Gulf General Atomic
Incorporated
P.O. Box 608, San Diego, California 92112

AEC RESEARCH AND
DEVELOPMENT REPORT

GA-9356

TESTS RELATING TO CORROSION PROTECTION FOR TENDONS OF THE PUBLIC SERVICE COMPANY OF COLORADO PRESTRESSED CONCRETE REACTOR VESSEL

by

J. F. Hildebrand

Prepared under
Contract AT(04-3)-633
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

Gulf General Atomic Project 901

August 6, 1969

SUMMARY

The nongrouted tendons of the Fort St. Vrain Nuclear Generating Station require corrosion protection starting at the wire manufacturer's works and continuing through the life of the prestressed concrete reactor vessel.

To ensure the adequacy of the corrosion-protection system, a variety of coating materials applied to wires and tendons were evaluated after exposure to several environments. The purpose of each test, the environments, and the results are summarized on page iv.

The results of these accelerated tests have demonstrated that the prescribed phosphate coating on the wires and the No-Ox-Id CM corrosion-inhibiting compound on the tendons provide excellent corrosion protection that can be expected to last throughout the life of the prestressed concrete reactor vessel.

SUMMARY OF TENDON WIRE CORROSION TESTS

Purpose	Specimens and Wire Type	Protective Coating	Test Environment	Test Results
General Corrosion Tests				
Effects of corrosion on tensile properties	12, stress-relieved	None	L. J. coastal; 0, 30, 180, and 365 days	Fine scaling rust after 365 days; no loss up to 180 days; 6% loss after 365 days
Evaluation of phosphate coatings	4, stress-relieved	Auto Bond (lead) Meta Bond (zinc) applied by mfr., moderate wt	L. J. coastal; 14 and 132 days	Performance good, 14 days; Meta Bond better than Auto Bond
Effectiveness of Kephos applied by wire mfr.	4, thermalized	2, none 2, Kephos (organic phosphate treatment)	L. J. coastal; 30 days	Coated-wire corrosion equivalent to bare-wire corrosion
Comparison Meta Bond and Kephos	4, thermalized 3, stress-relieved	2, none 3, Kephos 1, Meta Bond only 1, Meta Bond + Rustarest	L. J. coastal; 95 days	Meta Bond better than Kephos; Kephos equivalent to bare wire; Meta Bond + Rustarest best
Effectiveness of Meta Bond applied by tendon fabricator	2, thermalized	Meta Bond + Rustarest on wire-fatigue test specimens	L. J. coastal; 90 days	Relatively light coating; provided moderate protection
Effectiveness of Meta Bond applied by wire mfr.	12, thermalized	Meta Bond + Rustarest, 200 mg/sq ft min.	L. J. coastal; 6 mo	Moderate protection on partially protected wire; poor on fully exposed wire
Evaluation of No-Ox-Id compounds	6, stress-relieved	2, No-Ox-Id CM 2, No-Ox-Id 500 2, combination 500 plus CM	L. J. coastal; 2 yr	No-Ox-Id 500 exhibited rust spots; no corrosion on No-Ox-Id CM-coated wires
Selection of overseas packaging	11, thermalized coils	Coating code: A1, bare A2, Kephos Wrapping code: B1, none B2, VPI hessian, kraft hessian, adhesive tape B3, VPI hessian, kraft hessian B4, VPI hessian only	Overseas shipment; 4 coils in unsealed steel container	A1B1, light haze of rust, top coil A1B4, light haze of rust, bottom coil (Rust may have been on wire before packaging.) A2B1, no rust, top coil A2B2, no rust A2B3, no rust A2B4, no rust
Accelerated Corrosion Tests				
Comparison of Kephos and Meta Bond by wire mfr.	20, thermalized	10, bare 2, Kephos 4, Meta Bond 4, Meta Bond + Rustarest	10, freely suspended in fog chamber 10, protected by glass tube in fog chamber	Order of decreasing corrosion protection after 100- and 200-hr exposures: Meta Bond + Rustarest, Meta Bond, Kephos, and bare
Comparison of Kephos and Meta Bond	48, thermalized	4, bare 4, bare + Rustarest 4, light Meta Bond 4, light Meta Bond + Rustarest 4, heavy Meta Bond 4, heavy Meta Bond + Rustarest 4, Kephos 4, Kephos + Rustarest	24, freely suspended in fog chamber 24, protected by glass tube in fog chamber	After 100- and 200-hr exposures, Kephos and Meta Bond + Rustarest equivalent, Meta Bond alone slightly better than Kephos alone, thin Meta Bond poor

SUMMARY OF TENDON WIRE CORROSION TESTS (continued)

Purpose	Specimens and Wire Type	Protective Coating	Test Environment	Test Results
Tendon Corrosion Tests				
Stress relaxation and corrosion protection	25 straight wires, stress-relieved, 91 ft long	Chassis black grease	L. J. test bed; 120 F for 1 yr	No corrosion observed
Stress relaxation and corrosion protection	25 straight wires, stress-relieved, 91 ft long	No-Ox-Id CM	L. J. test bed; 68 F for 1 yr	No corrosion observed
Stress relaxation and corrosion protection	25 straight wires, thermalized, 91 ft long	No-Ox-Id CM	L. J. test bed; 120 F for 1 yr	No corrosion observed
Stress relaxation and corrosion protection	25 straight wires, thermalized, 91 ft long	No-Ox-Id CM	L. J. test bed; 68 F for 1 yr	No corrosion observed
Stress relaxation and corrosion protection	168 curved wires, thermalized, 73 ft long	No-Ox-Id CM	L. J. test bed, 120 F for 1 yr	Light corrosion observed on uncoated areas of wire and anchor assemblies
Bearing-plate reinforcing and corrosion protection	168 straight wires, thermalized, 21 ft long	No-Ox-Id CM	L. J. test bed, 130 F for 1 yr	No corrosion observed
Stress Corrosion Test				
Effectiveness of corrosion protection for notched specimen	4, thermalized wire, 0.001-in. notch root radius	1, Meta Bond + Rustarest 3, Meta Bond or Kephos + No-Ox-Id CM	Wire stressed, 75% F_{ntu},* L. J. coastal; 9 mo	Notch badly corroded on Meta Bond + Rustarest sample; no failures
Runoff and Self-Healing Tests				
Tenacity of protective compound	5, stress-relieved	Corrosion-inhibiting compounds No-Ox-Id CM, No-Ox-Id 2W, No-Ox-Id A spec., No-Ox-Id 490, No-Ox-Id 500; Vertical drainage	L. J. coastal; 1500-hr drainage; 95 days	No corrosion evident on No-Ox-Id CM-coated wire
Effect of temp 120 F on tenacity of protective compound	5, stress-relieved		L. J. coastal; 100-hr drainage; 60 days	No corrosion evident on No-Ox-Id CM-coated wire
Effect of temp 160 F on tenacity of protective compound	5, stress-relieved		L. J. coastal; 1000-hr drainage; 95 days	No corrosion evident on No-Ox-Id CM-coated wire
Ability of denuded wire to self heal	9, stress-relieved	No-Ox-Id CM and CM high-temp; horizontal wire partially covered	Humid air, 100 to 480 hr; L. J. coastal; 95 days	Nuclear grade No-Ox-Id CM self-heals; high-temp. grade does not
Hydrogen Embrittlement Tests				
Susceptibility of notched wire to charged hydrogen	6, stress-relieved 0.005-in. notch root radius	Cathodically charged	Sustained load test stress at 75% F_{ntu}	All specimens survived over 200 hr without failure
Susceptibility of notched wire to Meta Bond treatment	2, stress-relieved 1, thermalized	Meta Bond treatments	Sustained load test stress at 75% F_{ntu}	All specimens survived over 200 hr without failure; wire not susceptible to hydrogen embrittlement
Radiolysis Tests				
Effect on wire of irradiated corrosion-inhibiting compounds	6, stress-relieved 0.005-in. notch	No-Ox-Id CM, grease, and paraffin	TRIGA irradiation $4(10)^8$ rads, $1.7(10)^{17}$ nvt (>1 MeV); stress at 75% F_{ntu}	All specimens survived exposure; no embrittlement
Effect on wire of irradiated protection for PSC tendons	6, thermalized 0.001-in. notch	Meta Bond-Rustarest-No-Ox-Id CM	TRIGA irradiation $4(10)^9$ rads, $1.3(10)^{17}$ nvt (>1 MeV)	All specimens survived exposure; no embrittlement

*75% F_{ntu} = specimen stressed at 75% of notched ultimate strength of wire.

CONTENTS

FIGURES

FIGURES (continued)

TABLES

1. INTRODUCTION

Prestressed concrete structures in the United States are generally stressed by either the posttensioning or pretensioning method; occasionally, a combination of both is used. In posttensioned structures, the tendons are grouted following the stressing operation; in pretensioned structures, the strands are embedded in the concrete. In both cases, the corrosion protection of the wires is obtained mechanically by the exclusion of corrosive environments and chemically by the high alkalinity of the portland cement. Szilard (Ref. 1) has recently completed a survey of the state of the art concerning the corrosion protection of grouted tendons.

Nongrouted tendons are designated for the prestressed concrete reactor vessel (PCRV) of the Fort St. Vrain Nuclear Generating Station. Corrosion protection must be achieved by a means permitting removal of the tendons for inspection and allowing for the possibility of either replacement or retensioning. Two approaches to the problem of corrosion protection are suggested: (1) the tendons, including the anchor hardware, can be encapsulated and maintained under either a static or dynamic inert-gas atmosphere; and (2) the tendons, including the anchor hardware, can be coated with a corrosion-inhibiting compound (CIC) and then capped to isolate them entirely from injurious environments.

Since the wires and the tendons will also need corrosion protection during shipments and storages on the way to installation, the use of a CIC throughout the entire procedure offers significant economies. The CIC may be applied when the tendon is fabricated and supplemented by a further application as the tendon is threaded into the duct. Unfortunately, little published information is available concerning the suitability and adequacy of CICs for this type of application, particularly where irradiation of the CIC is an important consideration.

The purpose of the present test program was to evaluate a few of the available CICs considered suitable for use on both the wires and tendons with the intention of developing a plan for the corrosion protection of the Fort St. Vrain prestressing system.

2. MATERIALS

2.1. WIRES

The wire purchased for the Fort St. Vrain PCRV was selected to conform with ASTM Specification A 421-65, Type BA. The Type BA wire is necessary where a cold-end deformation is used for anchoring purposes. Some tests for this program were conducted using U.S.-produced stress-relieved wire and some using the British-produced Thermalized* (low-relaxation) wire.

Thermalizing is a process whereby cold-drawn wire is subjected to the simultaneous action of heat and stress rather than simply to stress relieving. The application of a specific tensile load in conjunction with a low-temperature heat treatment produces a wire with a high proportional limit and low relaxation losses. The tensile properties of the stress-relieved wires and the Thermalized wires are given in Tables 2.1 and 2.2, respectively.

For the general exposure tests, both straight lengths of wire and buttonheaded lengths of wire were used. For the tests requiring a stressed wire, buttonheaded specimens were used. Samples of the two wire types, approximately 6.5 in. long, were buttonheaded on each end for gripping purposes. Each specimen was then notched circumferentially at the center of the length with a 60-deg V as shown in Fig. 2.1. To prevent burning of the steel, the notches were ground under flood-cooling.

It should be noted that for the first, stress-relieved set of wire specimens, the notch root radius was specified as 0.005/0004 in. max/min.;

*Trademark of Richard Johnson and Nephew Ltd.

TABLE 2.1

TENSILE PROPERTIES OF STRESS-RELIEVED TENDON WIRE

Spec. No.	Notch Radius (in.)	UTSN* (ksi)	UTS (ksi)	TYS† (ksi)	Elong. (% in 2 in.)
A	--	--	257.0	229.5	10
B	--	--	258.2	227.5	9
C	--	--	256.1	225.4	9.5
Avg.			257	228	9.5
1	0.004	353.5			
2	0.004	349.6			
3	0.004	350.6			
Avg.		351			

*UTSN = ultimate tensile strength of notched specimen.

†TYS = tensile yield strength, 0.2% offset.

Note: Notch Ratio = UTSN/UTS = 351/257 = 1.36.

TABLE 2.2

TENSILE PROPERTIES OF THERMALIZED TENDON WIRE

Spec. No.	Notch Radius (in.)	UTSN* (ksi)	UTS (ksi)	TYS† (ksi)	Elong. (% in 2 in.)
A	--	--	251.3	218.2	11
B	--	--	250.5	216.2	11
C	--	--	250.5	218.2	11
Avg.			251	218	11
1	0.001	299.0			
2	0.001	311.0			
3	0.001	315.0			
Avg.		308			
10	0.004	315.0			
11	0.005	326.0			
12	0.005	308.0			
Avg.		316			

*UTSN = ultimate tensile strength of notched specimen.

†TYS = tensile yield strength, 0.2% offset.

Note: Notch Ratio = UTSN/UTS = 316/251 = 1.26 (0.005-in.-notch root radius).

Notch Ratio = UTSN/UTS = 308/251 = 1.22 (0.001-in.-notch root radius).

