

NATIONAL BUREAU OF STANDARDS REPORT

10 968

Interim Report No. 4
Screening Tests for Evaluating Materials

NONMETALLIC COATINGS FOR CONCRETE REINFORCING BARS

Sponsored by

Federal Highway Administration
U. S. Department of Transportation
Washington, D. C. 20590



U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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NBS PROJECT

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U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

PHYSICS 350

LECTURE 1

1.1. Introduction

1.2. Kinematics

1.3. Dynamics

1.4. Energy

1.5. Angular momentum

1.6. Summary

ABSTRACT

The possibilities of protecting steel reinforcing bars embedded in concrete from corrosion by using organic barrier-type coatings are being investigated in this project. This corrosion is accelerated by the chloride ions of the most commonly used de-icing materials, calcium chloride, and sodium chloride.

In this report, the methods of selecting and procuring coating materials are described. Screening tests have been developed in order to choose the best coating materials. In these screening tests, the relative chemical and physical durabilities as well as the protective qualities of the coating materials have been determined. Powder epoxy coatings appear to have the best overall properties as potential coatings for steel reinforcing bars embedded in concrete.

Certain commercial materials are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material identified is necessarily the best available for the purpose.

Key Words: Concrete; corrosion; epoxy coatings; organic coatings; polyvinylchloride coatings; steel reinforcing bars

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1. Project Information. Order No. 2-1-0614 Title: Nonmetallic Coatings for Concrete Reinforcing Bars.

Date Project Initiated. 9-17-71

Research Agency. National Bureau of Standards

2. Introduction

2.1 Background. The early deterioration of the concrete of bridge decking, due to the corrosion of steel reinforcing bars, has become a major problem during the past decade. The annual cost of repairing bridge decks damaged in this manner is probably over 70 million dollars.

Normally, reinforcing steel is passive to corrosion when in an environment of the high basicity inherent in portland cement concrete. Chloride ions, however, are able to depassivate steel and thereby promote the active corrosion of steel.

Sodium chloride and calcium chloride are extensively used as de-icing agents on highways and bridges. When dissolved in water, these de-icing agents permeate through concrete decks to the regions where reinforcing bars are located. This leads to the corrosion of steel and subsequent cracking and spalling of the concrete. The amounts of sodium chloride and calcium chloride used as de-icing agents has increased substantially during the past decade.

2.2 Objectives. To investigate the protective qualities of organic coatings, especially epoxy systems, and to select the most promising materials. The selection is to be based upon physiochemical testing with consideration given to economics involved in coating and fabrication

3. Discussion of Activities. The methods of selecting promising coating materials, specimen preparation, and screening tests are discussed in detail, since these portions of the project have been completed.

3.1 Materials

3.1.1 Selection of Potential Coating Materials. The selection of coating materials, to be evaluated as protective coatings on steel reinforcing bars, was done on a generic basis and was essentially restricted to organic formulations. Some of the most important criteria for selection were: inertness to the constituents of portland cement paste and chloride ions; creep characteristics; film integrity and protective qualities; as well as cost considerations.

The coatings selected for evaluation are listed in table 1. Also included are some unsolicited coatings submitted by the respective firms who produce them. The coating materials have been assigned code numbers for laboratory identification purposes. The code number sequence has no significance other than indicating the chronological order in which the materials were received.

The polyurethanes and epoxies consist of two components and are classified as thermosetting systems because their cure is accelerated by heat. After curing, they normally retain their shape up to their decomposition temperatures. The other coatings in table 1 can be classified as thermoplastics since they soften and change shape when heated.

The emphasis has been on thermosetting materials and especially epoxies because these materials seem to best satisfy the previously mentioned criteria. Altogether 36 epoxy coatings, both powder and liquid systems, have been evaluated.

Some materials, especially powders, were submitted only in the form of cured films on steel reinforcing bars.

3.2 Curing Methods and Specimen Preparation

3.2.1 Two-Component Liquid Systems. The epoxy liquid systems consisted of two components, an epoxy resin and a curing component. The curing of epoxies is attributed to chemical reactions between the resin and curing agents leading to polymerization of the mixture.

In the present work the ratio of curing component to epoxy resin and the mixing and curing times were closely controlled and were the same as those specified by the manufacturers' instructions. The epoxy resin and curing component were mixed at room temperature, ca. 24°C (75°F), relative humidity of ca. 35 percent, using either an electric stirrer (solventless systems) or a metal spatula (solvent containing systems). The two component urethanes and zinc filled coatings were similarly mixed.

Test specimens of the pure materials were fabricated and steel plates and steel reinforcing bars were coated with thin films. Specimen discs of 2 1/4 inches diameter of thickness of ca. 3/8 inches (thickness of solvent containing systems were reduced to 3/16 inches) were cast using aluminum weighing dishes as molds. The molds were stripped after the mixture had cured for seven days. Films of 3-7 mils thickness were formed immediately after mixing by applying the coatings with a Baker film applicator to the gel side of photographic paper or to sheets of Teflon. The cured films were then stripped from the photographic film after being immersed in water at room temperature for 16 hours. Cured films were easily stripped from Teflon sheets using a thin-bladed spatula.

Coating materials were applied to 4 x 4 .050 inch cold-rolled steel plates and No. 6 steel reinforcing bars using paint brushes. The steel plates had been degreased previously using mineral spirits and the reinforcing bars had been sand blasted to a white surface.

3.2.2 One-Component Liquid Systems. The two one-component liquid systems, a polyvinylchloride and a phenolic nitrile, were hardened by the evaporation of solvents. Test specimens were formed as described above.

3.2.3 Powder System. It was not necessary to mix the epoxy powders since the two components are contained within each powder particle. The powders were applied to steel and Teflon substrates [preheated to ca. 200°C (392°F) in an electric oven] by immersing the substrates into a fluidized bed of the powders. The coatings were then cured in the electric oven under the conditions specified by the manufacturers. When allowed to cool to room temperature, the cured epoxy films were easily removed from the Teflon substrate by using a thin-bladed spatula. Both No. 6 steel reinforcing bars and 4 x 4 x .050 inch cold-rolled steel plates were coated with the powders.

Specimen discs were not fabricated from the epoxy powders. Porous solids were produced that expanded the specimen volume by a factor of two when sufficient masses to make 3/16 inch thick discs were heated to their specified curing temperatures. Even reducing the masses four fold did not yield satisfactory specimens. Only one of the powder epoxies did not exhibit this phenomenon. Possibly, some of the curing components are vaporized at the curing temperatures which causes the formation of porous

structures when attempts to make large castings are made. No similar difficulties were encountered when films less than 20 mils were formed from the powder epoxies.

3.2.4 Reinforcing Bars Coated by Applicators: The coating materials that were judged to have the most promise as potential protective coatings for steel reinforcing bars were applied by the applicators or manufacturers handling the respective coatings. No. 6 steel reinforcing bars, four feet in length having two different deformation patterns, were supplied to each applicator. The surfaces of the bars were cleaned, usually by sand blasting by the applicator, coatings applied, and then the bars were returned to the National Bureau of Standards for evaluation.

3.3 Testing Procedures and Results:

Descriptions of the test methods used to evaluate coating materials are given in this section along with the experimental results.

Not all of the 47 coating materials were subjected to the same degree of testing. Some were quickly judged not to be acceptable for such reasons as: gel times for two component systems longer than eight hours, coatings No. 10 and 11 (table 1); poor film integrity and excessive entrapped air in the cured state, No. 12 and 13; the tendency of thermoplastics to soften at 60°C (140°F), No. 14 and 47; rubber-like expansion qualities (500 to 600 percent elongation) of two urethanes, No. 35 and 36; (obviously these two coatings would not pass the pull-out and creep requirements); and extreme brittleness of some epoxy systems, No. 5 and 13.

3.3.1 Immersion Testing

3.3.1.1 Epoxy Disc Specimens. Disc shape castings of cured epoxy specimens (liquids in their uncured states) were immersed in water and aqueous solutions of 3M CaCl_2 , 3M NaOH, and a solution saturated with Ca(OH)_2 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and containing 0.5M CaCl_2 . The specimens were immersed in water for a few minutes and wiped dry before measuring the original weights. Original weights of the discs varied from ca. 20 grams for solvent containing systems to ca. 50 grams for the solventless epoxy systems. The temperatures of the test solutions were $24 \pm 1^\circ\text{C}$.

