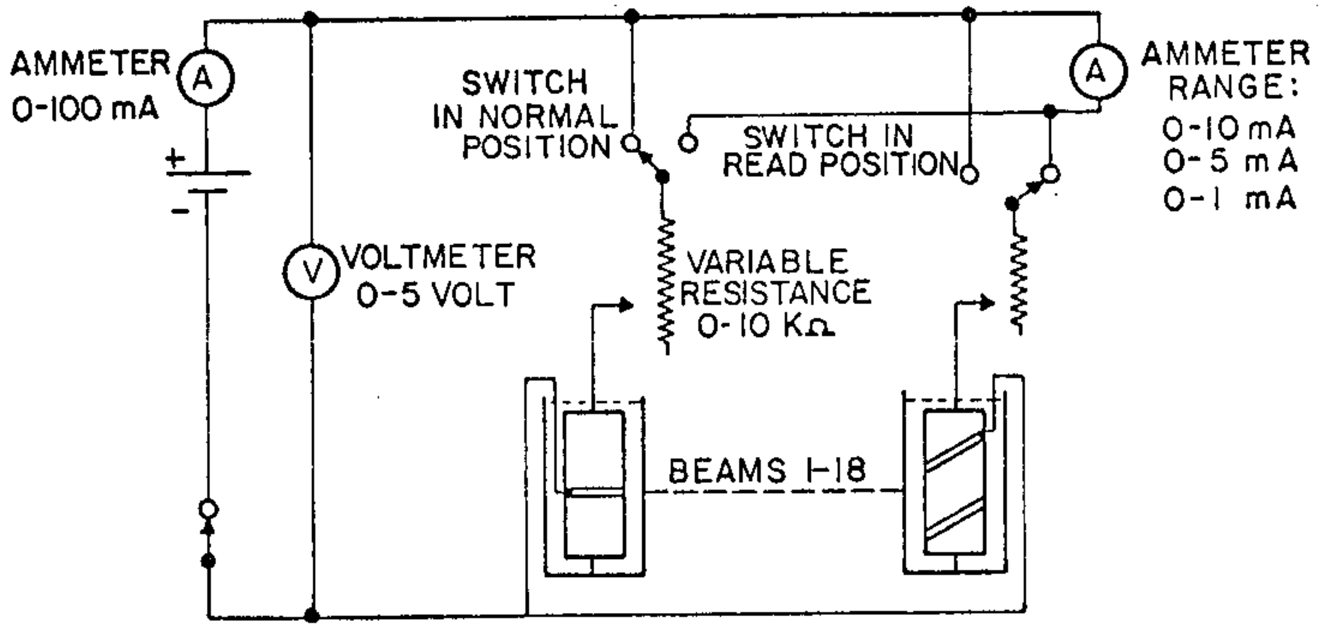
Component	grams/100 liters of solution
Calcium Chloride	220
Magnesium Chloride	1100
Potassium Bromide	90
Potassium Chloride	20
Sodium Chloride	2300
Sodium Sulfate	353