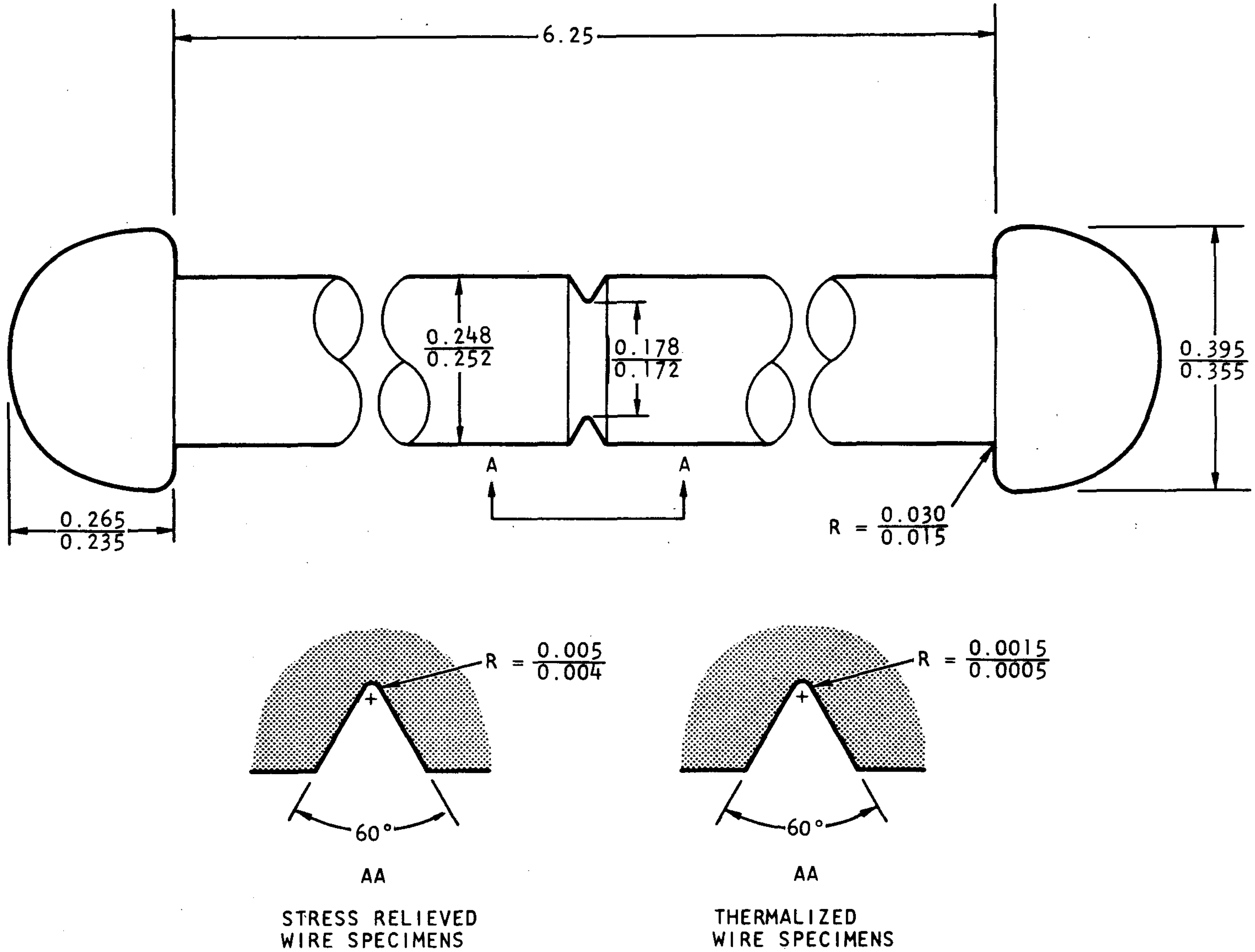


Fig. 2.1. Buttonheaded and notched tendon wire specimen

but to increase the notch acuity for the second, Thermalized wire set, the radius was specified as 0.0015/00005 in. max/min. This change was made to obtain a more stringent test because Johnson (Ref. 2) has suggested that in sustained-load hydrogen-embrittlement tests, good sensitivity to high degrees of embrittlement is obtained with specimens having notch root radii of 0.001, 0003, and 0.005 in., whereas for low degrees of embrittlement, the notch root radius should be 0.003 in. or smaller for maximum sensitivity.

2.2. COATINGS

The coating materials selected for evaluation are described in Table 2.3. Selection of these materials was influenced by three factors: the time available for conducting corrosion tests; previous experience with the materials; and their performance as a lubricant during a tendon posttensioning test.

The paraffin and Lubriplate were primarily selected for their lubricity. At the opposite extreme, pitch was selected for its water repellency and stability when exposed to irradiation. The No-Ox-Id compounds are materials with intermediate lubricity; of particular interest was the CM casing filler, which has been accepted for use on the tendons of the secondary containments of the Brookwood, Turkey Point, and Palisades nuclear generating stations.

In a friction test performed at Gulf General Atomic (GGA) (Ref. 3) using a seven-wire (0.250-in.-diameter) tendon, the pitch was eliminated as a candidate material when it solidified before the tendon could be threaded through the tendon tube. The friction factor obtained for the No-Ox-Id CM was essentially the same as that of the paraffin. As a result, paraffin, which does not contain corrosion inhibitors, was eliminated from the atmospheric exposure tests, but it was included as a coating on one of the irradiated specimens.

TABLE 2.3
COATING MATERIALS EVALUATED AS CORROSION PROTECTION FOR TENDON WIRE

Name and Type of Material	Manufacturer	Description
1. Paraffin wax, commercial grade, white	Unknown	A wax, softening point at 140 F
2. Lubriplate, Type A, Multilube Grease	Standard Oil of Calif. San Francisco, Calif.	A soft grease used to lubricate automobiles
3. Pitch, waterproof roofing, Type A	Koppers Co., Inc. Pittsburgh, Penn.	A coal-tar pitch, softening point at 140 F
4. Kephos No. 253	Amchem Products, Inc. Ambler, Penn.	A nonaqueous liquid chemical used to produce a phosphate coating on steel
5. Meta Bond 39 and Rustarest 452	International Rustproof Co. Cleveland, Ohio	An aqueous solution used to produce a phosphate coating on steel. Rustarest 452 is a water emulsifiable oil used to seal the Meta Bond phosphate coating.
6. No-Ox-Id CM, nuclear grade	Dearborn Chemical Co. Chicago, Ill.	A casing filler consisting of a petroleum base, microcrystalline wax, and surface active agents
7. No-Ox-Id CM, high-temp grade	Dearborn Chemical Co. Chicago, Ill.	A casing filler specially modified to have a softening point near 110 F
8. No-Ox-Id 500	Dearborn Chemical Co. Chicago, Ill.	A solvent-cutback, dry wax to short-term indoor storage of steel parts
9. No-Ox-Id 490	Dearborn Chemical Co. Chicago, Ill.	A solvent-cutback, light grease containing a fingerprint suppressor, suitable for short-term shop-handling of steel parts
10. No-Ox-Id 2W	Dearborn Chemical Co. Chicago, Ill.	A solvent-cutback, dry wax, heavier than "500," suitable for long-term indoor storage
11. No-Ox-Id A Special	Dearborn Chemical Co. Chicago, Ill.	A grease type suitable for long-term indoor storage of steel parts

2.2.1. Kephos Phosphate

The two phosphate treatments (items 4 and 5 of Table 2.3) were selected primarily to provide protection for the wire during shipment and storage prior to tendon fabrication. This added measure of corrosion protection will last throughout the service life of the tendon.

Kephos is a nonaqueous solution used to produce a corrosion-resistant phosphate coating on steels. The manufacturer states that the coating will protect steel products against fingerprints and rust during a temporary indoor storage of about 6 months. This treatment is specified for the Thermalized wire being manufactured for the Dungeness prestressed concrete reactor vessel. The coating is applied by spraying the solution on the wire after the thermal treatment, but before coiling; as-coiled, the wire is dry to the touch. Samples of wire having this Kephos coating were included in the GGA general corrosion test program.

2.2.2. Meta Bond Phosphate

The Meta Bond 39 treatment forms a calcium-zinc phosphate coating on steel parts to act as a base for paint or provide a corrosion-inhibiting film. The manufacturer says that the treatment produces an extremely fine microcrystalline coating by either the spray or immersion method. The bath is prepared by mixing two liquids, Meta Bond 39 and Additive 164; the Additive 164 is a proprietary solution. Accelerators such as sodium nitrate are not used in the phosphating bath.

Shreir (Ref. 4) indicates that conventional phosphate coating processes are based on dilute phosphoric acid solutions of iron, manganese, and zinc primary phosphates either separately or in combination. The free phosphoric acid present reacts with the steel, producing soluble ferrous phosphate and hydrogen. Local depletion of the phosphoric acid leads to the formation of insoluble tertiary phosphates such as zinc phosphate on the surface of the steel.

The phosphate coatings tend to be porous and hence provide minimal corrosion protection unless sealed by either a paint or another CIC. For this reason, the zinc phosphate film produced on the steel wire for the tendons was sealed with Rustarest 452, a water-emulsifiable rust preventive, which dries without leaving an oily or greasy film.

In addition to the Meta Bond, a lead phosphate coating, Auto Bond, was evaluated on the basis of the exposure test.

2.2.3. No-Ox-Id CM

According to the Dearborn Chemical Company, CM casing filler was conceived in 1946 and first marketed in 1947 for use in the annulus of cased underground pipes to prevent corrosion. For this application, it has reportedly functioned satisfactorily and has been widely accepted.

No-Ox-Id CM contains a paraffin-base refined mineral oil, a microcrystalline petroleum-derived wax (petrolatum), and the additives lanolin and sodium petroleum sulphonate. The oil and wax are long chain molecules which are resistant to oxidation and physical degradation within the normal range of service temperatures. The lanolin is a polar substance that ensures wetting of the steel surface by No-Ox-Id CM. The sulphonate is a surface-type corrosion inhibitor.

In 1966, the Bechtel Corporation obtained an analysis of No-Ox-Id CM which indicated the following impurities:

Water-soluble chlorides (Cl^-)............ $<0.001\%$ by weight
Water-soluble nitrates (NO_3^-)............ $<0.002\%$ by weight
Water-soluble sulfides ($S^=$).............. $<0.001\%$ by weight
Phenolic bodies (as phenol).............. $<0.001\%$ by weight

No solvents were found. Further details relating to the physical properties of No-Ox-Id CM are given in Appendix A.

3. COASTAL EXPOSURE

Samples of the wires coated by various corrosion-inhibiting treatments were exposed to a coastal environment at a site located 4000 ft from, and 400 ft above, the ocean in La Jolla, California. A rack holding the samples inclined at 30 deg was positioned to face south; it was partially protected against falling but not against wind-driven rain. The samples, spaced about 1/2 in. apart, were supported on Teflon knife-edges.

The samples were exposed to numerous fogs, occasional rains, and continuous mild salt mists. The chloride content of the air as measured at GGA was 11 micrograms/cubic meter. Monahan (Ref. 5) reported in his thesis that the air near the ocean contained chlorides ranging from 1 to 300 micrograms/cubic meter of air; at "cloud level," the chloride content was 1 to 30 micrograms/cubic meter of air. Although the chloride content of the air at the exposure site was not measured, it seems reasonable to assume that it averaged between 11 and 300 micrograms/cubic meter of air.

Air temperatures, as measured on a shaded high-low thermometer, ranged from 35 to 96 F during the 2-yr test program.

4. TEST PROCEDURES

Basically, the test program consisted of exposing wire samples with and without coatings of CICs to a coastal environment. In addition, samples were used to determine the susceptibility of the wire to hydrogen embrittlement and stress-corrosion cracking. Still other coated samples were exposed in a TRIGA reactor to determine the effects of the products of irradiated CIC on the wire.

4.1. GENERAL CORROSION TESTS

The corrosion protection needed for the wire and tendons falls into two time categories: (1) the preinstallation period, including shipment of the wire, tendon fabrication, and shipment and storage; and (2) the installation period, including final protection. Although the first period will be relatively short, during this time the wire and tendons may be exposed to more corrosive environments than the tendon will experience during the projected life of the Fort St. Vrain PCRV. Preinstallation protection is especially important now that the wire will be shipped overseas from the wire manufacturer's plant in England.

The GGA specification requires that the wires be rust-free when made up as a tendon and that the tendon be installed in a rust-free condition. For these reasons, the corrosion-protection system must be introduced at the point of wire manufacture and must remain effective throughout the life of the vessel.

The purpose of this phase of the test program was to evaluate the effectiveness of corrosion-protection systems on the basis of exposures to a coastal environment.

4.1.1. Bare Stress-Relieved Wire

As a prelude to investigating various types of protective coatings, the effect of corrosion on the tensile properties of the wire was determined. Twelve samples were selected from stock coils of 0.250-in. stress-relieved wire and were upset at both ends to produce the 1.5FS buttonhead developed by Western Concrete Structures, Inc. (WCS).

Three of the samples were tested to determine the tensile properties of the wire. The remaining nine wires were exposed to the coastal environment, three for 60 days, three for 180 days, and three for 365 days. In Table 4.1 the tensile properties of the as-received wires are compared with those of the exposed wires. The results indicate that an insignificant change occurred as a result of the first two exposures. After 365 days, a small (6%) loss in yield and ultimate strengths was observed, but the elongation remained about the same.

Figure 4.1 shows the condition of the wire as-received and following the 60- and 180-day exposures. After 60 days, the wire was covered by a light haze of rust which could be easily removed by wiping with a soft cloth; after 180 days, the wire was rusted but did not exhibit scaling. Figure 4.2 shows the condition of the wire after 365 days. It was covered by scaling rust, but was not pitted.