The immersion data are presented in table 2. In some cases two separate castings were made; indicated by two sets of data with different immersion times. The epoxies which in their uncured state contained solvents, generally, lost weight and had greater weight changes than the solventless epoxies. An exception to the solvent containing epoxies is No. 7, which had the largest weight increase of all epoxies studied. The surfaces of both No. 7 and No. 9 were converted from smooth to rough textures during the immersion period. No apparent deterioration was observed with the other epoxy specimens.

The weight losses of solvent containing epoxies possibly, may be associated with the gradual loss of retained solvents. Large weight increases are probably indicative of porous structures.

3.3.1.2 Coatings on Reinforcing Bars. The chemical resistances of powdered epoxy systems were investigated by immersing coated reinforcing bars in aqueous solutions of 3N NaOH and saturated Ca(OH)_2 . The coatings were inspected for evidence of softening, color change, disbonding

and changes in film integrity. The data are presented in table 3 for three polyvinyl chloride coatings, Nos. 23, 24, and 30, one psuedo-powder epoxy, No. 19, and 10 powder epoxy coatings.

The rusting of some coated reinforcing bars in saturated Ca(OH)_2 solutions during the early part of the immersion study is an interesting phenomenon, especially since the uncoated rebars were passive to corrosion in a similar solution. Furthermore, the corrosion was only observed in the weaker alkaline solution, i.e. saturated Ca(OH)_2 rather than 3N NaOH. The pH of saturated Ca(OH)_2 , however, is near 13 which is sufficient to passivate steel. Therefore, the cause of the corrosion apparently lies in either the surface preparation or in the composition of the coatings. Note that the surfaces of the rusting specimens of numbers 38, 39 and 40 were phosphatized, while the surfaces of the non-rusting specimens were only sand blasted. It is not obvious at this date why the same rusting phenomenon was not observed when the rebars were immersed in the 3N NaOH.

3.3.2 Chloride Permeability. The chloride permeability characteristics of thin films of cured epoxies have been measured using permeability cells of the type shown in figure 1. A cell consists of two glass compartments separated by an epoxy film sandwiched between two glass plates, each having centered one-inch diameter holes. One compartment contains 175 ml of 3N NaCl and the other has 115 ml of distilled water. The activities of chloride ions passing through an epoxy membrane were measured using an Orion Specific Ion Meter, Model 401, along with an Orion Chloride Electrode, Model 94-17, and an Orion Double Junction Electrode, Model 90-02. Activity readings were converted into

concentration values of moles per liter by using a conversion diagram constructed by plotting measured chloride ion activities versus known chloride ion concentrations.

Films selected for the permeability studies were carefully handled and examined for any defects before installation in the cell.

The permeability data are presented in table 4 in the form of both permeability units and concentrations. Many of the epoxy films appear to be essentially impervious to chloride ions. Only two films permitted sufficient chloride ions to migrate through so that the corrosion threshold concentration of 0.2M was reached. Diagrams of the accumulative permeating chloride ion concentrations versus time are given in figure 2 for four epoxy films. These plots represent the varying degrees of impermeabilities. The graphic position of distilled water was arbitrarily defined, probably leading to some initial distortion in the curves. The permeability rates were largest during the first six weeks of testing; afterwards the values were lower and more constant.

3.3.3 Impact and Abrasion Resistances of Epoxy Coatings on Steel Plates. Both direct and reverse impact resistances of cured epoxy coatings on 4 x 4 x .050 in cold-rolled steel plates were determined in accordance with ASTM Designation G14-69T. A Gardner Laboratory impact tester was used along with a four pound hammer.

The impact data are presented in table 5. The reverse impact is more severe than the direct impact and probably gives a better indication of the flexibility of a coating (low reverse impact values are indicative of brittle materials). However, it is felt that the impact values for

for the powder material (Nos. 25, 28, 29, 31, and 38 to 40) are too low and are not reliable indicators of their properties. Possibly, the low values can be attributed to the application techniques, applied with a fluidized rather than an electrostatic spray gun, or to poor adherence to the particular steel substrate. The bend testing of coated reinforcing bars, discussed later, is considered to yield more reliable results.

The abrasion resistances of epoxy coating on similar steel panels were determined in accordance with ASTM Designation D1044-56 by using a Taber Abraser and Taber CS-10 wheels with 1000g load per wheel. After each 200 cycles the wheels and specimens were gently cleaned with a soft bristle brush. The abrasion data are given in table 5 in units of weight loss in mg per 1000 cycles. Two of the solvent containing systems (in the uncured state), Nos. 3 and 16, had weight losses over 100 mg indicating poor abrasion resistances.

3.3.4 Inspection of Coated Reinforcing Bars. The film thicknesses, the number of holidays per unit bar length (4 feet), and the visual evaluations of reinforcing bars coated with the most promising materials, applied by the respective firm handling them, are given in table 6. The film thicknesses were measured with a Mikrotest Model 790000 Magnetic Gage. The number of holidays were estimated using a Tinker and Razor Model M-1 Detector.

The following tentative conclusions concerning the integrity of the coating films are implicit in the results given in table 6:

1. The effectiveness of the application methods in producing

thin films free of defects decrease in the sequence; electrostatic spray gun > fluidized bed > dipping > brush.

2. Powder coatings yield better defined deformation patterns than most liquid coatings.

3. Good application practices, including proper surface preparation, are imperative if a coating material is to realize its fullest potential.

3.3.5 Physical Durabilities of Coated Reinforcing Bars. The physical durabilities of coated reinforcing bars were evaluated on the basis of bend tests, impact tests, and pencil hardness measurements (table 7). The tests were carried out on either the same or companion specimens to those listed in table 6.

3.3.5.1 Bend Tests. The No. 6 bars were bent at a 120° angle with a radius of curvature of ca. 3 in. using a Green Lee Tool Company Model 770 Bar Bender. Portions of the bars in contact with the bending machine were protected with rubber tubing of 1 1/2 in. o. d. and 3/4 in. i. d.

Cracking and disbonding took place on the area of some bars that were under tension during the bending. The four different polyvinylchloride coated rebars (No. 23, 24, 26 and 30) gave excellent performances even though their film thicknesses ranged from 2 to 35 mils. A greater variation in performance was observed for the epoxy coated rebars as some performed well while a few were classified as failing. Generally, the epoxy coatings which did not perform well were either brittle or were applied heavily producing a thick film (over 10 mils thick). The effect of the film thickness is illustrated by comparing the coated reinforcing bars

number 22 and 31 which were both coated with the same materials, but the application method was different. Number 22 had a film thickness of ca. 25 mils while the film thickness of No. 21 was ca. 8-9 mils. When bent, substantial cracking was visually observed in the film of No. 22, while No. 31 was completely free of cracking.

Another factor effecting the bending characteristics of coated reinforcing bars was the type of surface preparation of the substrate prior to application of the coatings. In two series of reinforcing bars, No. 18B and No. 32, epoxy coatings were applied to unprepared surfaces which were covered with mill scale. Almost total disbondment was observed when both series of bar were bent; while the epoxy adhered tenaciously to the mill scale, the mill scale was disbonded from the steel substrate. A portion of the coated rebars 38, 39, 40 were sand blasted and phosphatized prior to being coated while the remainder were only sandblasted to a white surface. The latter coated rebars gave no indication of coating failures when bent while the phosphatized bars were susceptible to varying degrees of coating failures.

3.3.5.2 Impact Tests. The impact resistances of coatings were evaluated by dropping an 18 in. length of coated No. 6 reinforcing bar on a slab of concrete so that impact occurred lengthwise as follows:

1. A single bar was dropped one meter from a horizontal position to the concrete.
2. The same bar was dropped from a height of two meters.
3. A companion specimen was taped loosely between two bare No. 7 bars of the same length and the assembly was dropped from a height of 2 meters to the concrete slab. The bars were inspected after each

drop for the following types of damages:

1. Shattering of the coating to expose bare metal.
2. Cutting of the coating to expose bare metal.
3. Cracking of the coating.
4. Disbonding of the coating from the steel substrate.