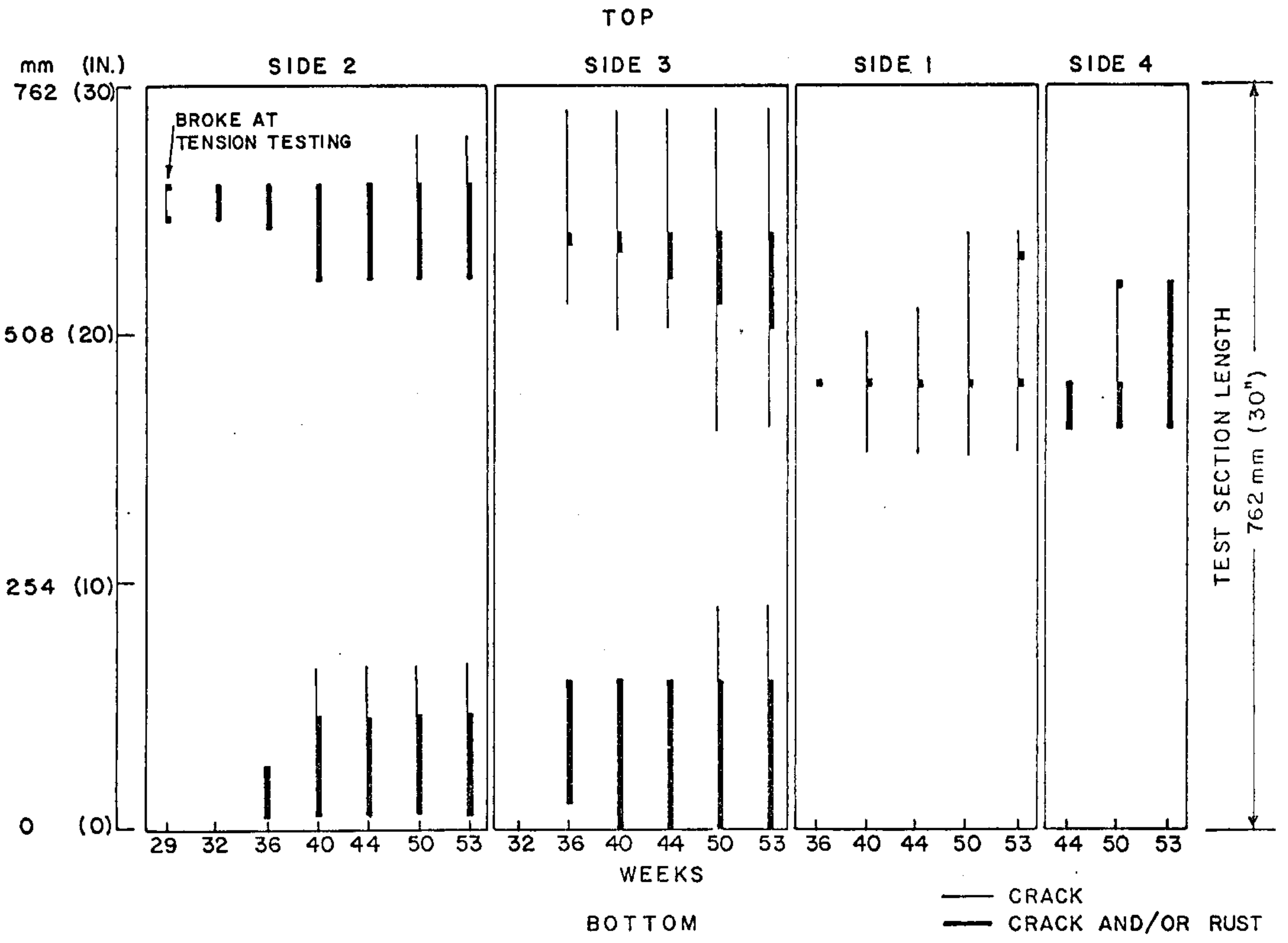
Table 3 - Resistance Change After Exposure to Sea Water