4.1.2. Meta Bond and Auto Bond Phosphate Coatings*

Phosphate coatings have been used to protect steels, but the protection afforded has been minimal and suitable only for relatively short (6-month), noncoastal exposures. However, a lead phosphate coating, Auto Bond, developed by the International Rustproof Company (IRCO), appeared particularly attractive. It was felt that any metallic lead would be

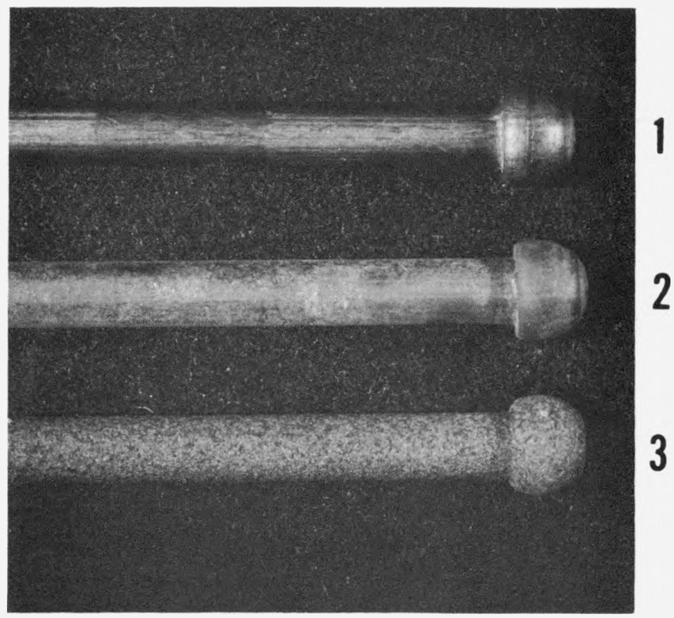
*During the original screening of candidate coatings, metallic coatings such as galvanizing were in general ruled out. It was feared that galvanic activity at defects in the coating could produce hydrogen that could in turn cause embrittlement of the highly stressed wire. Later, it was found that the wire was not prone to hydrogen-embrittlement failure.

TABLE 4.1

TENSILE PROPERTIES OF STRESS-RELIEVED TENDON WIRE EXPOSED TO COASTAL ENVIRONMENT

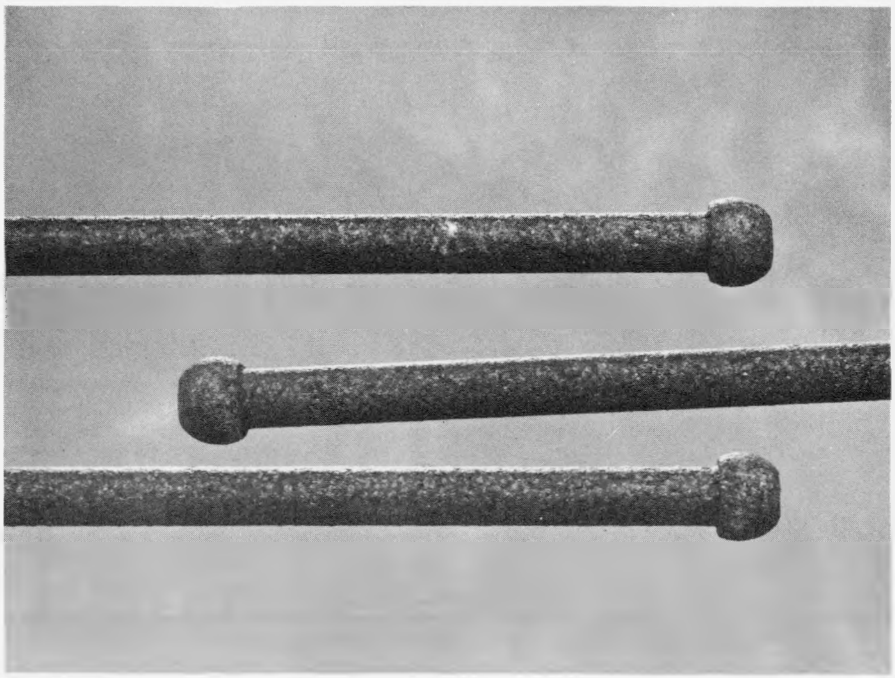
Condition		UTS (ksi)	TYS (ksi)	E (% in 2 in.)
As-received, no exposure		257.0	229.5	--
		258.2	227.5	--
		256.1	225.4	--
	Avg.	257	227	9(est.)
After 30 days		254.5	222.2	10
		253.3	222.2	9
		253.3	222.2	11
	Avg.	253	222	10
After 180 days		251.7	222.2	9.5
		254.1	222.2	9.0
		251.3	220.2	o.g.*
	Avg.	252	222	9
After 365 days		242.3	213.6	10
		240.5	211.9	10
		244.6	217.2	9
	Avg.	242	214	10

*o.g. = fracture outside gage marks.



M21424-1

Fig. 4.1. Bare stress-relieved wire after coastal exposure: (1) as-received, (2) after 60 days, (3) after 180 days



HT61428

Fig. 4.2. Bare stress-relieved wire exposed to coastal environment for 365 days

less damaging to the wire than residual zinc. Nevertheless, IRCO's zinc phosphate Meta Bond was evaluated for comparison.

Samples of tendon wire were sent to IRCO to be treated with Auto Bond, the lead phosphate coating, or with Meta Bond, the zinc phosphate coating. The treated samples were then exposed to the coastal environment. As shown in Fig. 4.3, both treatments provided satisfactory corrosion protection during a short (14-day) exposure. After 132 days, however, the Auto Bond coated specimen was badly rusted; the Meta Bond coated wire was free of rust except on the outer curvature of a slight kink put in the wire prior to exposure.

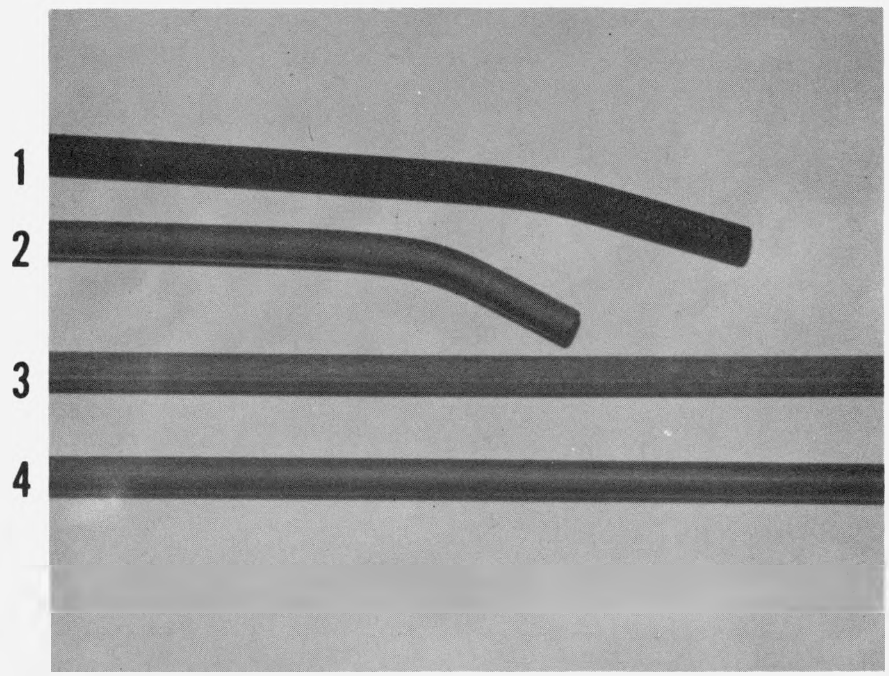
In further discussions with IRCO, it was learned that their coatings are routinely overcoated with Rustarest 452, a water-emulsifiable compound used to seal the pores of the phosphate and to inhibit corrosion. Subsequent tests (see Section 4.1.4) revealed that this overcoating was needed to obtain optimum protection for the wire.

Based on these results, the Meta Bond coating was selected for use in further tests and production trials (described in subsequent sections of this report). Auto Bond was not included in subsequent evaluations.

4.1.3. Kephos Phosphate Coating

Based on an evaluation by Armson and co-workers (Ref. 6), Kephos was selected as the corrosion-protection coating for the wire used in the Dungeness PCRV. Kephos is applied by the wire manufacturer primarily to protect the wire during shipment to and a brief storage at the tendon fabricator's plant. Immediately upon completion of a tendon, it receives further protection in the form of a coating of grease.

Samples of Thermalized wire, both bare and production-coated with Kephos, were obtained from the wire manufacturer. These wires were stood vertically in a container, so that the lower portion of wire in the container was partially protected, and exposed to the coastal environment.



Z0233

Fig. 4.3. Phosphate-coated wires exposed to coastal environment: (1) Auto Bond plus Rustarest, exposed 132 days;(2) Meta Bond plus Rustarest, exposed 132 days;(3) Auto Bond only, exposed 14 days;(4) Auto Bond plus Rustarest,exposed 14 days

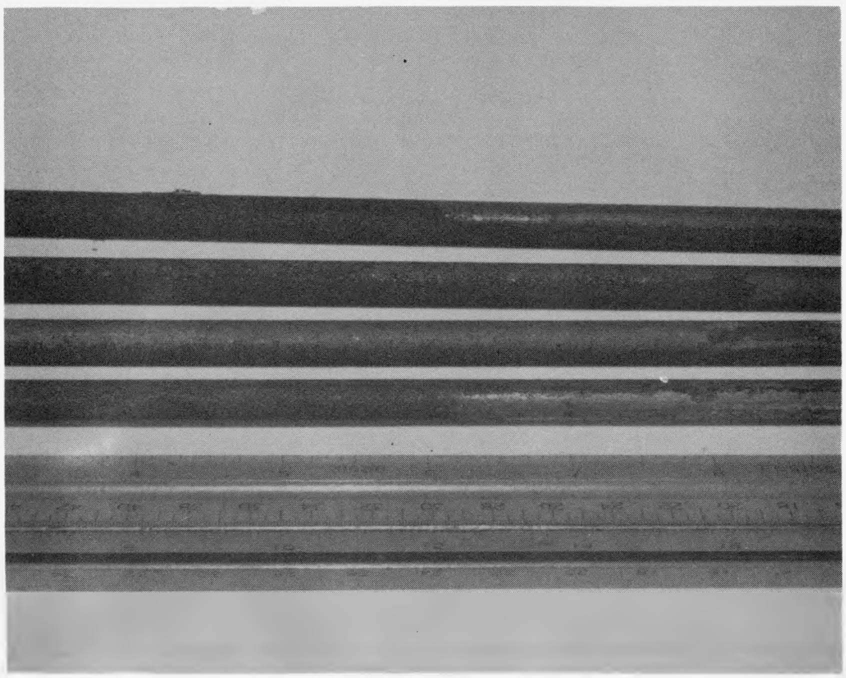
The condition of the samples following a short (30-day) exposure is shown in Fig. 4.4. There is little apparent difference between the bare and coated samples in either the fully exposed or partially exposed areas of the wire; both samples were badly rusted.

4.1.4. Meta Bond-Kephos Comparisons

Another set of Kephos-coated samples was obtained for comparison with Meta Bond coated wires following an exposure to the coastal environment. Kephos-coated and bare-wire samples were taken from production coils. In addition, one sample of bare wire was Kephos-coated in the GGA laboratory according to the manufacturer's application procedure. Another of the bare wires was lightly rubbed with steel wool and wiped with an alcohol soak cloth to remove traces of oxide and handling contamination; one of the Kephos-coated production wires was also wiped with alcohol. The Meta Bond coating was applied in the IRCO laboratory, one wire being overcoated with Rustarest.

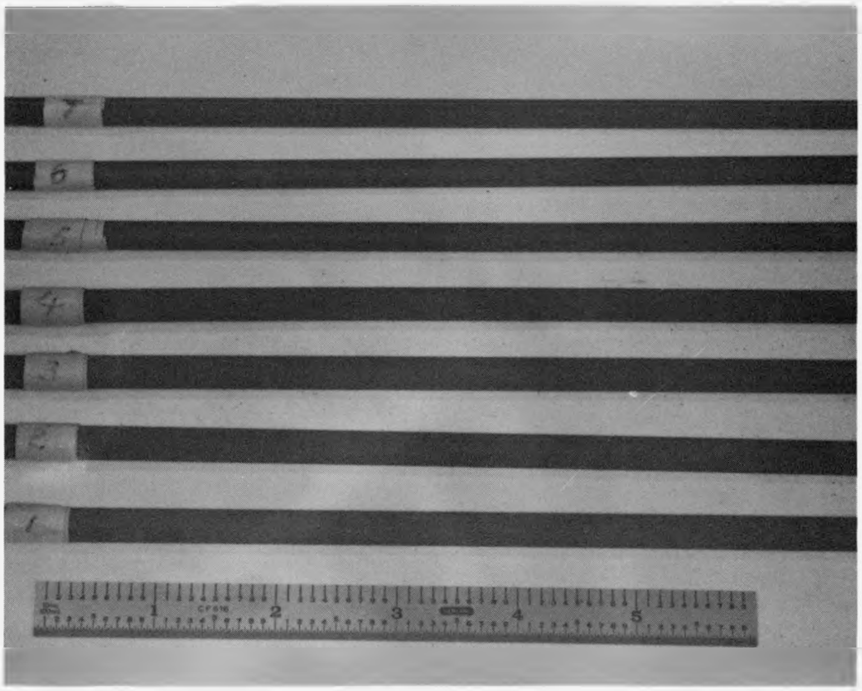
The results of the 95-day exposure test are shown in Fig. 4.5. The two bare-wire samples were included as controls to demonstrate the severity of the environment. The Kephos-coated wires, including the one prepared at GGA, were comparably rusted, indicating that little if any protection was afforded by the coating. The Meta Bond coated sample without Rustarest exhibited a light haze of rust, whereas the sample overcoated with Rustarest was essentially free of rust.