The coatings were rated on a relative basis. There is a fair direct correlation between the results of the bend tests and the impact tests.

3.3.5.3 Pencil Hardness. The pencil hardness values were determined using a series of lead pencils covering the hardness ranges from H to 8H with one hardness increments. The hardness is designated as the softest lead that imparts a scratch to the coating. All of the epoxy coatings had ratings above 8H, while the polyvinyl chloride coatings were softer with ratings of H, No. 24 and 30, and 8H, No. 23.

3.3.6 Accelerated Corrosion Tests

3.3.6.1 Impressed Voltage Studies. The effects of electrical and electrochemical stresses on the bond of barrier coatings to steel were assessed by modifying the disbonding test, ASTM Designation G8-69T. The cathode and anode were No. 6 reinforcing bars, 6 inches long, both coated with the same material. The electrolyte was an aqueous solution of 7 percent NaCl. A potential of two volts was applied and the electrodes were observed periodically for evolution of hydrogen gas at the cathode and for evidence of corrosion products of iron at the anode. Before immersion, any bare ends or obvious mechanically damaged areas on the electrodes were covered with a film of silicone rubber, and no intentional holidays were induced. The source of any corrosion, therefore, would be holidays in the films (an impressed voltage of two volts should not cause any breakdown in the coating films).

The results of the impressed voltage studies are listed in table 8. It is felt that coatings which permitted the evolution of hydrogen gas within 15 minutes are of doubtful value (when applied in the indicated thicknesses).

3.3.6.2 EMF and Ohmic Measurements. Alternate means of assessing the protective qualities of barrier coatings are electrical potential measurements on coated rebars immersed in corrosive solution and the simultaneous measurements of the dielectric properties of the coating films. Such measurements were taken for coated reinforcing bar partially immersed in 3 1/2 percent aqueous solutions of NaCl. The electrode potentials were measured using a Coleman Model 37A pH Meter with a standard Calomel electrode as the reference electrode. Measurements of the resistance of the films were made using a Yellow Springs Instrument Company Model 31 Conductivity Bridge along with a platinum electrode.

The electrical potential and resistance data are presented in table 8. Low resistance readings, below 500 ohms, are indicative of films which either have many holidays or are permeable by water and/or chloride ions. The thicker films, above 15 mils, were free of holidays and had resistance higher than 25×10^5 ohms, which was beyond the capacity of the measuring device. The same films did not permit the passage of any current, therefore, the potential of these bars could not be measured.

Potential and resistance data for three sets of reinforcing bars, each set coated with a different epoxy, are given in figures 3, 4, and 5. The large variance in the initial millivolt and ohmic measurements of duplicate and triplicate specimens decreased so that after

1000 hours of testing smaller derivations were obtained for companion specimens. A rapid decrease in the resistance of a coatings is estimated to be attributal to the creation of holidays while an increase in resistance is indicative of an autogenous healing mechanism inherent in the coating.

The ratings of coatings (table 8) are based on their overall protective qualities. It is felt that adequate protection are provided by coatings with ratings of 1 or 2. The coatings with ratings 3 may have performed badly because of poor application techniques, improper curing or inadequate film thicknesses.

4. Future Work. Concrete prisms will be cast containing coated and uncoated bars for comparative purposes. Corrosion specimens will also be cast.

The pull-out tests will be completed during the next three months, also the creep tests will be started. Corrosion testing of coated reinforcing bars embedded in concrete immersed in aqueous solutions of 3 1/2 percent NaCl will be undertaken.

Figure Captions

Figure 1 Permeability Cell

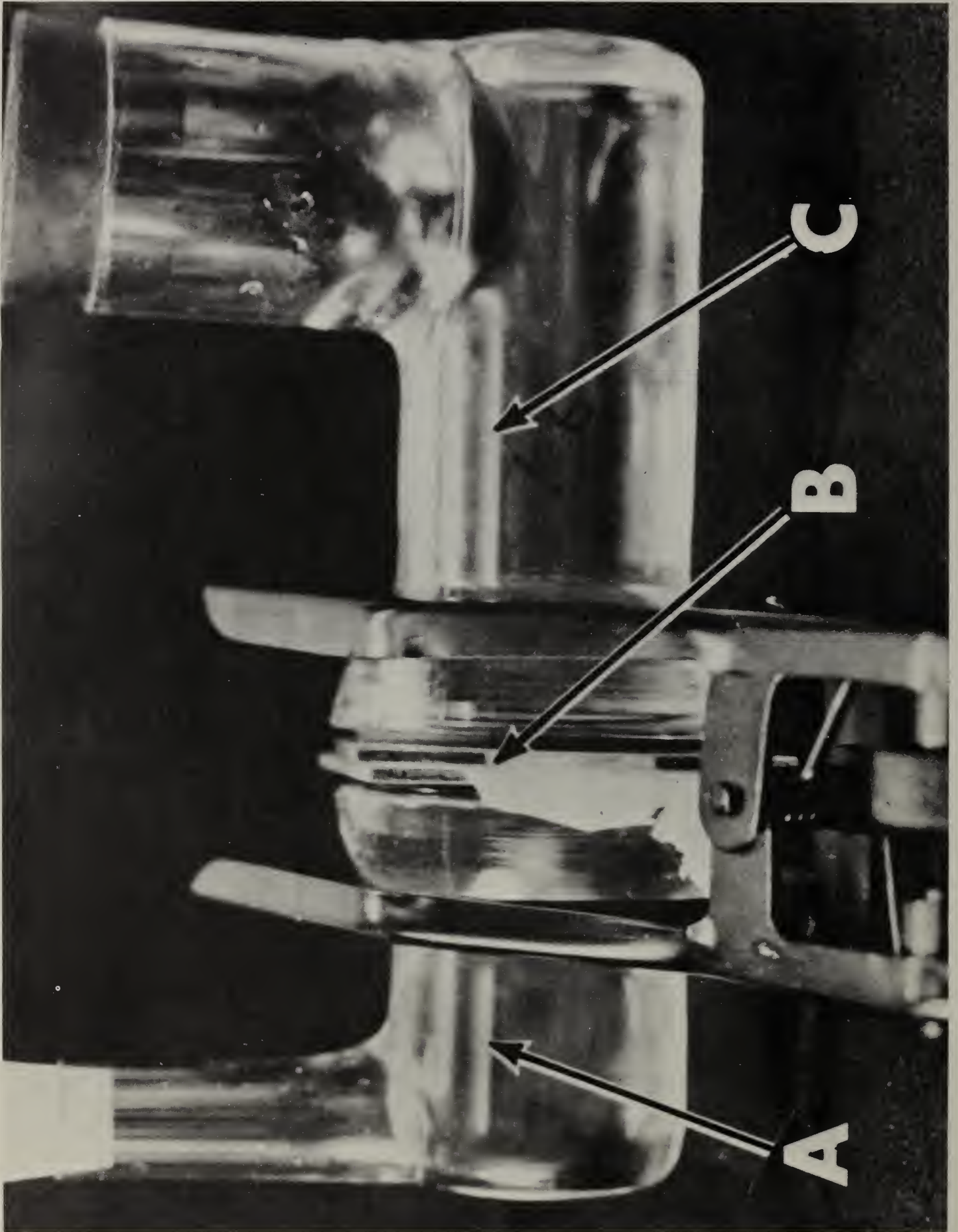
- Components:
- A. compartment containing distilled water;
 - B. epoxy film sandwiched between two glass plates each having centered one-inch diameter holes;
 - C. compartment containing 3N NaCl.