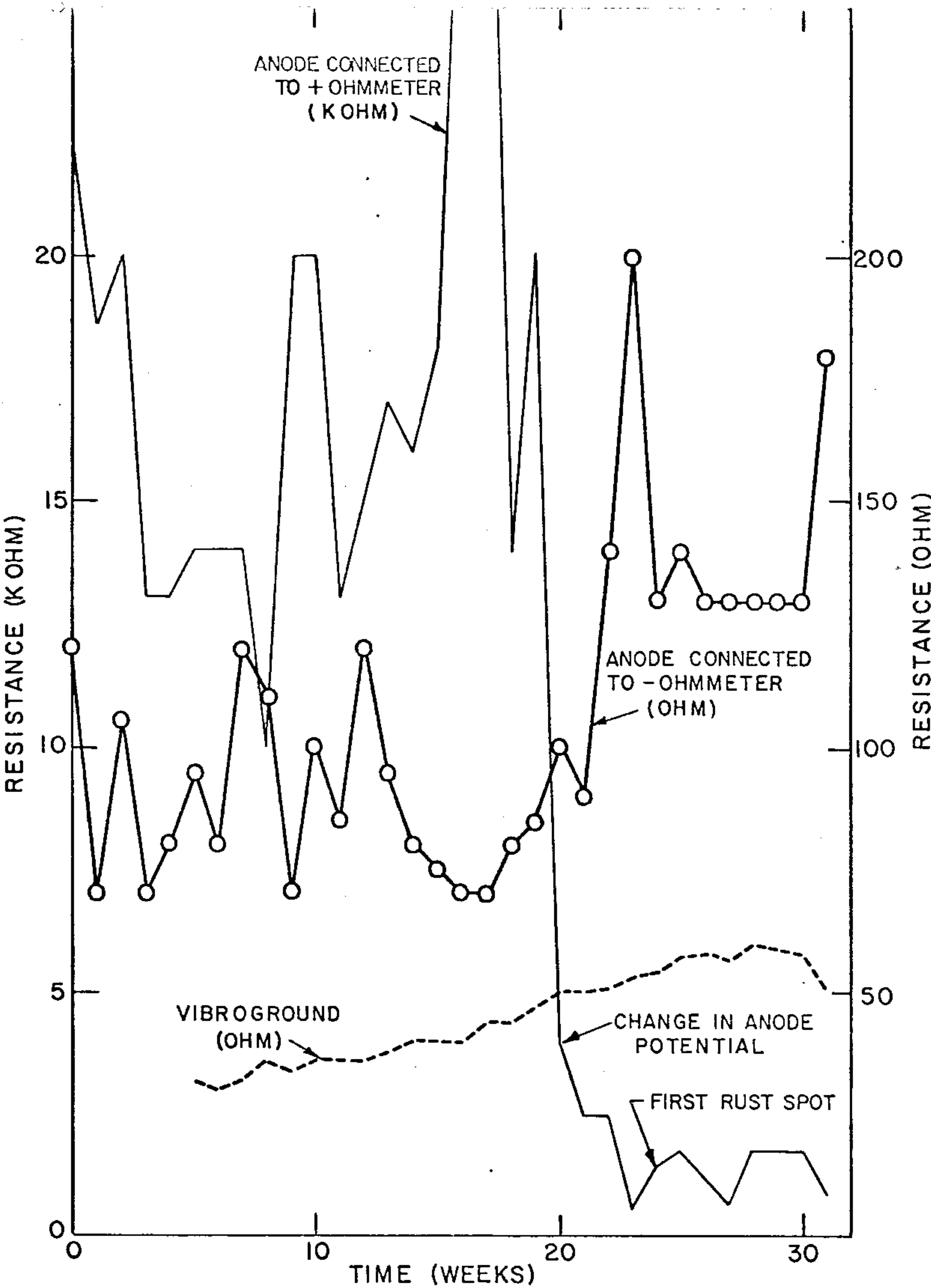
Time of Immersion (min)	1	5	15	270
Resistance (ohm)	76	71	70	62