The importance of the Rustarest in protecting the wire was further demonstrated by comparison tests performed by Richard Johnson and Nephew Ltd., using their fog chamber. The test details and results are contained in two reports included here as Appendixes B and C. From this work, it was concluded that the Rustarest was the principal factor contributing to the corrosion protection of the wire. In addition, the tests indicated that further experimentation on the Meta Bond procedures would be necessary to obtain a suitable thickness of coating on the wire produced for the



Z0234

Fig. 4.4. Thermalized wire exposed to coastal environment for 30 days. Top two samples were bare, uncoated wire; bottom two were Kephos-coated. Right half of each pair was partially protected; left half was fully exposed.



HT62997-C

Fig. 4.5. Comparison of Kephos and Meta Bond coated wires following 95-day exposure to coastal environment: (1) uncoated, bare; (2) uncoated, precleaned; (3) production Kephos; (4) production Kephos, precleaned; (5) Meta Bond; (6) Meta Bond plus Rustarest; (7) GGA-applied Kephos.

Fort St. Vrain PCRV. A minimum required coating thickness of 200 mg/sq ft was achieved through changes in the bath concentration and the application time.

4.1.5. Meta Bond on Production Wire

Twelve samples representing each coil of the first production run of Thermalized wire coated using Meta Bond plus Rustarest were exposed to the coastal environment for 6 months. At the end of this period, all the samples exhibited some degree of rusting, none of which had reached the point of scaling. The samples were exposed standing in a jar which covered about one-half the sample length. That portion in the jar was considerably less rusted than the protruding portion (see Fig. 4.6).

4.1.6. Protection for Overseas Shipment

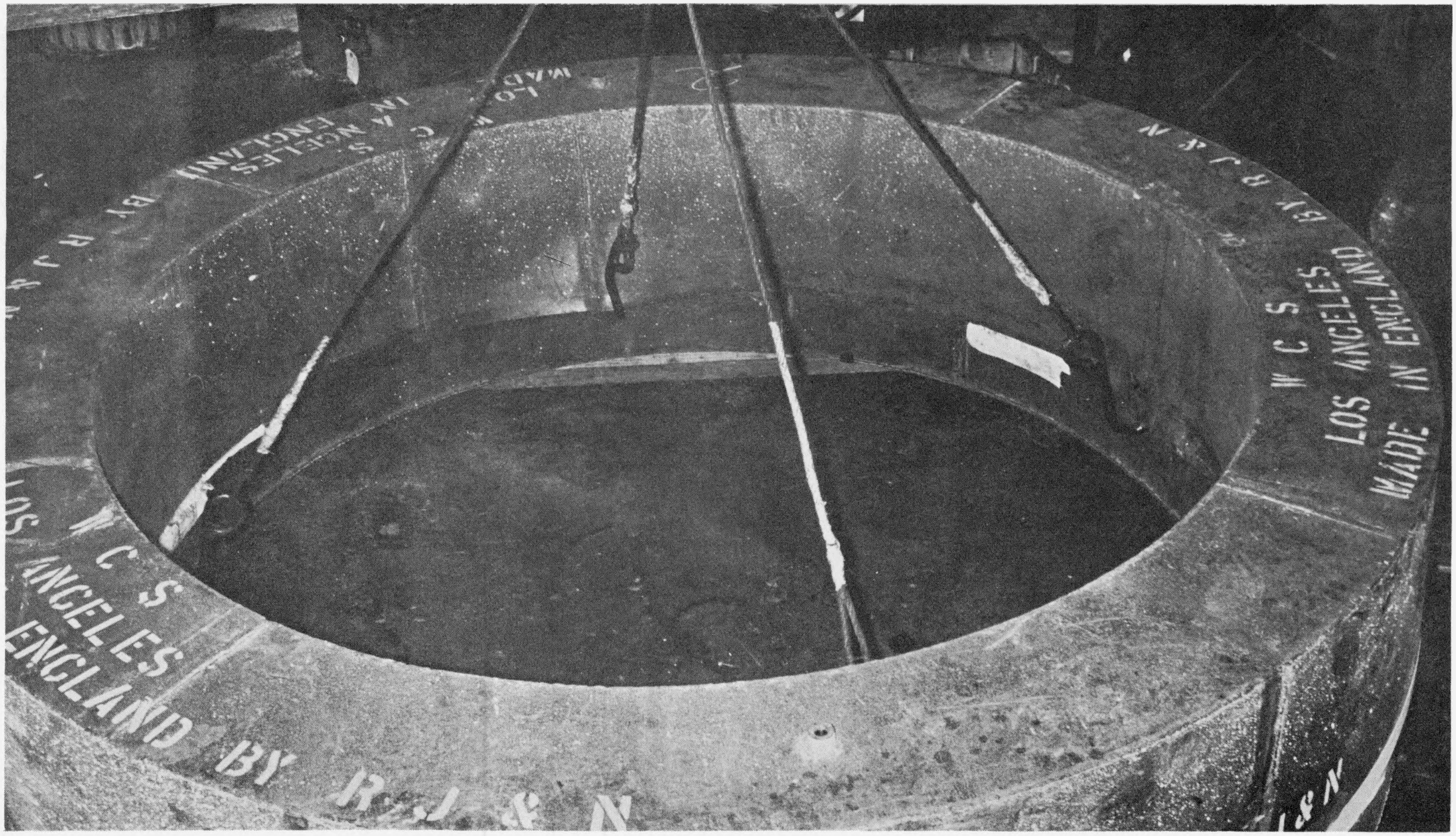
As part of the corrosion-protection investigation, sample coils of wire were shipped from the manufacturer's works in England to the tendon fabricator's plant in Los Angeles. Eleven 1000-lb coils in various wrappings were packed in three steel, donut-shaped containers having telescoping lids (Fig. 4.7). The top and bottom of the 6-ft-ID by 7-ft-OD container were fabricated from 1/4-in. steel plate with 18-gage sheet-steel skirts overlapped approximately 12 in. The joint was sealed with 4-in. cotton adhesive tape.

Wires were shipped in two conditions: uncoated (bright) and Kephos-coated. (The Kephos coating was used in lieu of the Meta Bond treatment because wires coated with Meta Bond were not available at the wire manufacturer's works.) The coils were either banded but unwrapped or banded and spirally wrapped in one of the following:

1. Hessian-backed (HB), vapor-phase-inhibited (VPI) paper
2. Same as item 1, overwrapped with an HB kraft paper
3. Same as item 2, overwrapped with cotton adhesive tape

HT72666

Fig. 4.6. Samples of production Meta Bond coated wire after 6-month exposure to coastal environment: (1) and (2) fully exposed; (3) partially exposed



135-95-11

Fig. 4.7. Overseas shipping container for coils of tendon wire as-received in Los Angeles. Cotton adhesive tape on joint between top and bottom of container has been removed.

The spiral wraps overlapped approximately one-half the width of the tape.

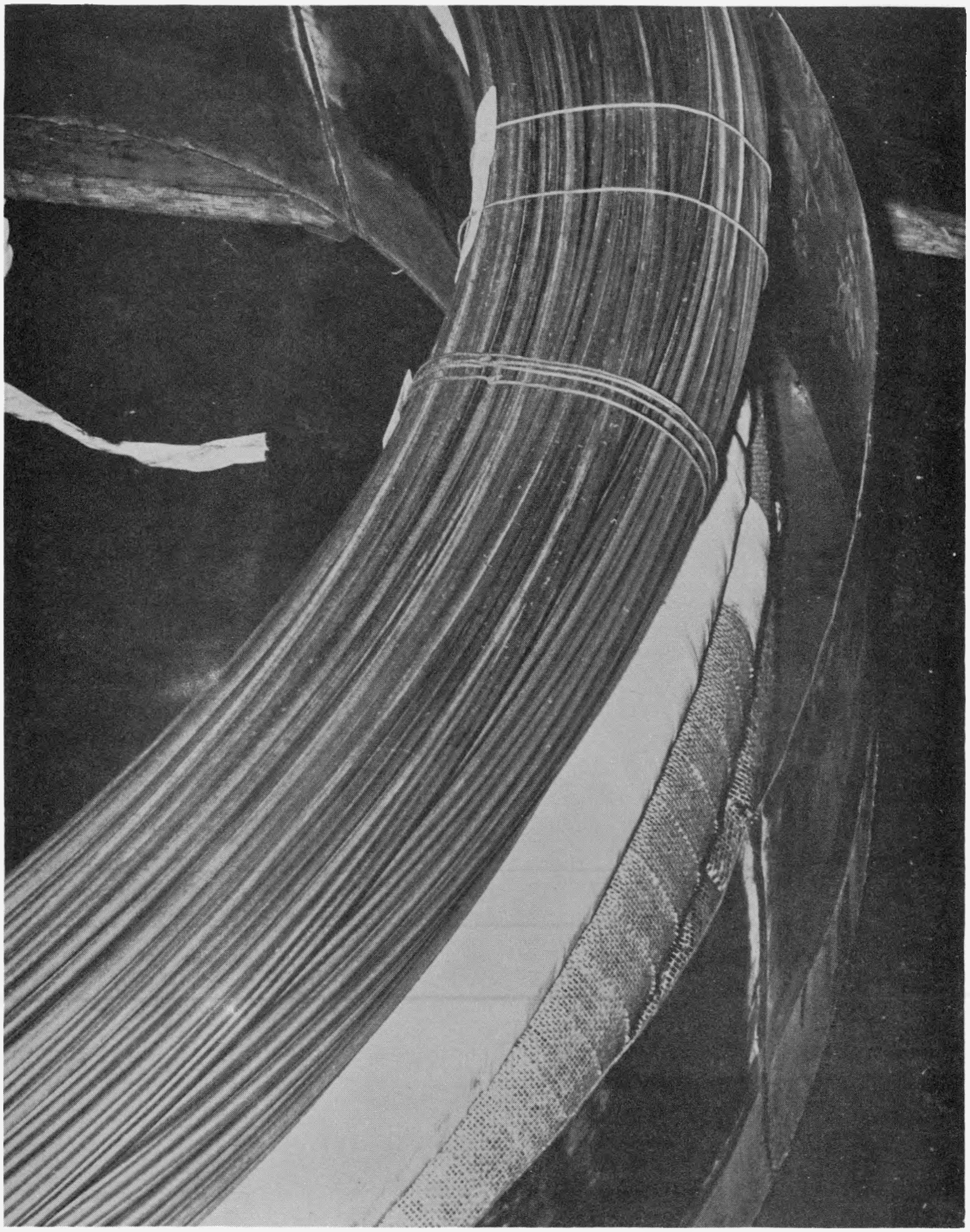
The containers arrived at the tendon fabricator's plant in good condition; they were dented but not punctured. Although rusted, the containers showed no signs of having been exposed to water or sea spray. The cotton-adhesive-tape seal on the telescoping joint was ineffective; it is believed that as the coils shifted and settled, the adjacent cargo compressed the container, causing the tape to roll under the container skirt.

The coils and coil wrappings were in excellent condition (see Fig. 4.8). A light haze of rust was evident on the uncoated, unwrapped coil and on a few loops of the uncoated coil wrapped only with the VPI paper (item 1 above). None of the other coils was visibly rusted. It was therefore concluded that the two slightly rusted coils were probably packed in that condition.

The general appearance of the coated wire and wrappings is shown in Fig. 4.9.