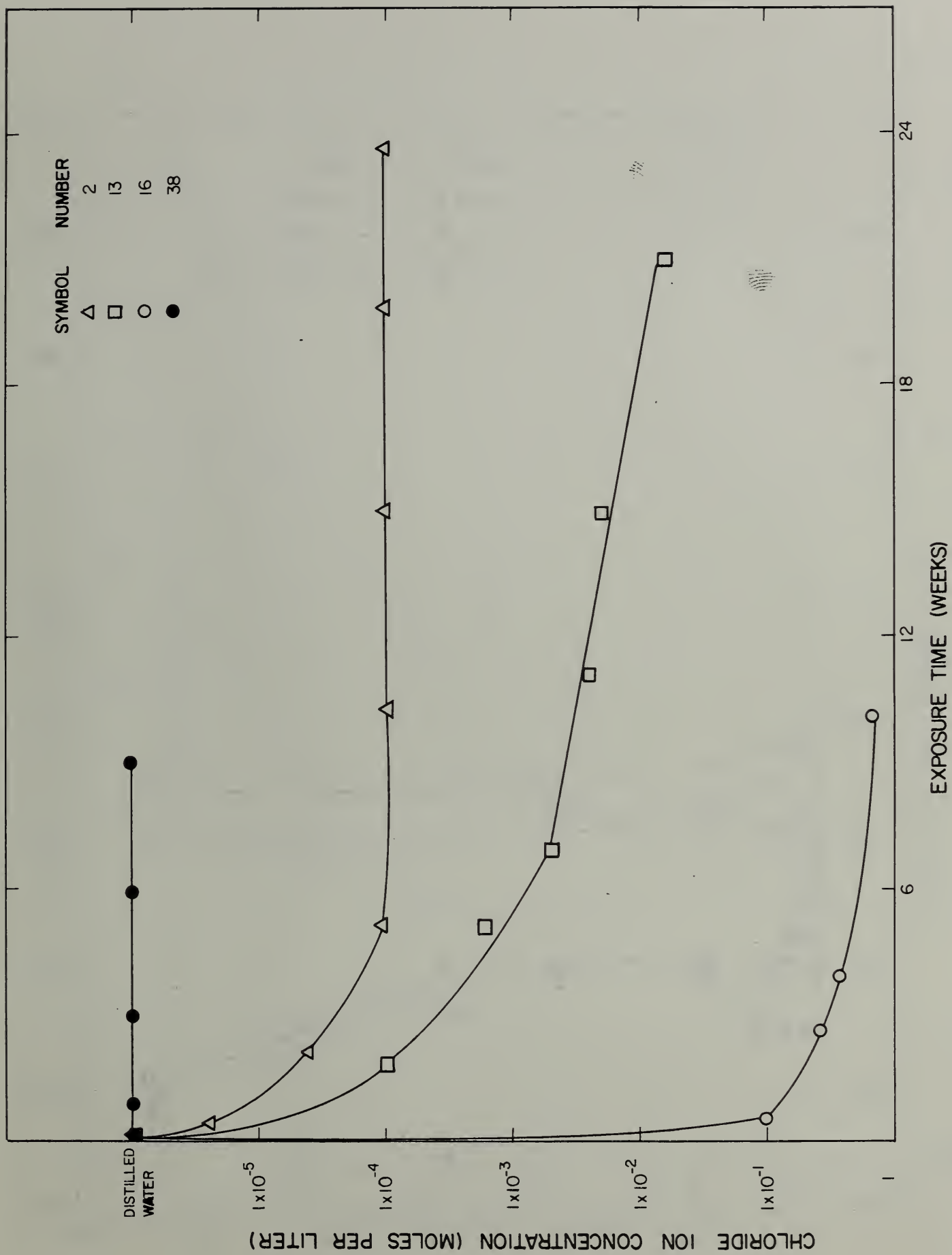
Figure 2 Concentration of chloride ions passing through epoxy films 2, 13, 16 and 38.

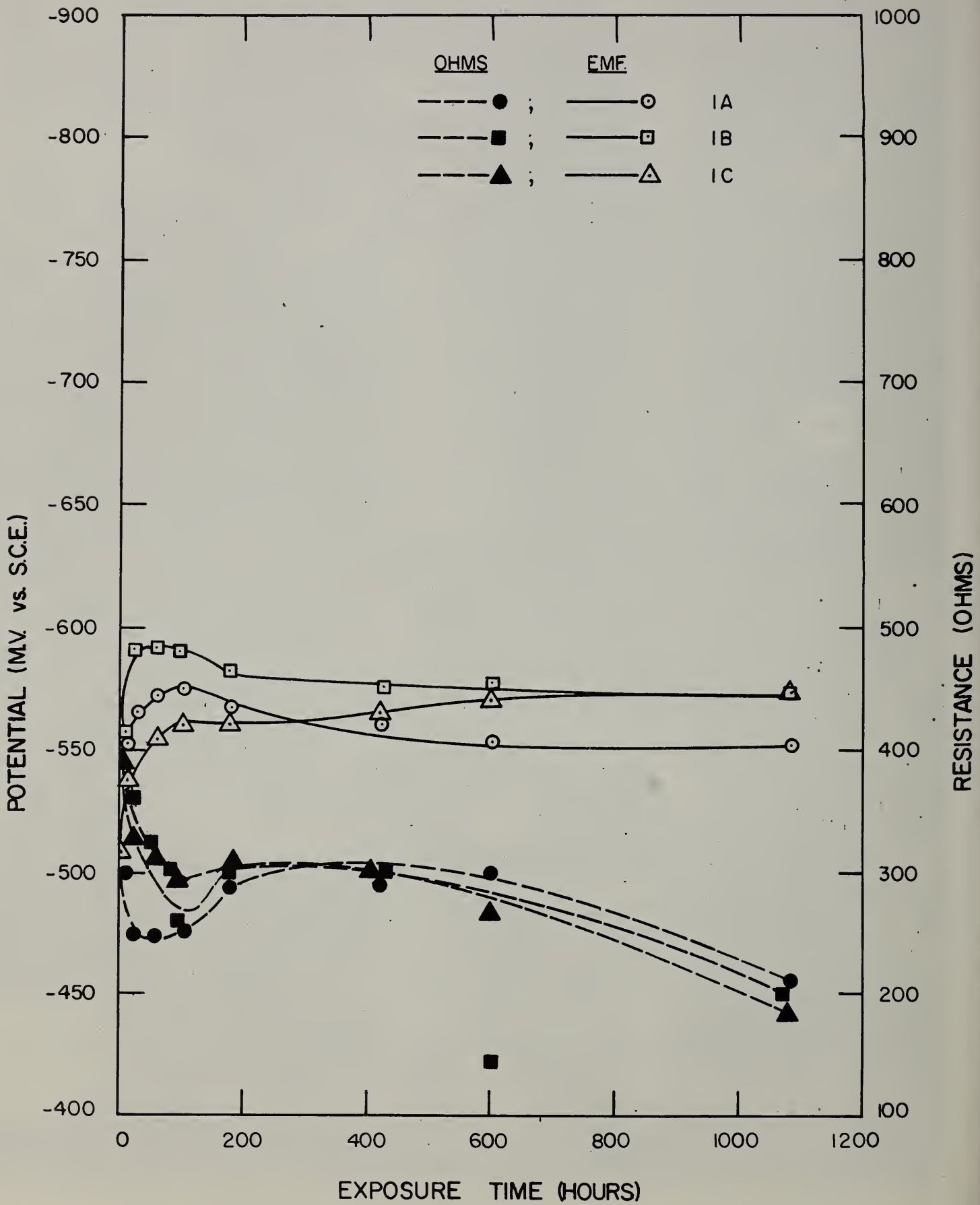
Figure 3 Electrical potential and resistance measurements of coated reinforcing bars No. 1 immersed in 3 1/2 percent NaCl.