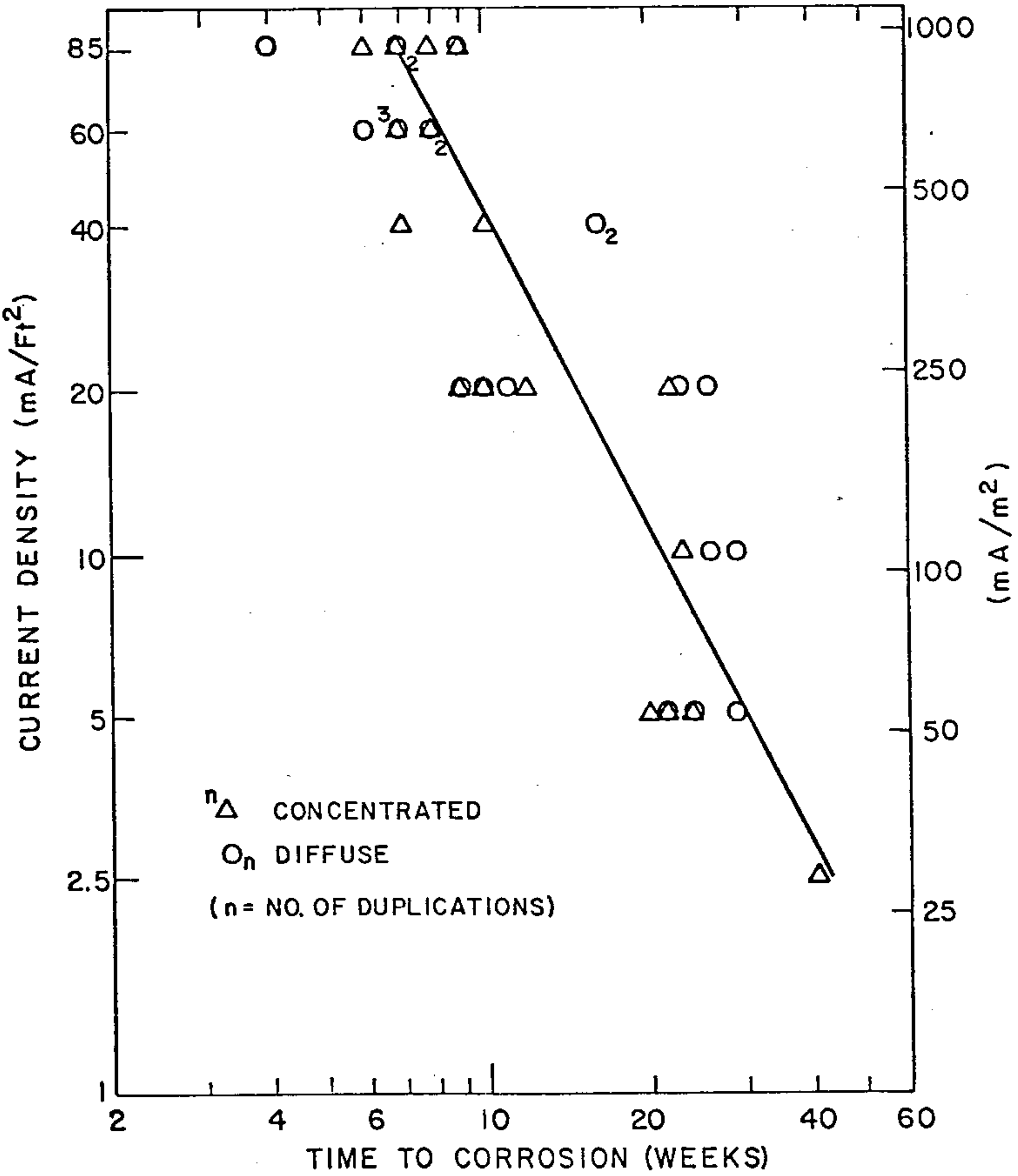
(Beam V 12, aged 52 days)