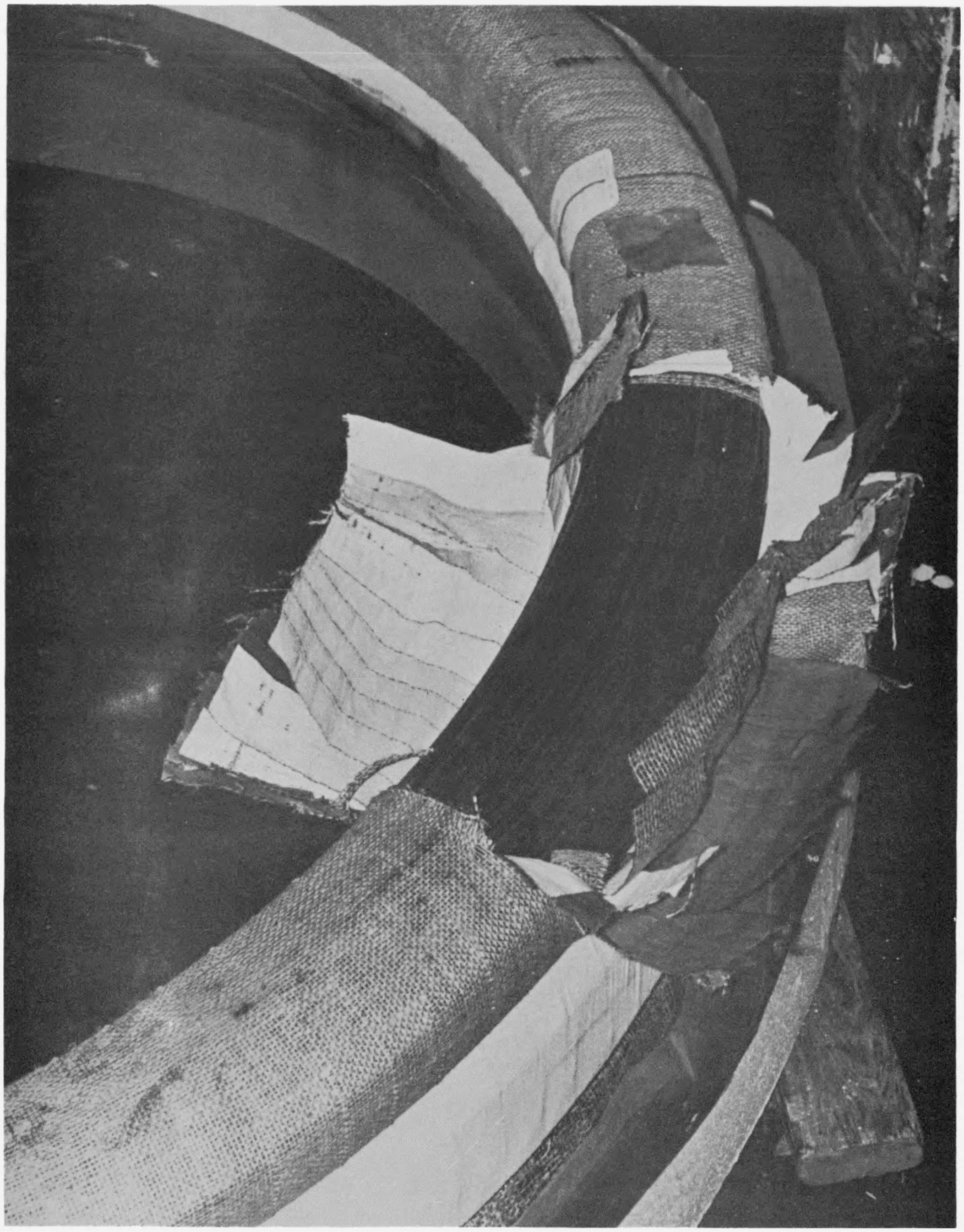
4.1.7. No-Ox-Id CM

Based on its successful use on pipes in underground casings and its acceptance for use on tendons of secondary containments for reactor vessels, No-Ox-Id CM was tested as a candidate protectant for the Fort St. Vrain PCRV tendons. For an exposure to the coastal environment, three samples of wire were coated, one with No-Ox-Id 500, one with No-Ox-Id CM, and a third with 500 overcoated with CM. In addition, four 25-wire tendons and two 168-wire tendons, one straight and one curved, were coated with No-Ox-Id CM and exposed in the GGA test bed for full-sized tendons as a part of the stress-relaxation test program (Ref. 7).



Z0229

Fig. 4.8. Coils of wire in overseas shipping container. The bare-wire coil exhibited a light haze of rust. The other coils shown were wrapped with (from top to bottom): (1) HB-VPI paper plus HB kraft paper plus cotton adhesive tape, (2) HB-VPI paper plus HB kraft paper, and (3) HB-VPI paper only



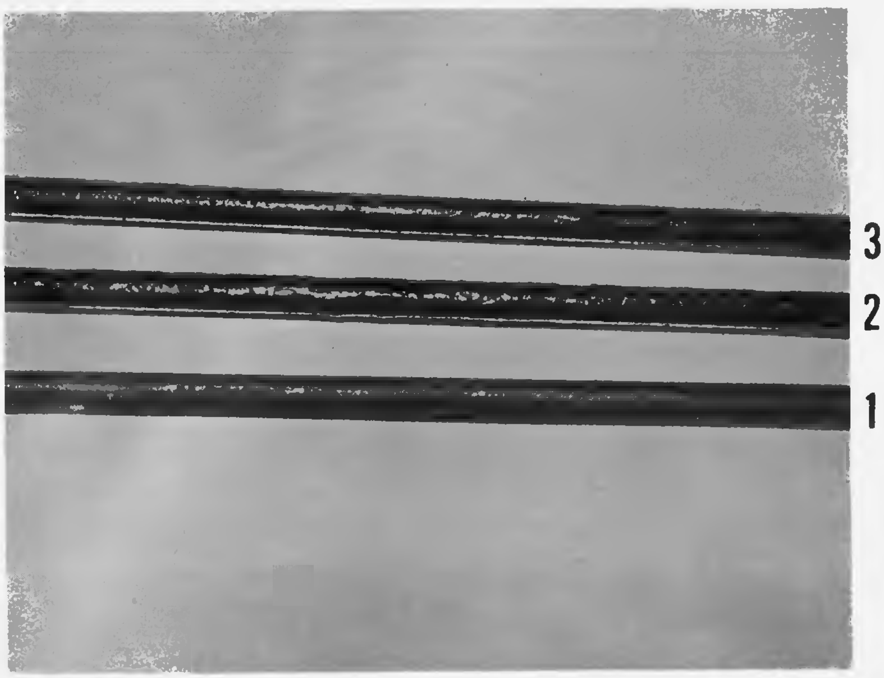
Z0230

Fig. 4.9. Coil wrappings. The cut wrappings on this coil show the HB-VPI layer (white) overwrapped with HB kraft paper and the degree of overlap. The Kephos-coated wire was in excellent condition.

The condition of the wire samples after 18 months of coastal exposure is shown in Fig. 4.10. The No-Ox-Id 500 coated sample exhibited some rust, but none was apparent on the other two wires. The heavier coatings had collected considerable air-borne dirt. Runoff was not caused by solar heat, nor was the wire denuded by the occasional rains. After 2 yr of exposure, the coating on half the specimens was stripped using a solvent. Again, the No-Ox-Id 500 coated sample revealed a film of adherent rust, while the other two sets of wires coated with No-Ox-Id CM had been completely protected (see Fig. 4.11).

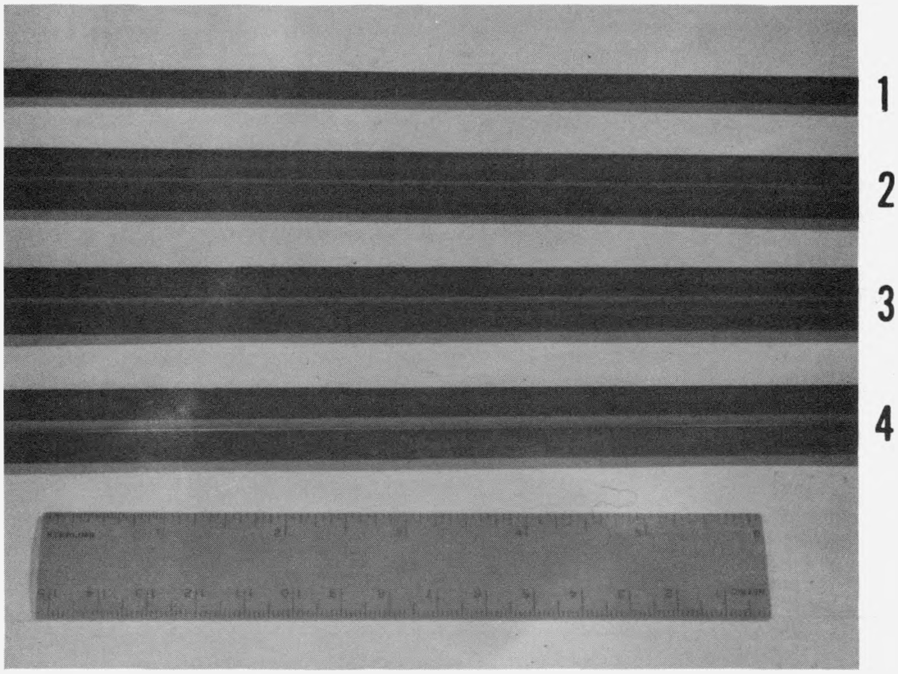
Northup and co-workers (Ref. 7) have described the testing of some large tendons under simulated service conditions. Although the 25-wire tendons are still undergoing stress-relaxation tests and hence cannot be examined for corrosion, the curved 168-wire tendon was detensioned and examined after 1 yr of testing. At openings in the tendon tube, the wire was examined and found free of corrosion. When the anchor caps were removed, it was discovered that the buttonheads at one end had not been coated with No-Ox-Id and that some were heavily rusted (see Fig. 4.12). At the opposite end, where the coating was continuous, there was no evidence of rust on the buttonheads or the anchor assembly. Later, when the tendon had been detensioned and the split-shims had been removed, droplets of rusty water and rust spots were observed on many of the wires immediately behind the stressing washer (see Fig. 4.13). It was evident that the wires had not been thoroughly recoated with No-Ox-Id CM after buttonheading and before prestressing.

From these observations it was concluded that moisture from humid air trapped in the totally enclosed tendon had condensed on the wires and buttonheads and that severe corrosion had been prevented only by the phosphate coating. All other parts of the tendon and anchor assemblies were well protected by the No-Ox-Id CM coating.



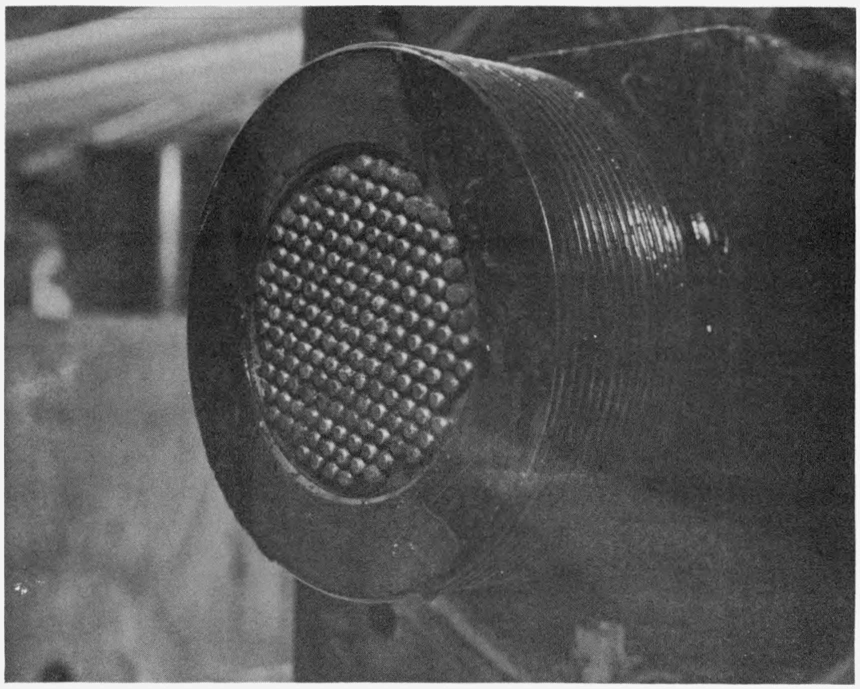
Z0232

Fig. 4.10. Coated tendon wires after 18-month coastal exposure. Wire coated with No-Ox-Id 500 (1) exhibited some rust; wires coated with No-Ox-Id 500 plus CM (2) and with CM alone (3) were not visibly rusted.



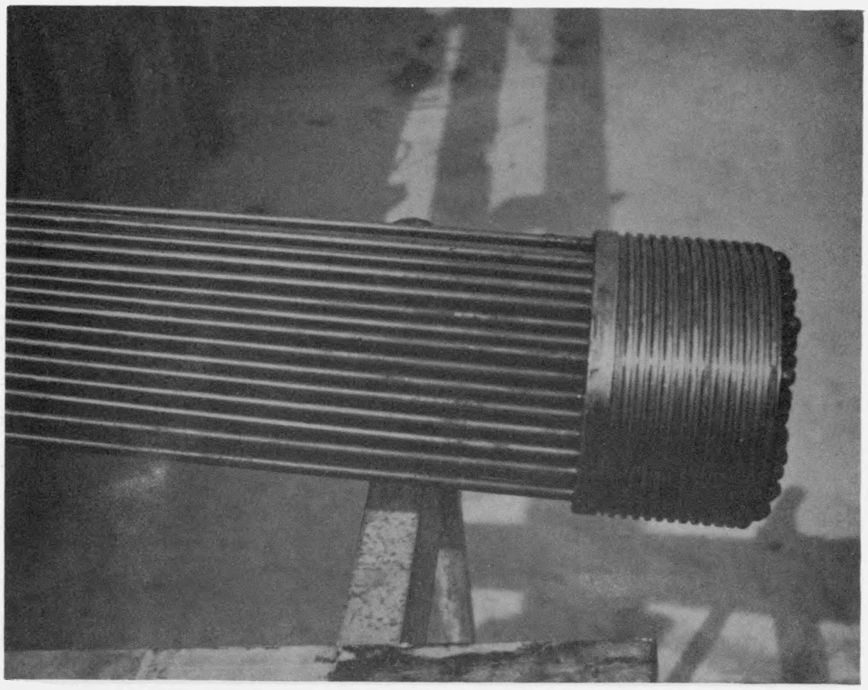
G72129-C

Fig. 4.11. Coated tendon wires after 2-yr exposure. Right half of each specimen was cleaned with a solvent. Uncoated sample (1) exhibited scaling rust; sample coated with No-Ox-Id 500 (2) was rusted; and samples coated with No-Ox-Id 500 plus CM (3) and with CM only (4) were free of rust.