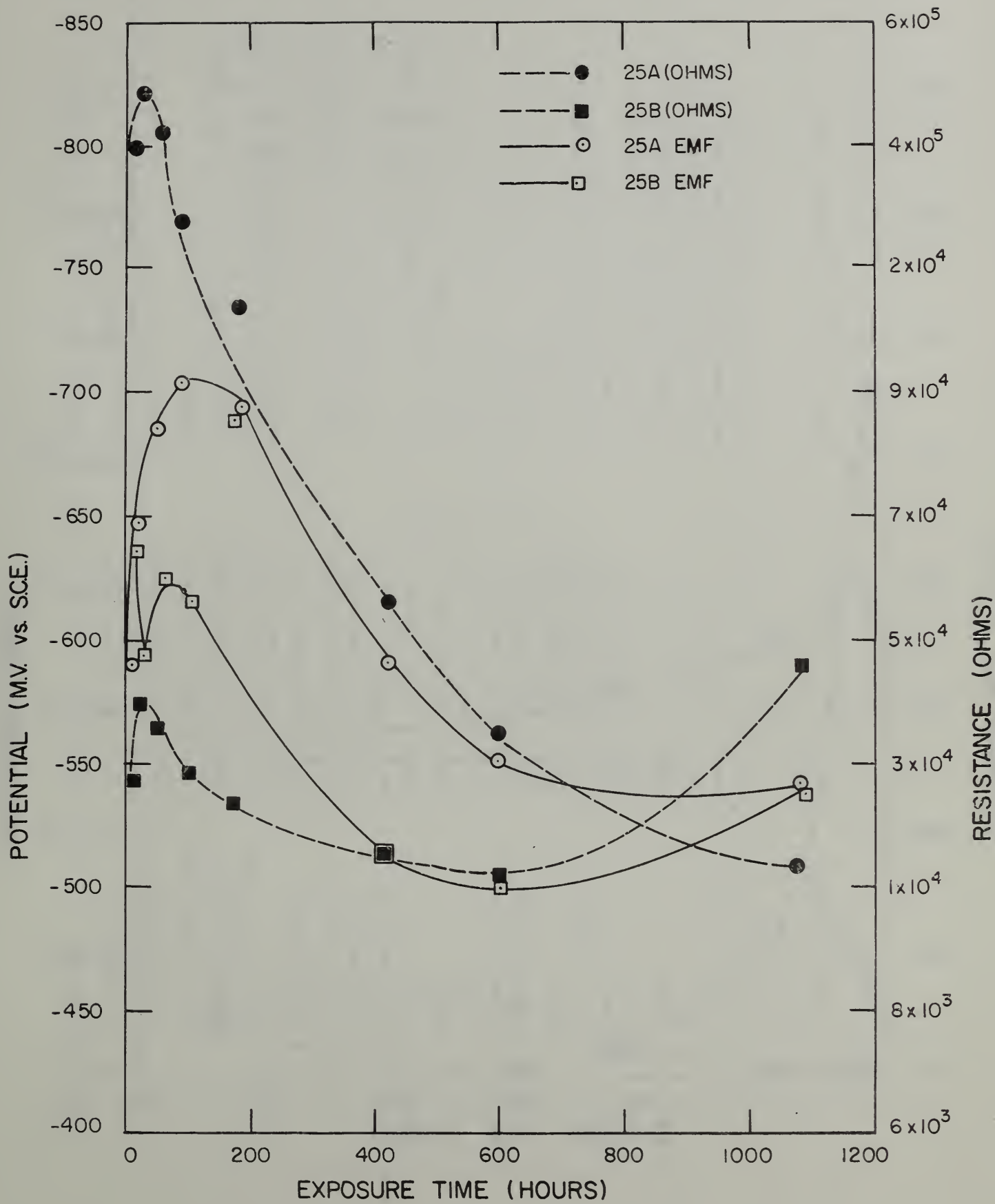
Figure 4 Electrical potential and resistance measurements of coated reinforcing bars No. 25 immersed in 3 1/2 percent NaCl.

Figure 5 Electrical potential and resistance measurements of coated reinforcing bars No. 31 immersed in 3 1/2 percent NaCl.









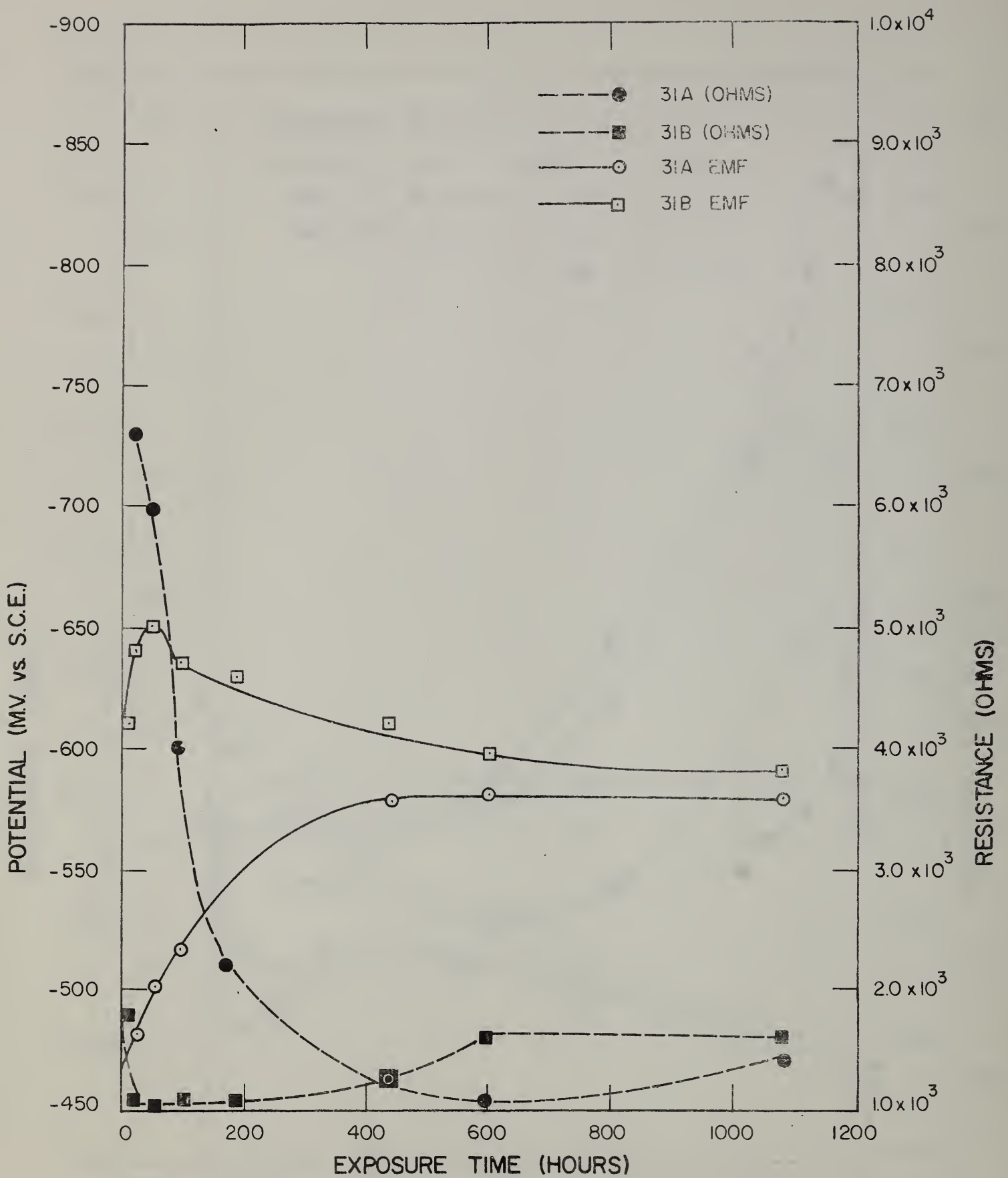


TABLE 1 COATING MATERIALS

Code Number	Type	Uncured State	Comments
1	Epoxy-Polyamide	Liquid - 100 percent solids	Used for concrete overlays
2	Epoxy-Polyamide	Liquid - 100 percent solids	Has been previously tested as coating for steel rebars
3	Epoxy-Polyamide	Liquid - 100 percent solids	Primer
4	Epoxy-Modified amine	Liquid - 100 percent solids	Primer
5	Epoxy-Polysulfide	Liquid - 100 percent solids	Used to bond fresh concrete to old concrete
6	Epoxy-Modified amine	Liquid - 100 percent solids	Topcoat
7	Epoxy	Liquid - 50 percent solids	Water emulsion activated system
8	Epoxy-Polyamide	Liquid - 60 percent solids	
9	Epoxy-Polyamide	Liquid - 50 percent solids	Primer
10	Epoxy-Ketamine	Liquid - 100 percent solids	High Viscosity
11	Epoxy-Ketamine	Liquid - 100 percent solids	
12	Epoxy	Liquid - ca. 100 percent solids	Cures at relative humidity above 50 percent
13	Epoxy	Liquid - ca. 100 percent solids	Limited flexibility
14	Vinyl	Liquid - 20 percent solids	Primer paint
15	Epoxy-Polyamide	Liquid - 50 percent solids	Epoxy paint
16	Epoxy-Polyamide	Liquid - 50 percent solids	Epoxy paint
17	Epoxy	Liquid - 100 percent solids	Low Viscosity
18	Coal tar epoxy	Liquid - 100 percent solids	Protective overlay on concrete pavements
19	Epoxy	Liquid - 46 percent solids	One component, cures by heating
20	Epoxy	Powder	Only coated rebars have been received
21	Epoxy	Powder	Only coated rebars have been received
22	Epoxy	Powder	Only coated rebars have been received
23	Polyvinylchloride	Powder	Only coated rebars have been received
24	Polyvinylchloride-Plastisol	Powder	Only coated rebars have been received
25	Epoxy	Powder	
26	Polyvinylchloride	Powder	Only coated rebars have been received

TABLE 1 COATING MATERIALS (cont.)