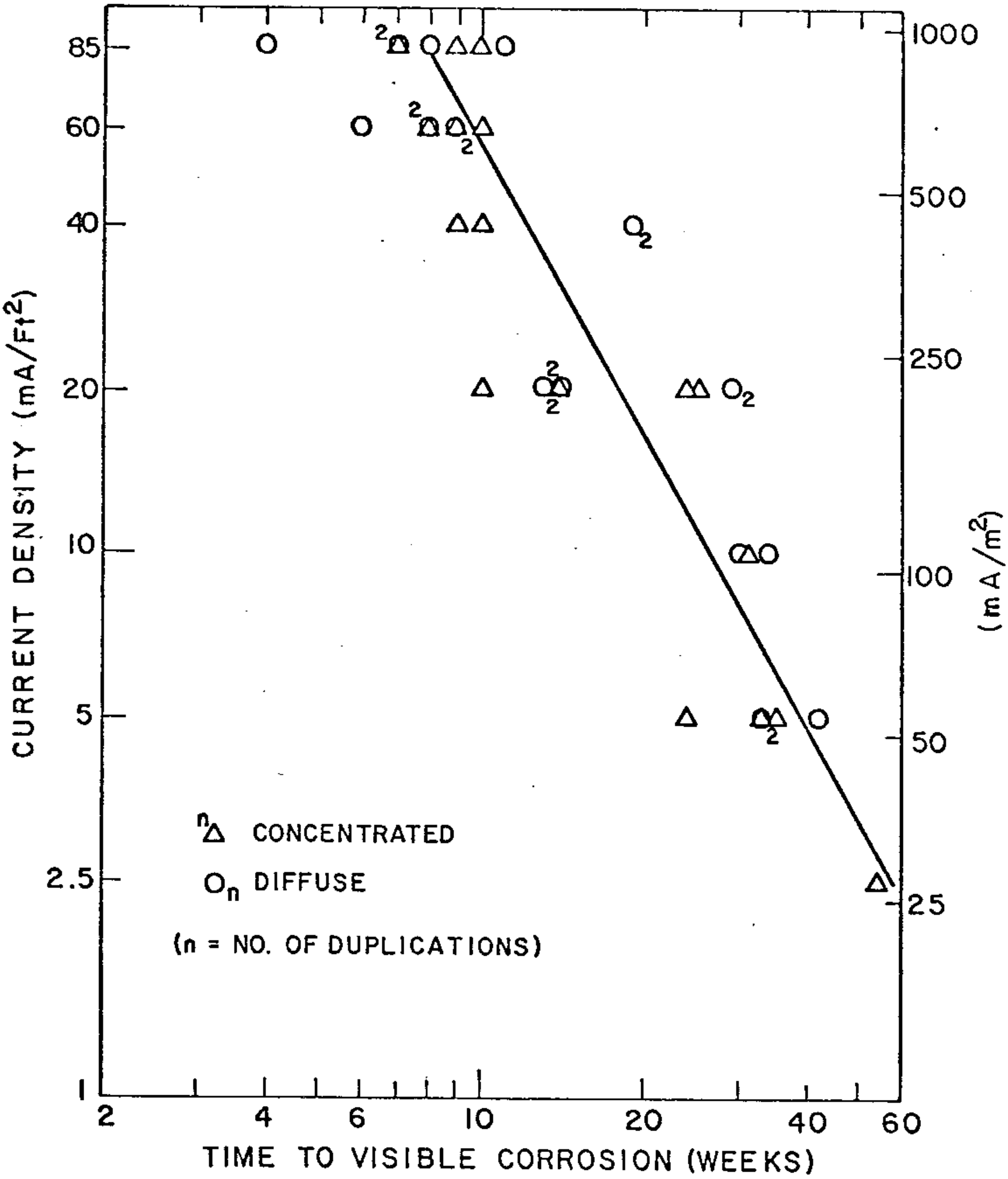
(+)
(–)
63.5 mm x 63.5 mm
(2½" x 2½")
EPOXY COATING
CONCENTRATED
COPPER CATHODE
SIDE 4
SIDE 3
SIDE 2
SIDE 1,
TOP SURFACE
AT THE CASTING
EPOXY COATING
SEALED ENDS
(+)
(–)
DIFFUSE
COPPER
CATHODE
228.6 mm
(9")
762 mm
(30")
228.6 mm
(9")
4.4 mm ϕ
(0.172")