HT72025-C

Fig. 4.12. Rusted buttonheads on test-bed tendon. These buttonheads had not been coated with No-Ox-Id CM.



HT72927-C

Fig. 4.13. Rust spots on wires of test-bed tendons

4.2. RUNOFF AND CORROSION TEST

Since the candidate organic CICs are semifluids and gels, it is likely that at slightly elevated temperatures they may creep and flow, leaving denuded wire exposed to corrosive environments. The consequences of such an occurrence were investigated in a test program wherein samples of wire coated with the No-Ox-Id compounds were held to selected temperatures and subsequently exposed to the coastal environment.

4.2.1. Test Details

Three specimens consisting of five wire samples were each dip-coated with a different candidate CIC, which covered approximately 10 in. of the 15-in. sample length. The No-Ox-Id compounds listed in Table 2.3 were applied individually to the wire samples. The wires were then clamped in a phenolic block and suspended vertically, one specimen at room temperature and the other two at 120 F and 160 F.

After 100 hr at 120 F, one specimen was exposed to the coastal environment for 60 days in a horizontal position. As a further test of the corrosion protection offered by the compounds, a strip approximately 1/16 in. wide along the top surface of each sample was scraped clean.

The other two specimens were allowed to hang at room temperature and 160 F for 1500 and 1000 hr, respectively, before being exposed to the coastal environment. These specimens were exposed in a vertical position for 95 days but were not scraped to expose a strip of bare wire on each sample.

4.2.2. Test Results

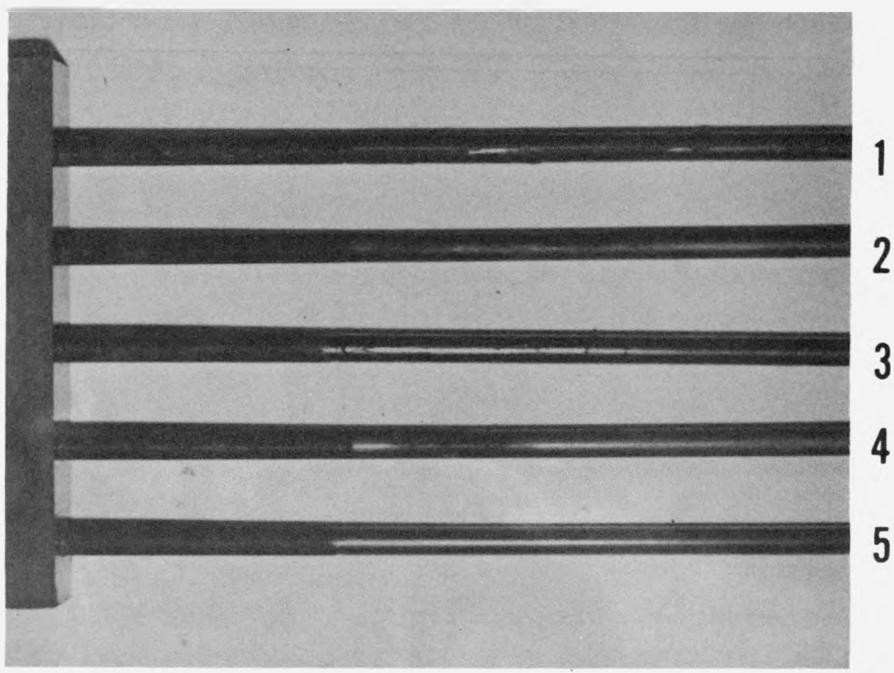
Although the principal interest was in the protection provided by the No-Ox-Id CM, the A Special, 2W, 490, and 500 were available and tested simply for a comparison. After the initial exposure at temperature, all the samples of each specimen exhibited a film of the compound with which it had been coated. At 160 F, the CM and 500 were thinned considerably; at 120 F and room temperature, there was relatively little observable change in the compound thickness.

After the 60-day exposure to the coastal environment, the appearance of the 120 F specimen was as shown in Fig. 4.14. The specimens coated with the 500 wax or the 490 grease exhibited a light haze of rust; the specimen coated with 2W, a tar-like material, was rusted along the scraped surface; the CM and A Special effectively healed the exposed surface, and no rust was evident. The severity of the exposure is evident from the condition of the uncoated portion of the wire samples.

After the 95-day exposure of the two other test specimens, the condition of the samples was as shown in Fig. 4.15. The corrosion on the bare portion of the wire again illustrates the relatively severe nature of the environment during the exposure period.

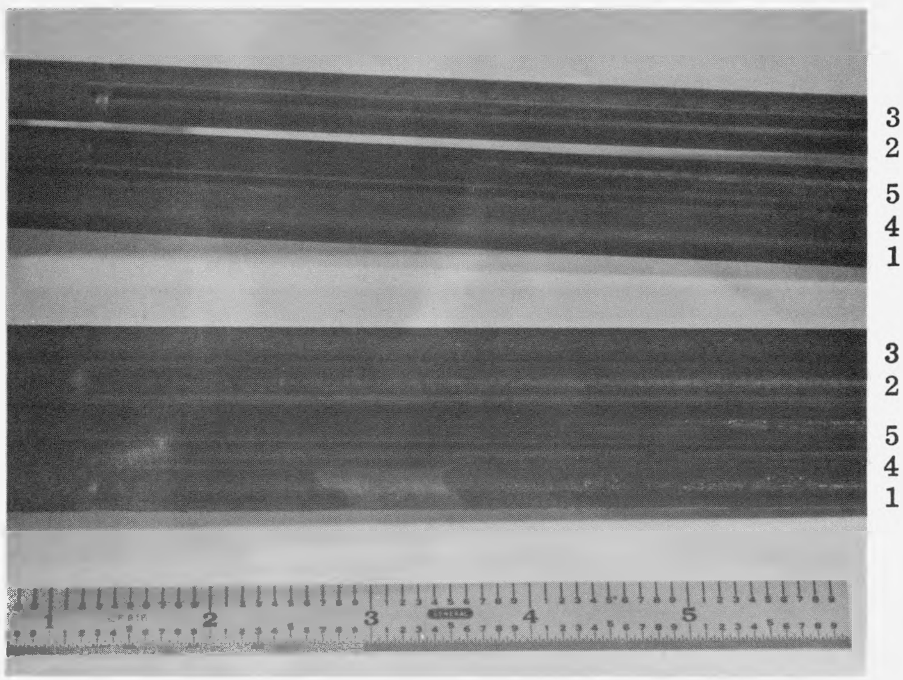
The specimen receiving the prior room-temperature exposure revealed that the sample coated with the 490 compound (primarily an indoor protective) was uniformly rusted; the 500 compound afforded some protection, while the other three compounds, the 2W, A Special, and CM, provided complete protection. It should be noted, however, that at one point on the specimen coated with CM, the compound had been inadvertently removed. In this area, the wire exhibited a very light film of rust.

The specimen receiving the prior exposure at 160 F exhibited somewhat less severe corrosion on the bare portions of the wire than its comparison specimen (discussed above). This protection was undoubtedly the result of some vaporization at 160 F and condensation of the compounds on the bare wire. As expected, the 490 compound was not protective. The A Special had apparently run off, leaving the specimen unprotected, whereas the 500 and 2W remained fully protective. The CM had also run off the specimen, thereby reducing its effectiveness as a coating. Even though the wire was rusted, this waxy-appearing film was adhering tightly to the wire (see Fig. 4.15).



Z0231

Fig. 4.14. Samples of No-Ox-Id coatings heated at 120 F for 100 hr and exposed to coastal environment for 60 days: (1) 2W, (2) 500, (3) CM, (4) 490, (5) A Special. Note condition of uncoated portions of wires at left side of photograph.



HT62998-C

Fig. 4.15. Runoff specimens having prior exposure at room temperature (bottom set) and 160 F (top set) as they appeared following 95-day exposure to coastal environment: (1) CM, (2) 500, (3) 490, (4) A Special, and (5) 2W. Note condition of bare wire at left side of photograph.

These tests have shown that even under extremes of temperature (160 F) and exposure (coastal environment), the No-Ox-Id CM has provided effective protection for the wire. Under normal operating conditions, where the temperature does not exceed 120 F and the environment is static dry air, the tendons for the Fort St. Vrain PCRV receive more than adequate protection from the specified No-Ox-Id CM coating.

4.3. SELF-HEALING AND CORROSION TEST

One of the potential problems arising from handling the tendons is that the wire may be denuded of corrosion protection. This condition may occur at any time during shipping and storing and is certain to occur on some peripheral wires when the tendon is put into the tendon tube.

Precautions are being taken to minimize such damage by requiring that the tendon tube be coated with No-Ox-Id CM before the tendon is installed and that the tendon be recoated as it is drawn into the tube. Nevertheless, it was considered important to examine the self-healing characteristics of the No-Ox-Id CM. The questions to be answered were: (1) whether the compound would flow sufficiently to heal locally denuded areas on the wire, and (2) whether the healed areas would be protected against corrosion.

4.3.1. Test Details

The experimental approach was to place samples of clean wire in a shallow pool of compound and then expose them to corrosive environments. Wire samples approximately 1-1/4 in. long were laid in a pool of the compound, the depth of the pool being approximately one-third the diameter of the wire. Before samples were put in the pool, they were thoroughly cleaned and degreased with acetone.

The dishes containing the samples were heated at 130 and 150 F over a container of hot water for up to 480 hr. During this time, the water vapors were in contact with the wire. After this exposure, some of the samples were exposed to the coastal environment for 95 days.

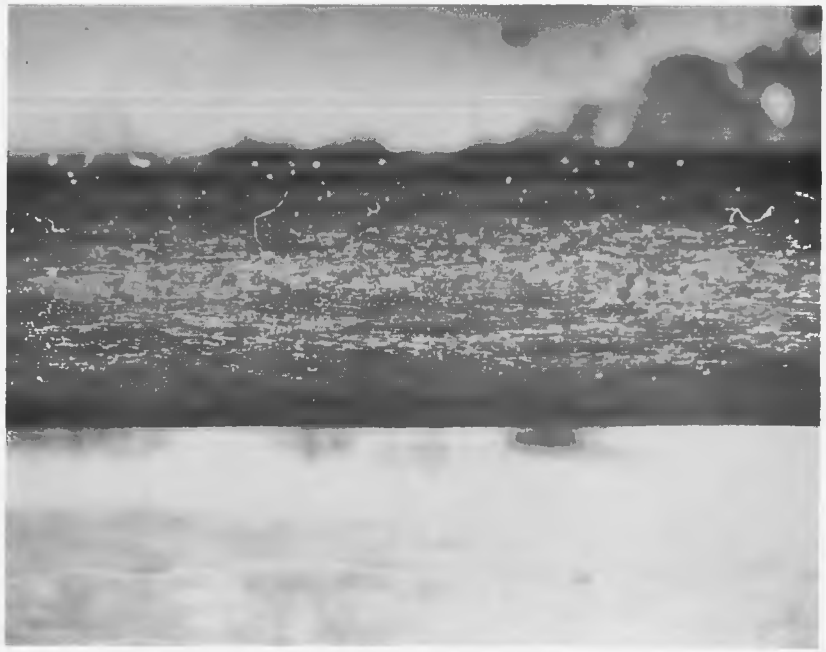
The coatings used for these tests were No-Ox-Id CM nuclear grade and a special grade prepared by adding asbestos fibers to raise the flow-point temperature. In the first test, bare-wire samples were used; in the second test, one specimen of a pair was precoated by the Meta Bond phosphate plus Rustarest treatment.

4.3.2. Test Results

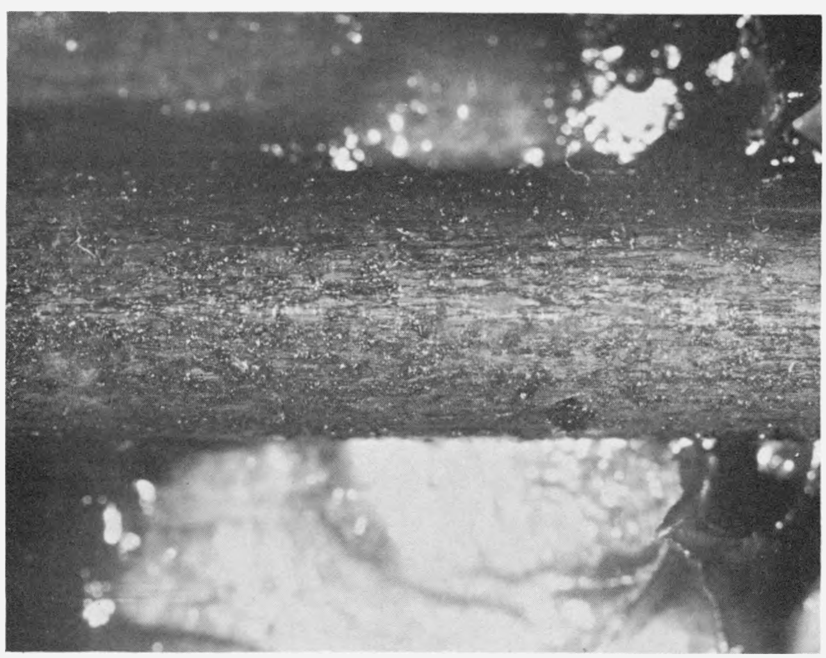
From the first test comparing the No-Ox-Id CM nuclear grade with the special grade, it was observed that after 312 hr of exposure to humid air created by a water bath at 130 F, the nuclear grade had recoated the denuded area of the wire sufficiently to prevent rust. On the other hand, the special grade had failed to protect the wire, which showed evidence of corrosion (Fig. 4.16).