Code Number	Type	Uncured State	Comments
27	Epoxy	Powder	
28	Epoxy	Powder	
29	Epoxy	Powder	
30	Polyvinylchloride	Powder	Only coated rebars have been received
31	Epoxy	Powder	Same material as No. 22, but coated rebars submitted from a different applicator and also the pure powder was submitted.
32	Epoxy	Powder	
33	Polyurethane	Liquid	Only coated rebars have been received
34	Phenolic nitrile	Liquid - 10 percent solids	Adhesive for metals
35	Polyurethane	Liquid - 100 percent solids	Elastomer, elongation - 600 percent
36	Polyurethane	Liquid - 100 percent solids	Elastomer, elongation - 550 percent
37	Epoxy	Liquid - 100 percent solids	Adhesive for metals
38	Epoxy	Powder	
39	Epoxy	Powder	
40	Epoxy	Powder	
41	Epoxy	Powder	Only coated rebars have been received
42	Epoxy	Powder	Only coated rebars have been received, same material as number 41, but different application procedure.
43	Epoxy	Powder	
44	Zinc filled-zinc silicate	Liquid - 80 percent solids	Metallic Zinc filler and liquid base are mixed, hardens by solvent evaporation
45	Coal tar epoxy	Liquid	One component, epoxy resin and coal tar, no curing components.
46	Epoxy-Polysulfide	Liquid	
47	Polypropylene	Powder	Only coated rebars have been received. Coating very brittle.

TABLE 2 WEIGHT CHANGES OF CURED EPOXY DISCS IMMERSSED IN AQUEOUS SOLUTIONS

Code Number	Immersion Time (Weeks)	PERCENT WEIGHT CHANGES				Saturated Ca(OH) ₂ Saturated CaSO ₄ ·2H ₂ O and 0.5M CaCl ₂
		Water	3M CaCl ₂	3M NaOH		
1	31	2.3	1.3	1.9	2.4	
	18	3.5	0.4	2.4	3.0	
2	31	3.1	1.8	1.9	3.7	
	18	2.4	1.6	1.8	2.3	
3	31	-1.9	-2.1	2.1	-2.0	
	18	-2.3	-2.6	1.9	-2.3	
4	31	2.3	1.6	1.6	1.9	
	18	1.5	0.7	1.3	1.6	
5	31	1.2	1.1	1.6	1.8	
	18	1.1	0.5	0.9	1.2	
6	31	2.7	1.5	2.1	2.7	
	18	1.7	0.7	1.0	2.1	
7	31	17	20	15	18	
8	31	-4.8	-5.7	-2.7	-4.8	
9	31	-6.8	-10	9.3	-14	
12	29	1.2	0.0	1.3	1.5	
13	29	1.3	1.2	1.8	2.5	
16	22	-0.8	-1.7	-7	-1.7	
	18	-3.1	-3.1	-5	-3.4	
17	24	2.1	0.7	1.6	2.4	
	18	1.5	0.7	2.0	1.7	
18	24	0.6	0.0	0.1	0.8	
	18	0.9	0.4	0.7	0.8	

TABLE 3 IMMERSION TESTING OF COATINGS ON REINFORCING BARS^{1/}

Code Number	3N NaOH ^{2/}	Saturated Ca(OH) ₂ ^{2/}
19	No Change	A. Rusted ^{3/} ^{5/} B. No Change ^{3/}
22	No Change	No Change
23	No Change	No Change
24	No Change	No Change
27	No Change	No Change
28	No Change	No Change
29	No Change	No Change
30	No Change	No Change
31	No Change	No Change
32	No Change	No Change
38	No Change	B. Rusted ^{4/} ^{5/} P. Rusted ^{4/} ^{5/}
39	No Change	B. No Change ^{4/} ^{5/} P. Rusted ^{4/} ^{5/}
40	No Change	B. No Change ^{4/} ^{5/} P. Rusted ^{4/} ^{5/}
41	No Change	No Change
Uncoated Rebar	No Change	No Change

^{1/} No. 6 reinforcing coated by firms handling the respective coatings.

^{2/} Immersion time of 45 days.

^{3/} A and B are specimens from companion bars.

^{4/} B denotes bars that were only sandblasted prior to application of the coating, while P indicates that their surfaces was also phosphatized prior to being coated.

^{5/} Rusting took place during the first 15 days of immersion, afterwards no changes observed.

TABLE 4 PERMEABILITY OF CHLORIDE IONS THROUGH EPOXY FILMS

Code Number	Film Thickness (mils)	Exposure Time (weeks)	Concentration ^{1/} (Moles per liter)	Permeability Units
1	3	16	1×10^{-5} ^{3/}	$< 1.7 \times 10^{-6}$
2	3	23	1×10^{-4}	9.7×10^{-6}
3	3	16	$< 1 \times 10^{-5}$ ^{3/}	$< 1.7 \times 10^{-6}$
4	3	23	1×10^{-4}	9.7×10^{-6}
6	3	23	1×10^{-4}	9.7×10^{-6}
11	3	12	4×10^{-3}	7.5×10^{-4}
13	3	21	1×10^{-2}	5×10^{-4}
16	7	23	2×10^{-3}	6.2×10^{-4}
	3	10	8×10^{-1}	2.3×10^{-1}
17	3	16	$< 1 \times 10^{-5}$ ^{3/}	$< 1.7 \times 10^{-6}$
19	7	6	$< \text{N.C.}$ ^{4/}	
29	10	6	1×10^{-5}	3.5×10^{-6}
31	10	6	N.C. ^{4/}	
38	2.5	6	N.C. ^{4/}	
39	2.5	6	N.C. ^{4/}	
40	2.5	6	1×10^{-5}	3.5×10^{-6}

^{1/} Concentration of chloride ions in the chamber originally containing only distilled water.

^{2/} Permeability units are: (grams per day)/exposed area (in^2)/film thickness (mils); i.e. theoretically the number of grams of chloride ion passing per day through a film having an exposed area of one square inch and a thickness of one mil.

^{3/} Millivolt readings were near the region of distilled water and the lower limit of the chloride ion concentration was estimated.

^{4/} N.C. denotes that no changes from the original millivolt valves were measured.

TABLE 5 ABRASION AND IMPACT RESISTANCE OF CURED EPOXY COATINGS ON STEEL PANELS

Code Number	Film Thickness (mils)	IMPACT RESISTANCE ^{2/}		Direct Impact (in lb.)	ABRASION RESISTANCE ^{3/}	
		Reverse Impact (in lb.)	Weight loss per 1000 cycles (mg)		Weight loss per 1000 cycles (mg)	
1	7	20	90	71	71	
2	7	4	120 ^{4/}	56	56	
3	8	40	160	107	107	
4	5	4	40	70	70	
5	7	8	20	58	58	
6	6	4	20	71	71	
11	6	--	--	89	89	
16	5	8	50	148	148	
17	6	7	50	58	58	
18	7	12	110	52	52	
19	1	>160	>160	51	51	
	4	160	160	--	--	
25	7	4	60	--	--	
28	8	40	60	88	88	
29	8	50	60	57	57	
31	6	20	80	--	--	
38	7	20	80	--	--	
39	8	20	40	--	--	
40	11	20	-- ^{5/}	--	--	

1/ Epoxy coatings applied to 4x4x.050 inch steel plates (cold rolled).

2/ Four pound hammer used.

3/ Tabor GS-10 wheels, with 1000g load per wheel.