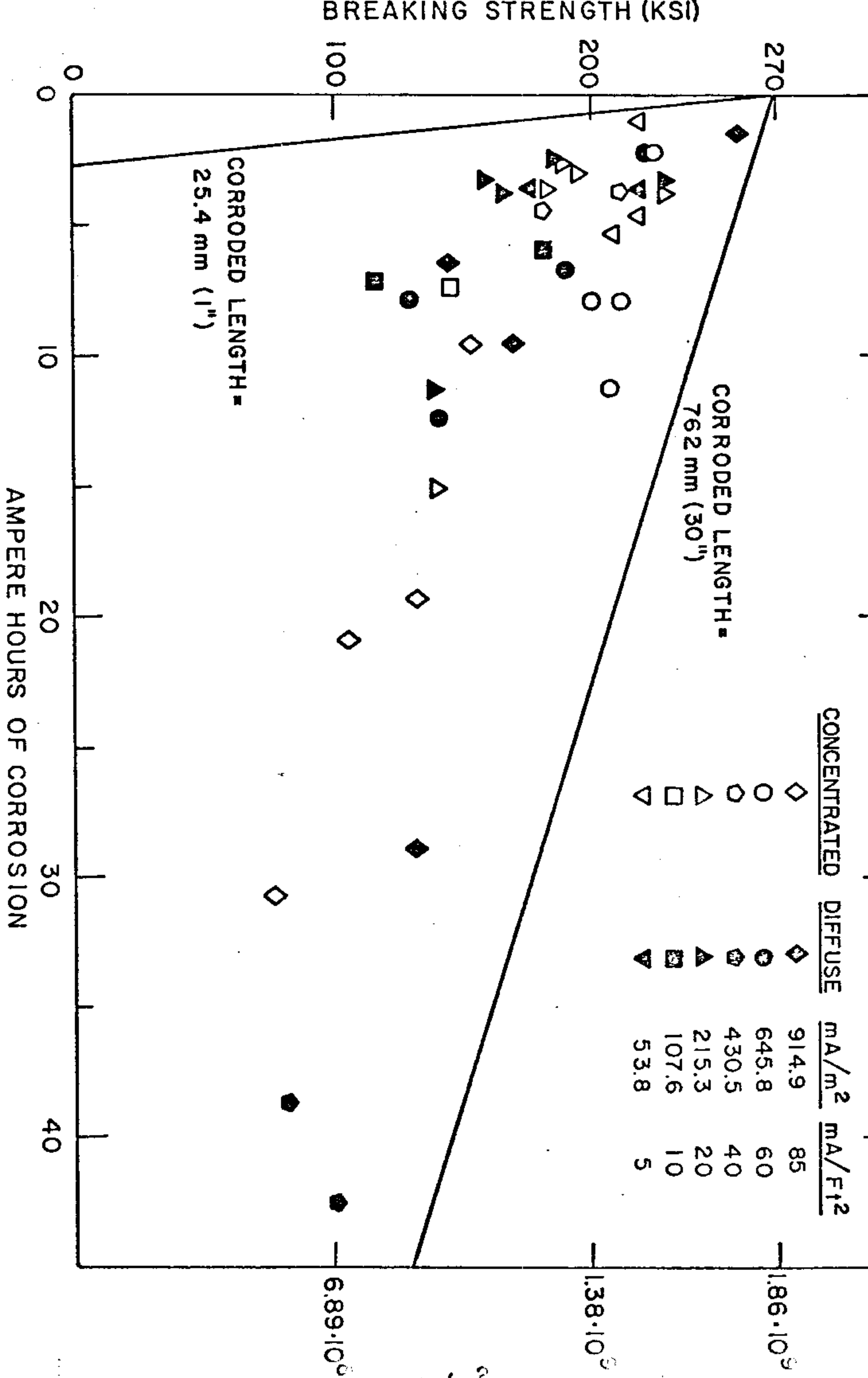

AMMETER
0-100 mA
+
-
VOLTMETER
0-5 VOLT
SWITCH
IN NORMAL
POSITION
SWITCH IN
READ POSITION
VARIABLE
RESISTANCE
0-10 KΩ
BEAMS 1-18
AMMETER
RANGE:
0-10 mA
0-5 mA
0-1 mA