In the second test, after 480 hr of exposure to humid air created by a water bath at 150 F, both the nuclear and special grades demonstrated an ability to self-heal. The control specimen exhibited general rusting, while the specimen residing in the pool of special-grade CM exhibited only small areas of rust. The specimen residing in the pool of nuclear-grade CM was free of rust. In this same test, samples of wire pretreated with Meta Bond plus Rustarest were exposed simultaneously with the other samples. The control sample without Meta Bond coating exhibited some rust spots, but the samples in the nuclear-grade and special-grade No-Ox-Id CM were free of rust (see Fig. 4.17). Although not shown in Fig. 4.17, the sample in the special grade was also free of rust, suggesting that the phosphate pretreatment had been unusually effective.

The Meta Bond coated samples exposed in the nuclear-grade and special-grade No-Ox-Id CM were given a further exposure to the coastal environment

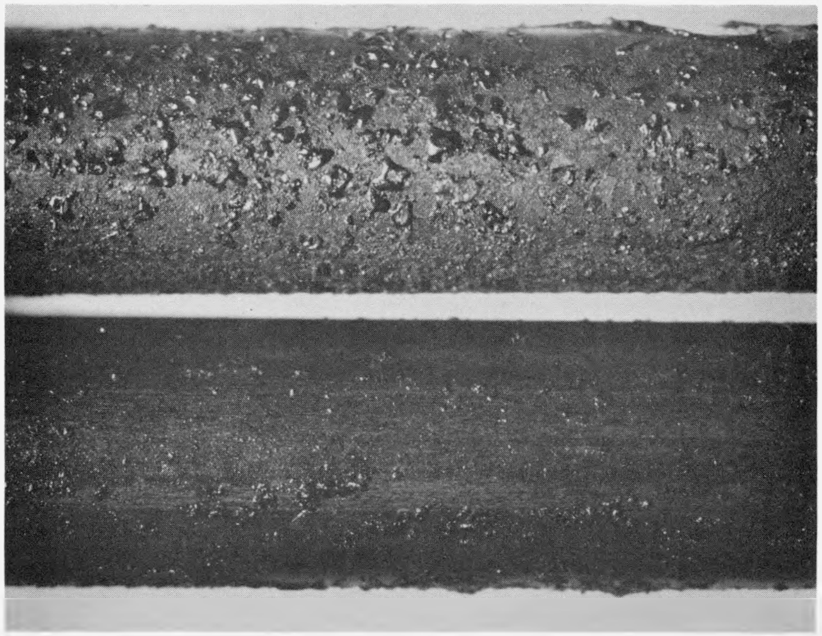


M24168-1 (4x)

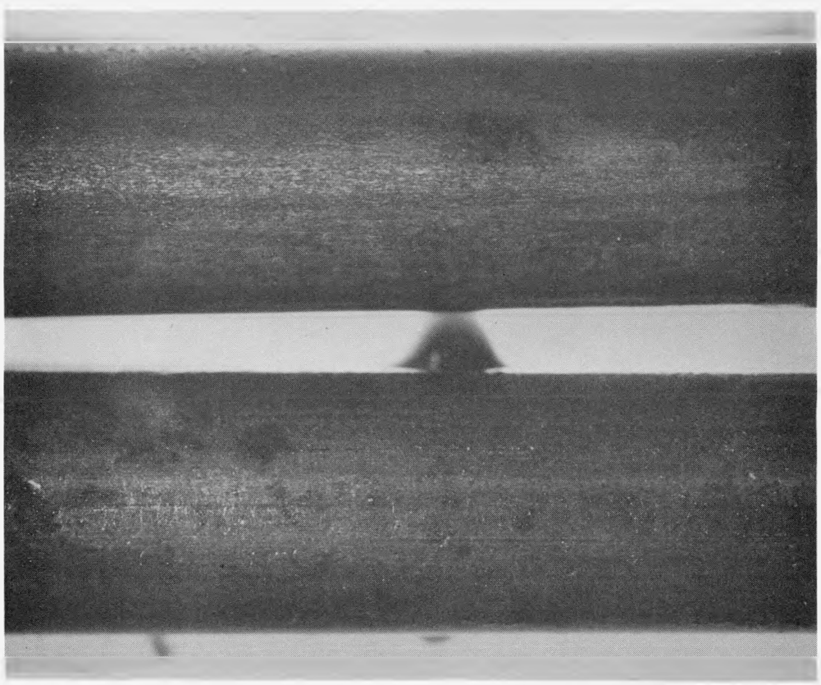


M24169-1 (4x)

Fig. 4.16. Self-healing samples of bare wire resting in a shallow pool of nuclear-grade (top) or special-grade (bottom) No-Ox-Id CM after exposure to humid air (130 F water bath) for 312 hr



M24175-1 (4x)



M24177-1 (4x)

Fig. 4.17. Self-healing samples after exposure to humid air (150 F water bath) for 480 hr. Control samples (top) exhibited some rust; samples in nuclear-grade No-Ox-Id CM were free of rust. (In each photograph, bare wire is at top and Meta Bond plus Rustarest is at bottom.)

for 95 days. In addition, a 4-in. piece of the Meta Bond coated wire was exposed standing slightly inclined in 1/2 in. of the nuclear-grade compound. Following the exposure, the samples were wiped clean. As shown in Fig. 4.18, the two small, self-healing specimens were free of rust. The standing specimen was rusted above the level of the compound; an accumulation of water had raised the level of the compound, but no corrosion was evident on the bottom portion of the sample exposed to the water layer.

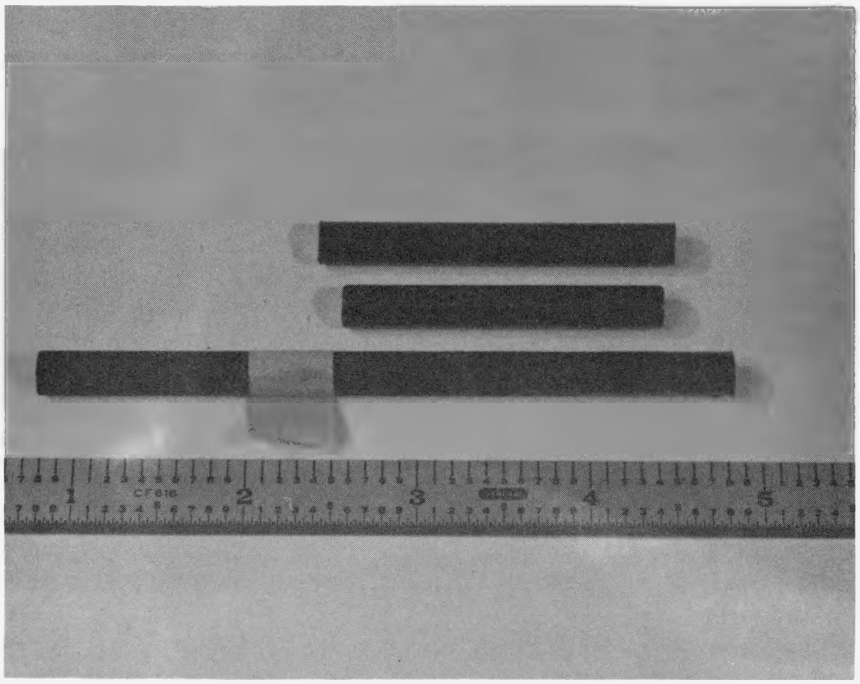
4.4. STRESS-CORROSION TESTS

In the present context, stress corrosion means cracking of the metal (wire) exposed to the simultaneous action of a sustained tensile stress and a corrosive medium. (In another sense, stress corrosion means general corrosion accelerated by stress in the metal.) Ordinarily, stress-corrosion tests are run using a smooth specimen subjected to a stress induced by either a constant-load or a constant-strain method. The constant-load arrangement accelerates crack propagation as the stress-supporting area is reduced, but it requires rather massive test equipment. On the other hand, the constant-strain fixture is smaller and can be taken to the environment, but the time-to-failure as the susceptibility indicator is prolonged as the crack propagates and the stress is relieved.

For such tests, the tensile load may be applied axially to cylindrical specimens, or the U-bend and bent-beam type specimens may be used to develop a range of tensile stress in the surface of the alloy being evaluated. Axially loaded specimens were used for the GGA tests. To increase the severity of the tests, the specimens were notched.

4.4.1. Test Details

Samples of Thermalized wire were coated, stressed, and exposed to the coastal environment. A buttonheaded specimen having a notch root radius of 0.001 in. is shown in Fig. 2.1. The coatings applied to the four specimens are listed in Table 4.2; these coatings were excluded from the notch by a rubber ring.



HT62999-C

Fig. 4.18. Self-healing samples after 95-day exposure to coastal environment: (1) No-Ox-Id CM,nuclear-grade, horizontal exposure; (2) No-Ox-Id CM, "high-temperature"-grade, horizontal exposure; (3) No-Ox-Id CM, nuclear-grade, vertical exposure

TABLE 4.2

COATINGS APPLIED TO THERMALIZED WIRE FOR STRESS-CORROSION TEST

Specimen	Coating
1	No-Ox-Id CM
2	Meta Bond 39 plus Rustarest 452
3	Kephos plus No-Ox-Id CM
4	Meta Bond 39 plus Rustarest 452 plus No-Ox-Id Cm

TABLE 4.3

LOADS APPLIED TO STRESS, DESTRESS, AND INDUCE FAILURE IN WIRE SPECIMENS USED FOR STRESS-CORROSION TESTS

Spec. No.	Stressing Load (lb)	Equivalent Stress (ksi)	Destressing Load (lb)	Ultimate Load (lb)	UTS (ksi)
1	5570	231	4900	7640	317
2	5570	231	4550	7960	330
3	5500	231	4400	7400	311
4	5570	231	4800	7320	304

A stress equivalent to 75% of the ultimate tensile strength of the notched wire was applied using a tensile-test machine. The test fixture is shown in Fig. 4.19. The threaded split-collar held the button-head on the specimen. The predetermined load was applied to the specimen by gripping the outboard ends of the split-collar in the test machine. The load was retained by torquing the nuts against the end-plates of the fixture housing. During the irradiation test preparations (see Section 4.6), it was determined that less than 3% stress relaxation occurred during the 72-hr period following the application of the load.

Before placing the loaded specimens on the rack for the coastal exposure, the rubber rings protecting the notches were removed. No effort was made to work a CIC into the notch.

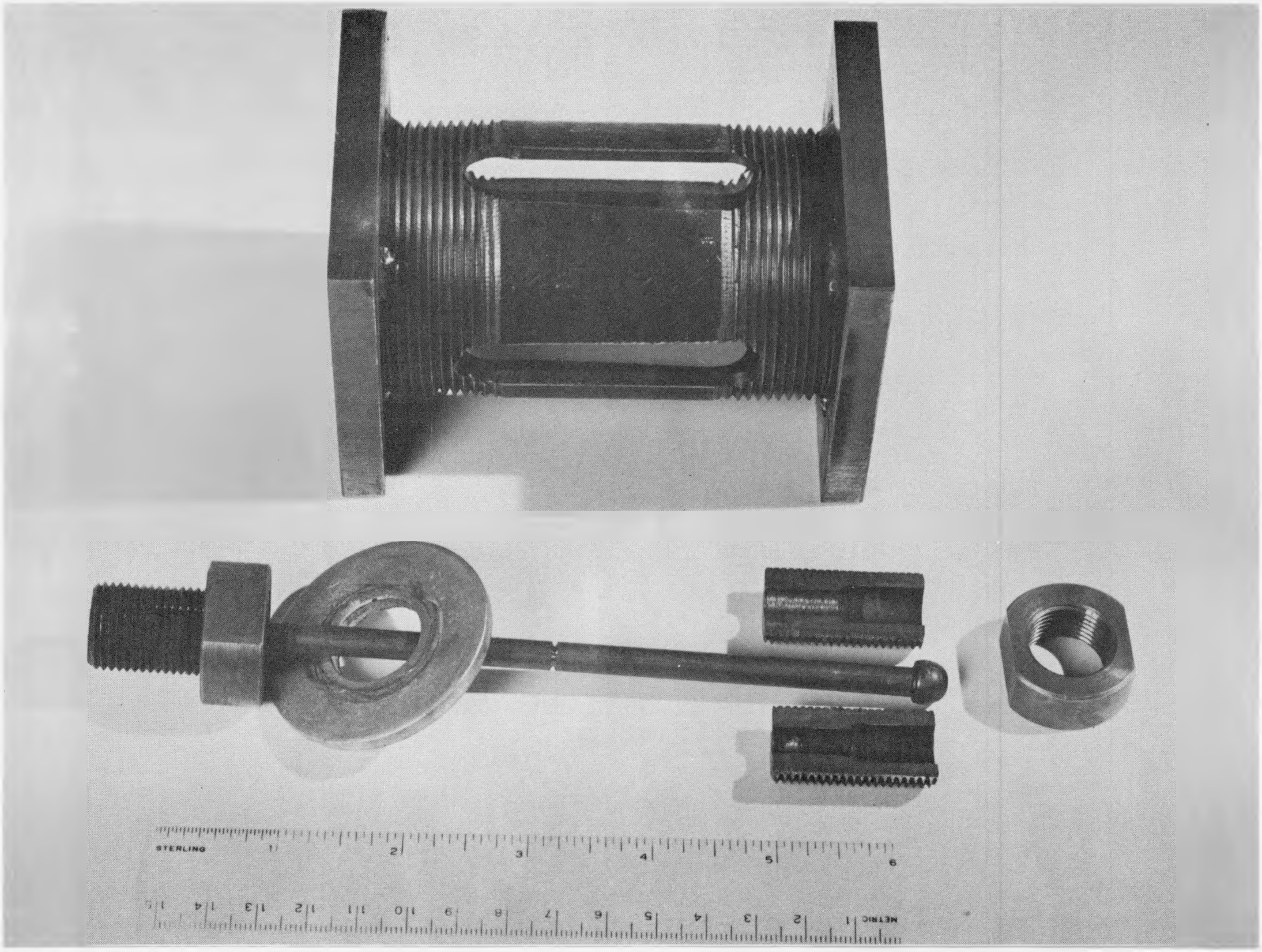
4.4.2. Test Results

After a 9-month exposure to the coastal environment, none of the specimens had failed. The fixtures exhibited the extent to which corrosion had occurred on the unprotected machined surfaces (see Fig. 4.20). A similar condition was evident in the notch of the specimen coated only with Meta Bond and Rustarest. The other three specimens, all coated with No-Ox-Id CM, were free of corrosion (see Fig. 4.21).