4/ Bond at the steel-epoxy interface severed at 10 in-lb.

5/ Coating shattered off of steel panel.

TABLE 6 INSPECTION OF COATED STEEL REINFORCING BARS ^{1/}

Code Number	Chemical Type	Color	Application Method	Film Thickness (mils)	No. of holidays per 4 foot bar	Visual Inspection and Comments
1	Epoxy, liquid	Reddish brown	Brush	4-5	40	Deformation not well coated and slightly exposed. Accumulation of epoxy in low lying regions.
2	Epoxy, Liquid	Clear	Brush	5-15	ca. 10	Deformations not well covered long uncovered regions. Material is brittle.
3	Epoxy, liquid with solvent	Dull Green	Brush	2-5	ca. 30-40	Deformations appear to be well covered.
4	Epoxy, liquid	Orange	Brush	10-20	none	Deformation not well defined as the epoxy is concentration in the low lying region between the deformations.
5	Epoxy, liquid	Dark Tan	Brush	10-15	to many to estimate	Longitudinal deformations are not well covered. Excess epoxy in regions between the deformations.
10	Epoxy, liquid	White	Brush	10	ca. 10	Susceptible to abrasion; coating comes easily off of rebars. Rough texture. Epoxy accumulated between deformations.
11	Epoxy, liquid	Orange	Brush	10-12	none	Coating easily chips off of rebar. Regions where deformations are not well covered. Evidence of epoxy dripping from bar.
16	Epoxy, liquid with solvent	White	Electrostatic spray gun	2-4	40	Deformation not well covered, accumulation of epoxy in low lying areas.

TABLE 6 INSPECTION OF COATED STEEL REINFORCING BARS $\frac{1}{4}$ " (cont.)

Code Number	Chemical Type	Color	Application Method	Film Thickness (mils)	No. of holidays per 4 foot bar	Visual inspection and comments
17	Epoxy, liquid	Gray	Brush	4	too many to estimate	Tops of deformations not well covered. Brittle materials that easily chips off of steel substrate.
18	Epoxy, coal tar	Black	Brush	4	too many to estimate	Bad adhesion to steel. Abrades easily off of rebar.
19	Epoxy, liquid with solvent	Reddish brown	Single dipping	1	40	Good coverage, well defined deformation pattern. No bad dipping regions observed.
22	Epoxy, powder	Light Green	Fluidized bed	25	none except at ends	Good even build-up film. Large thickness characteristic of fluidized bed application.
23	Polyvinyl-chloride, powder	Dark Olive Green	Fluidized bed	25	none except at ends	Good even build-up film. Thermoplastic coating.
24	Plastisol polyvinyl-chloride, powder	Purplish Black	Fluidized bed	35	none	Deformation pattern not well defined. Thermoplastic.
25	Epoxy, powder	Blue	Electrostatic spray gun	6-11	none	Good coating material. Some bad spraying techniques, bars were sprayed from one direction giving the underside of the deformations a thin coating.
26	Polyvinyl-chloride, powder	Clear	Electrostatic spray gun	2-3	too many to estimate	Top of deformations not covered. When received, coated rebars were sticky. Thermoplastic.
27	Epoxy, powder	Black	Electrostatic spray gun	8	ca. 1	High gloss coating. Even build up. Very tough coating that did not chip off.
28	Epoxy, powder	Black	Electrostatic spray gun	1-2	cannot estimate	Either very high number of holidays or electrical conducting pigments. Rough texture.
29	Epoxy, powder	Yellow	Electrostatic spray gun	1-2	cannot estimate	Either very high number of holidays or electrical conducting pigment. Deformation do not appear to be well coated. Tough coating that is not susceptible to chipping

TABLE 6 INSPECTION OF COATED STEEL REINFORCING BARS^{1/} (cont.)

Code Number	Chemical Type	Color	Application Method	Film Thickness (mils)	No. of holidays per 4 foot bar	Visual inspection and comments
30	PVC, powder	Dull Green	Fluidized bed	15-18	none	Thermoplastic coating. Deformation pattern not well defined possibly due to tendency of material to flow when cured at elevated temperatures.
31	Epoxy, powder	Green	Electrostatic spray gun	8-9	none	Good even build-up film. Deformations well covered. Tough coating that is not susceptible to chipping.
32	Epoxy, powder	White	Electrostatic spray gun	4-6	40	Mill scale was not removed and coating chips off easily due to disbonding between the mill scale & the steel rebars.
33	Urethane, liquid	Orange	Brush	3-4	too many to estimate	Coating easily damaged and chips off of rebar.
38	Epoxy, powder	Gray	Electrostatic spray gun	2-4	ca. 30-40	Deformation not well covered. Some bars were phosphatized.
39	Epoxy, powder	Brown	Electrostatic spray gun	2-4	ca. 30-40	Holidays located on deformation. Some bars were phosphatized.
40	Epoxy, powder	Red	Electrostatic spray gun	2-4	10	Tough coating that is not susceptible to chipping some bars were phosphatized.
41	Epoxy, powder	Red	Electrostatic spray gun	3-7	1	Good coverage. Bar heated prior to application of powder coating.
42	Epoxy, powder	Red	Electrostatic spray gun	3-4	too many to estimate	Same material as No. 41, but powder applied to cold rebars.
43	Epoxy, powder	Black	Electrostatic spray gun	3-4	too many to estimate	Material readily abrades off of rebar.

11/ Number 6 steel reinforcement bars coated by applicators or coating producers. Unless otherwise stated, the mill scale was removed by sand blasting.

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCEMENT BARS ^{1/}

Code Number	Chemical Type	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact ^{3/} Rating	Pencil ^{4/} Hardness
1	Epoxy, liquid	4-5	Slight cracking near edge of deformation, length of cracks were ca. 1/8 inch.	Good	>8H
2	Epoxy, liquid	5-15	Complete failure in bend area. Almost complete disbonding	Poor	>8H
3	Epoxy, liquid with solvent	2-5	Few small crack ca. 1/8 in. long. Good performance.	Good	>8H
4	Epoxy, liquid	20-30	Severe cracking at almost every transverse deformation in bend area. Lengths of cracks were 1/2 to 3/4 in.	Poor	
5	Epoxy, liquid	40-50	Severe cracking at deformations. Cracks were ca. 1/8 in. wide and undercutting disbondment between the films and steel took place.	Poor	>8H
10	Epoxy, liquid	10	Severe cracking which extended from longitudinal to longitudinal deformation. Disbonding between the coating and steel was observed.	Poor	>8H
11	Epoxy, liquid	10-12	Same as No. 10	Poor	>8H
16	Epoxy, liquid with solvent	2-4	Miniature cracks, good performance	Fair	>8H
17	Epoxy, liquid	4	Cracking started at 20° bend angle. Total disbondment in area under tension. Complete failure.	Fair	>8H
18	Epoxy, coal tar liquid	4	No cracking, excellent performance	Fair	>8H
19	Epoxy, liquid with solvent	4	No cracks, excellent performance.	Excellent	>8H
22	Epoxy, powder	25	Substantial cracking extending from longitudinal to longitudinal deformation, some disbonding between the coating and steel was observed.	Excellent	>8H

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCEMENT BARS^{1/} (cont.)

Code Number	Chemical Type	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact ^{3/} Rating	Pencil Hardness ^{4/}
23	Polyvinylchloride, powder	25	No cracks, excellent performance.	Excellent	8H
24	Plastisol polyvinylchloride, powder	35	No cracks, excellent performance.	Excellent	H
25	Epoxy, powder	6-11	Many small (ca. 1/8 in. long) thin cracks, considered as moderate cracking.	Good	> 8H
26	Polyvinylchloride, powder	2-3	No cracks, excellent performance.		
27	Epoxy, powder	8	Substantial cracking extending from longitudinal to longitudinal deformation. Some disbonding was observed.	Good	> 8H
28	Epoxy, powder	1-2	A. Slight cracking, good performance. B. Substantial cracking and disbonding observed. ^{5/}	Fair	> 8H
29	Epoxy, powder	3-4	No cracks, excellent performance	Good	> 8H
30	Polyvinylchloride, powder	15-18	No cracks, excellent performance.	Poor	H
31	Epoxy, powder	8-9	No cracks, excellent performance.	Excellent	> 8H
32 ^{5/}	Epoxy, powder	4-6	Complete failure as total disbonding in bend area; probably attributable to disbonding between mill scale and steel.	Fair	> 8H
33	Polyurethane liquid	3-4	No cracks, excellent performance	Good	8H
38 A ^{6/} B ^{6/}	Epoxy, powder	2-4 2-4	No cracks, excellent performance Severe cracking on every deformation in area under tension during bending	Excellent	> 8H
39 A ^{6/} B ^{6/}	Epoxy, powder Epoxy, powder	2-4 2-4	No cracks, excellent performance Two or three small cracks. Good performance.	Excellent	> 8H

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCEMENT BARS^{1/} (cont.)