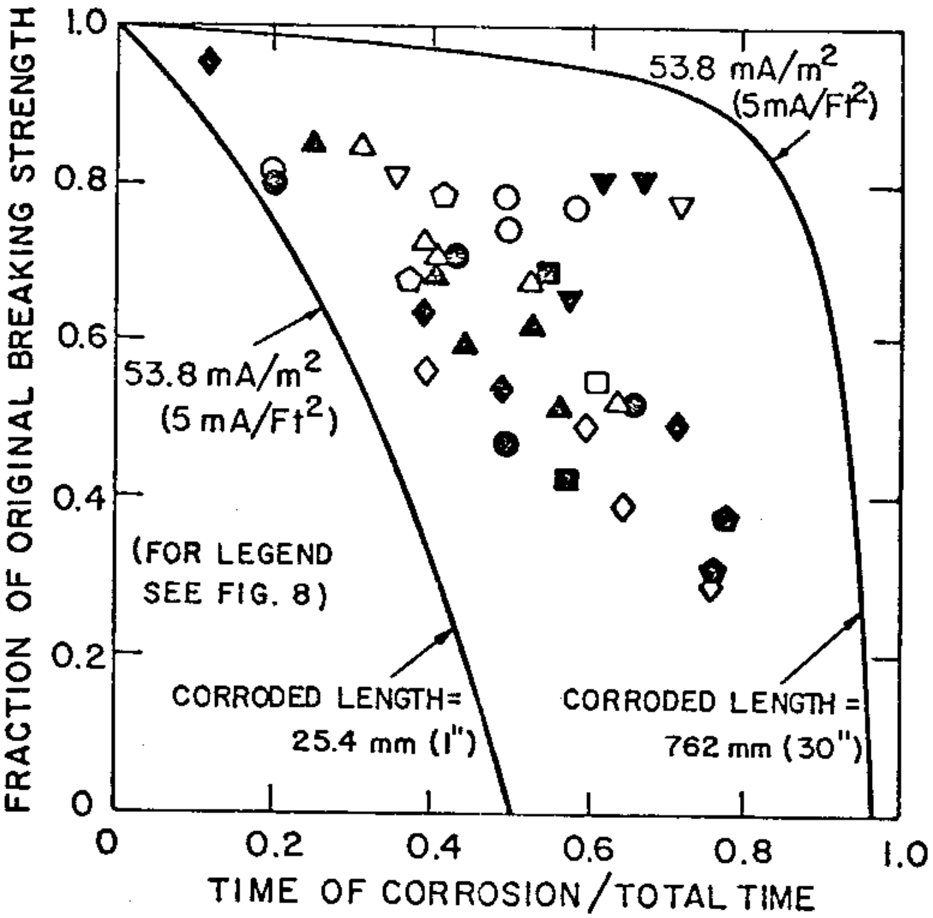

TOP
mm (IN.)
762 (30)
508 (20)
254 (10)
0 (0)
SIDE 2
SIDE 3
SIDE 1
SIDE 4
BROKE AT TENSION TESTING
29 32 36 40 44 50 53
32 36 40 44 50 53
36 40 44 50 53
44 50 53
WEEKS
BOTTOM
TEST SECTION LENGTH
762 mm (30")
CRACK
CRACK AND/OR RUST


ANODE CONNECTED TO + OHMMETER (KOHM)
ANODE CONNECTED TO - OHMMETER (OHM)
VIBROGROUND (OHM)
CHANGE IN ANODE POTENTIAL
FIRST RUST SPOT
RESISTANCE (KOHM)
RESISTANCE (OHM)
TIME (WEEKS)
0
5
10
15
20
50
100
150
200
0
10
20
30


85
60
40
20
10
5
2.5
1
CURRENT DENSITY (mA/Ft²)
1000
500
250
100
50
25
(mA/m²)
2
4
6
10
20
40
60
TIME TO CORROSION (WEEKS)
ⁿΔ CONCENTRATED
Oₙ DIFFUSE
(n = NO. OF DUPLICATIONS)
2
3
2
2


CURRENT DENSITY (mA/Ft²)
(mA/m²)
TIME TO VISIBLE CORROSION (WEEKS)
85
60
40
20
10
5
2.5
1
1000
500
250
100
50
25
2
4
6
10
20
40
60
ⁿΔ CONCENTRATED
Oₙ DIFFUSE
(n = NO. OF DUPLICATIONS)


BREAKING STRENGTH (KSI)
0
100
200
270
0
10
20
30
40
AMPERE HOURS OF CORROSION
6.89·10⁸
1.38·10⁹
1.86·10⁹
CORRODED LENGTH = 25.4 mm (1")
CORRODED LENGTH = 762 mm (30")
CONCENTRATED
DIFFUSE
mA/m²
mA/Ft²
914.9 85
645.8 60
430.5 40
215.3 20
107.6 10
53.8 5


FRACTION OF ORIGINAL BREAKING STRENGTH
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
TIME OF CORROSION/TOTAL TIME
53.8 mA/m²
(5mA/Ft²)
53.8 mA/m²
(5 mA/Ft²)
(FOR LEGEND
SEE FIG. 8)
CORRODED LENGTH=
25.4 mm (1")
CORRODED LENGTH =
762 mm (30")