Code Number	Chemical Type	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact ^{3/} Rating	Pencil ^{4/} Hardness
40 A ^{6/} B ^{6/}	Epoxy, powder	2-4 2-4	Excellent performance no cracking Failure. Phosphate coating adhered poorly to the steel substrate. Cracking of epoxy coating in complete area under tension during bending.	Excellent	> 8H
41 ^{7/}	Epoxy, powder	3-7	Excellent performance, no cracking	Good	> 8H
42 ^{8/}	Epoxy, powder	3-4	Substantial cracking	Good	> 8H
43	Epoxy, powder	3-4	Slight 'popping off' of coating. Good performance.	Good	> 8H

^{1/} Number 6 steel reinforcement bars coated by applicators or coating producers. Unless otherwise stated the mill scale was removed by sand bl.

^{2/} Crack rating in order of decreasing performance: Excellent > Good > Moderate > Substantial > Severe > Complete failure.

^{3/} Relative rating: Excellent > Good > Fair > Poor.

^{4/} Lead hardness which imparts a mark to the coating.

^{5/} Mill scale was not removed.

^{6/} Surface of A sandblasted prior to application of coating material.
Surface of B sandblasted and phosphatized prior to coating application.

^{7/} Bars heat to 190°C prior to applying powder coating.

^{8/} Same coating material as 41, but applied to cold reinforcing bars.

TABLE 8 CORROSION BEHAVIOR OF COATINGS ON REINFORCING BARS

Code Number	Chemical Type	Film Thickness (Mils)	Application Method	Time to Evolve H ₂ (g) ^{1/} (Hours) ^{2/}	Resistance (ohms) ^{2/}		Voltage (Millivolts) ^{2/}		Rating
					Beginning ^{3/}	1000 hours	Beginning ^{3/}	1000 hours	
1	Epoxy, liquid	4 - 5	Brush	<1/4	537	200	-340	-570	3
2	Epoxy, liquid	5 - 15	Brush	<1/4	250	190	-588	-576	3
3	Epoxy, liquid with solvent	2 - 5	Brush	<1/4	400	180	-615	-604	3
4	Epoxy, liquid	20 - 30	Brush	1/2	700	260	-470	-555	3
5	Epoxy, liquid	40 - 50	Brush	<1/4	1.1x10 ³	425 ^{5/}	-513	-617 ^{5/}	3
10	Epoxy, liquid	10	Brush	<1/4	--	--	--	--	3
11	Epoxy, liquid	10 - 12	Brush	<1/4	9.6x10 ³	800	-497	-560	3
16	Epoxy, liquid with solvent	8	Brush	1	400	250	-516	-593	2
17	Epoxy, liquid	4	Brush	<1/4	1.5x10 ³	700	-430	-545	3
18	Epoxy, liquid	4	Brush	<1/4	98	240	-516	-604	3
19	Epoxy, liquid with solvent	4	Brush	24	435	225	-503	-568	2
22	Epoxy, powder	25	Fluidized bed	>648 ^{5/}	>25x10 ⁵ 6/	>25x10 ⁵ 6/	N. R. ^{7/}	N. R. ^{7/}	1
23	Polyvinylchloride, powder	25	Fluidized bed	>120 ^{5/}	>25x10 ⁵ 6/	>25x10 ⁵ 6/	N. R. ^{7/}	N. R. ^{7/}	1
24	Polyvinylchloride, plastisol, powder	35	Fluidized bed	>480 ^{5/}	13x10 ⁵	>25x10 ⁵ 6/	N. R. ^{7/}	N. R. ^{7/}	1
25	Epoxy, powder	6 - 11	Electrostatic spray	6	2x10 ⁵	>25x10 ⁵ 6/	-613	-541	1
26	Polyvinylchloride, powder	2 - 3	Electrostatic spray	<1/4	--	--	--	--	3
27	Epoxy, powder	8	Electrostatic spray	<1/4	--	--	--	--	3

TABLE 8 CORROSION BEHAVIOR OF COATINGS ON REINFORCING BARS (continued)

Code Number	Chemical Type	Film Thickness (Mils)	Application Method	Time to Evolve H ₂ (g) ^{1/} (Hours)	Resistance (ohms) ^{2/}		Voltage (Millivolts) ^{2/}		Rating ^{4/}
					Beginning ^{2/}	1000 hours	Beginning ^{3/}	1000 hours	
28	Epoxy, powder	1 - 2	Electrostatic spray	< 1/4	250	240	-600	-606	3
29	Epoxy, powder	3 - 4	Electrostatic spray	< 1/4	475	300	-518	-565	2
30	Polyvinylchloride, powder	15 - 18	Fluidized bed	> 168 ^{5/}	> 25x10 ⁵ ^{6/}	> 25x10 ⁵ ^{6/}	N. R. ^{7/}	N. R. ^{7/}	1
31	Epoxy, powder	8 - 9	Electrostatic spray	> 96 ^{5/}	> 25x10 ⁵	1500	-532	-588	1
32	Epoxy, powder	4 - 6	Electrostatic spray	< 1/4	800	540	-617	-573	3
33	Polyurethane, liquid	2 - 4	Brush	< 1/4	550	400	-516	-565	3
38 B ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	< 1/4	360 ^{9/}	210 ^{10/}	-514 ^{9/}	-580 ^{10/}	3
38 P ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	< 1/4	380 ^{9/}	220 ^{10/}	-481 ^{9/}	-606 ^{10/}	3
39 B ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	< 1/4	380 ^{9/}	240 ^{10/}	-557 ^{9/}	-610 ^{10/}	2
39 P ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	3	410 ^{9/}	230 ^{10/}	-557 ^{9/}	-643 ^{10/}	2
40 B ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	< 1/4	280 ^{9/}	200 ^{10/}	-513 ^{9/}	-609 ^{10/}	3

TABLE 8 CORROSION BEHAVIOR OF COATINGS ON REINFORCING BARS

Code Number	Chemical Type	Film Thickness (Mils)	Application Method	Time to Evolve H ₂ (g) (Hours) ^{1/}	Resistance (ohms) Beginning ^{3/} 1000 hours	Resistance (ohms) ^{2/} 1000 hours	Voltage (Millivolts) Beginning ^{3/} 1000 hours	Rating ^{4/}
40 p ^{8/}	Epoxy, powder	2 - 4	Electrostatic spray	1/2	200 ^{0/}	240 ^{10/}	-481 ^{10/}	2
41	Epoxy, powder	3 - 7	Electrostatic spray	1/2	3.8x10 ⁵	3.0x10 ³	-451	2
42 ^{1/}	Epoxy, powder	3 - 4	Electrostatic spray	<1/4	400	370	-526	3
	Uncoated bar			immediate	200	370	-648	4

1/ Coated bar anodically polarized with 1 1/2 volt. Bars partially immersed in 7 percent NaCl.

2/ Bars partially immersed in 3 1/2 percent NaCl.

3/ Initial measurements taken after specimens were immersed for one hour.

4/ Ratings sequence in order of decreasing corrosion protection: 1, 2, 3, 4

5/ Test stopped after indicated time.

6/ Resistance values beyond capacity of measuring device.

7/ N. R. denotes no reading possible, i.e. no current flow because of holiday-free films.

8/ 8 represents sand blasted surfaces, only, while P indicates that the surfaces were phosphatized before applying the coatings.

9/ Initial measurement taken after immersion time of 120 hours.

10/ Measured after 606 hours.

11/ Same coating material as No. 41, however, applied to cold bars: coating applied to bars heated to 100°C in the case of No. 4.