The destressing loads listed in Table 4.3 indicate that during the exposure the sustained stress may have decreased from 231 to 180 ksi (approximately 75% of the ultimate strength of the unnotched wire). The ultimate strength of the specimens after the exposure was unchanged from that of the control specimens (see Table 2.2). This fact is considered particularly significant in view of the severely rusted notch in the specimen coated only with Meta Bond and Rustarest.

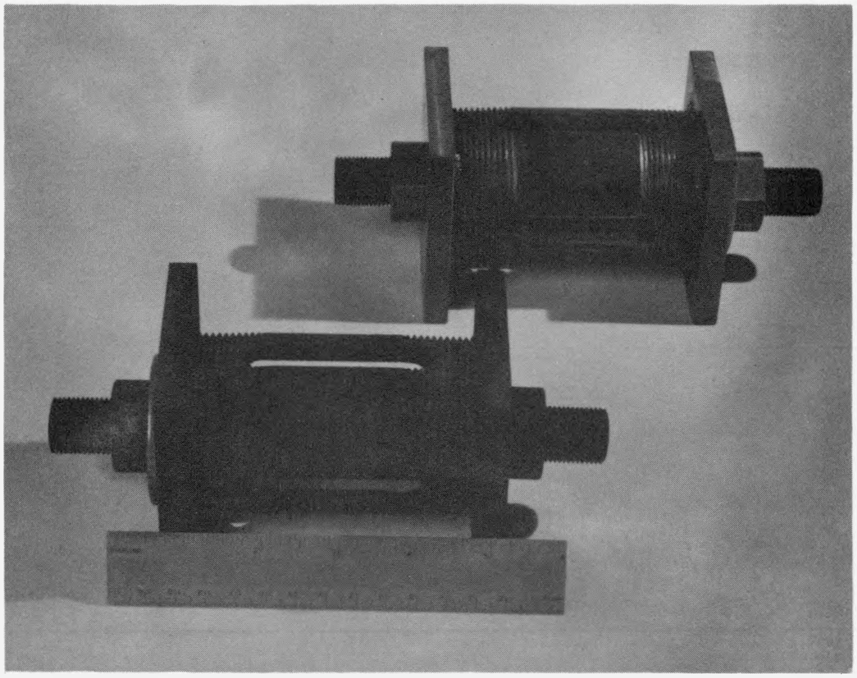
4.5. HYDROGEN-EMBRITTLEMENT TEST

Hydrogen embrittlement is also referred to as hydrogen-induced delayed brittle failure. It occurs in metals when hydrogen, usually



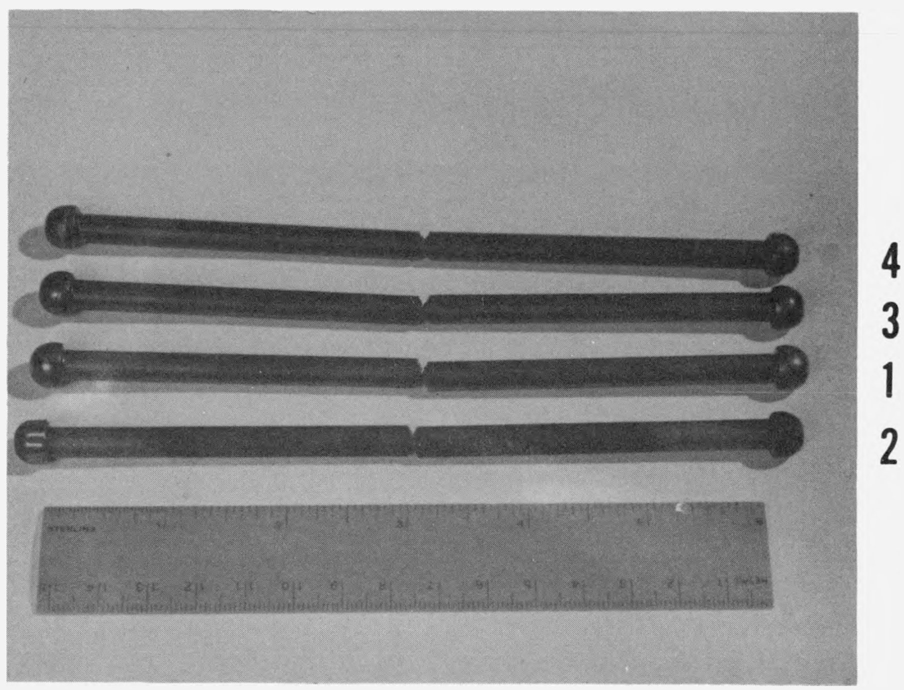
G71790

Fig. 4.19. View of disassembled stress-corrosion test fixture and test specimen



G72128-C

Fig. 4.20. Condition of test fixtures before and after 9-month coastal exposure



G72130-C

Fig. 4.21. Posttest condition of stress-corrosion specimens: (1) No-Ox-Id CM, (2) Meta Bond 39 plus Rustarest 452, (3) Kephos plus No-Ox-Id CM, (4) Meta Bond 39 plus Rustarest 452 plus No-Ox-Id CM

nascent hydrogen, enters a lattice which is under or may experience an externally applied sustained tensile stress. A critical combination of hydrogen and stress must be present in a susceptible metal at a location suitable for crack nucleation. Hydrogen tends to diffuse through the lattice to the area of highest stress, usually at the root of a notch or a crack front.

The hydrogen may result from a chemical process applied to the metal, such as electroplating or conversion phosphate coating. It may also be produced at the cathode of a corrosion cell. Further details on this subject are given in a review prepared by Elsea and Fletcher (Ref. 8).

The GGA test program was undertaken to determine the susceptibility of the tendon wire to hydrogen embrittlement resulting from the conversion phosphate coating treatment as well as from cathodic charging of a sample of the wire.

4.5.1. Test Details

For these tests, notched samples of wire were first treated to induce hydrogen and then subjected to a sustained tensile stress. The specimen dimensions are shown in Fig. 2.1. The stress, equivalent to 75% of the ultimate tensile strength of the notched wire, was applied by a constant load using a stress-rupture test machine. The strength of the notched and unnotched wire is shown in Tables 2.1 and 2.2. In accordance with commonly accepted procedure, the specimens were loaded with a minimum delay following the various surface treatments to be evaluated and were retained in a loaded condition for a minimum of 200 hr.

The treatments to induce hydrogen included both cathodic charging and Meta Bond treating of the wire specimens. In each case, the solution was excluded from direct contact with the machined surface of the notch by a rubber ring. Cathodic charging was done in the manner described by Frohmberg and co-workers (Ref. 9) and reviewed by Elsea and Fletcher (Ref. 8). The stress-relieved wire specimens were immersed in an electrolyte of 4% H_2SO_4 without a cathode poison and cathodically charged at 20 ma/sq in. for 5 min. Within 15 min of charging, the specimens were subjected to a load equivalent to a 260-ksi stress at the notch root.

Thermalized wire specimens were tested only after they had received a Meta Bond treatment. One sample was prepared by IRCO at their Cleveland plant; one was prepared at Western Concrete Structure (WCS) at the time specimens were coated for the fatigue test; and one was prepared in the GGA laboratory.

4.5.2. Test Results

As shown in Table 4.4, none of the specimens tested failed during 200 hr under sustained load. Several of the specimens were allowed to remain under load for longer periods, but no failures occurred.

One of the specimens (No. 4) which was originally charged cathodically at 20 ma/sq in. was recharged at 30 ma/sq in. It survived an additional 200 hr supporting the previously stated load.

The Meta Bond treatment was evaluated using one stress-relieved wire specimen and two Thermalized wire specimens. All three survived 200 hr while supporting a sustained load equivalent to 75% of the ultimate tensile strength of the notched wire. It should be noted that the stress-relieved wire specimen was coated by IRCO at their Cleveland laboratory, where the wire was precleaned with acid before application of the Meta Bond. This operation should have increased the amount of nascent hydrogen available to the specimen.

Only the specimen prepared in the GGA laboratory was loaded immediately upon completion of the Meta Bond coating process. Loading of the other

TABLE 4.4

HYDROGEN-EMBRITTLEMENT SUSTAINED-LOAD TESTS*

Spec. No.	Wire†	Treatment	Test Time** (hr)
1	SR	Control	>200
2	SR	Control	>200
3	SR	Control	>200
4	SR	Cathod. chgd.	>200
5	SR	Cathod. chgd.	>200
6	SR	Cathod. chgd.	>200
4A	SR	Recath. chgd.	>400
7	SR	Meta Bond, IRCO	>200
8	T	Meta Bond, GGA	>200
9	T	Meta Bond, WCS	>200

*All specimens had a notch root radius of 0.005 in., and the sustained load was equivalent to 75% of the ultimate tensile strength of the notched wire.

†SR = stress-relieved wire; T = Thermalized wire.

**None of the specimens failed during the test period.

two coated specimens was of necessity delayed by the shipping and notching time. These delays may have allowed sufficient hydrogen to effuse from the wire and hence masked evidence of susceptibility to hydrogen embrittlement.

Nevertheless, based on the results of these tests and other tests conducted as a part of this evaluation program, both the stress-relieved and Thermalized wire seem to have a low susceptibility to hydrogen embrittlement. However, this statement is not intended to indicate that the wire is immune to hydrogen-induced delayed brittle failure. Several investigators, including Sachs and Branch (Ref. 10), have shown that under special conditions, such as metallic contact between the wire and zinc or the presence of hydrogen sulfide in the corrosive medium, corrosion can cause delayed failure of the wire. It should be pointed out that neither of these conditions is ever likely to occur during the handling and service life of the PCRV tendons.

4.6. IRRADIATION TESTS

The effect of irradiation on the corrosion-protection system was an important consideration in designing the Fort St. Vrain PCRV. Present practice, as applied to secondary containments for nuclear reactor vessels, is to fill the tendon tubes with a petroleum-base CIC. These containments are remote from the nuclear reactor and hence experience a very low irradiation dose. In the case of a nuclear PCRV, tendons in closer proximity to the reactor core are expected to receive a wide range of irradiation doses. Some sections of a few tendons in the Fort St. Vrain PCRV may experience a dose of 1×10^{17} nvt fast neutrons (>1 MeV) and 5×10^{8} rad (gamma) during the expected 30-yr life of the plant.

The effect of a dose of this magnitude on the CIC could be partially anticipated from the work of Bolt and Carroll (Ref. 11), but the effects of irradiating the compound on a stressed wire remained to be investigated. Petroleum-base compounds break down under irradiation in air to produce acid radicals and hydrogen, both of which might damage or embrittle the highly stressed steel. The present investigation was undertaken to determine if hydrogen embrittlement occurs when a stressed tendon coated with a preselected corrosion-protection system is irradiated by the maximum dose predicted for the PCRV tendons. The principal system under consideration consists simply of a zinc phosphate conversion coating on the wire and a petroleum-base CIC on the tendon.

4.6.1. Experimental

Essentially, the test consisted of coating notched tendon-wire specimens with various CICs and exposing them, while stressed, to nuclear radiation using a TRIGA reactor. Failure of a specimen during or immediately following the exposure was to be considered evidence that irradiation products from the CIC had caused hydrogen embrittlement of the wire.

4.6.1.1. Stressing Fixture. An exploded view of the stressing fixture is shown in Fig. 4.22. The body of 6061 aluminum alloy was drilled to allow the buttonhead on the specimens to pass through and was bored to provide a slightly enlarged chamber surrounding the notched area of the specimen. Following insertion of the coated specimen, the plug at the left end of the body was welded in place. For the second set of specimens, the chamber was considered unnecessary and the body was made in one piece.

A steel washer at each end provided a bearing surface for the nut holding the split-collar around the buttonhead. By gripping the outboard ends of the split-collar in a test machine, a predetermined load was applied to stress the specimen. While the specimen was loaded, the nuts were torqued against the body to sustain the stress in the specimen. In another test in which a strain-gaged specimen was used, less than 3% stress relaxation occurred during the 72-hr holding period. It was therefore concluded that a negligible relaxation of the stress would be experienced by the specimen during the irradiation exposure.

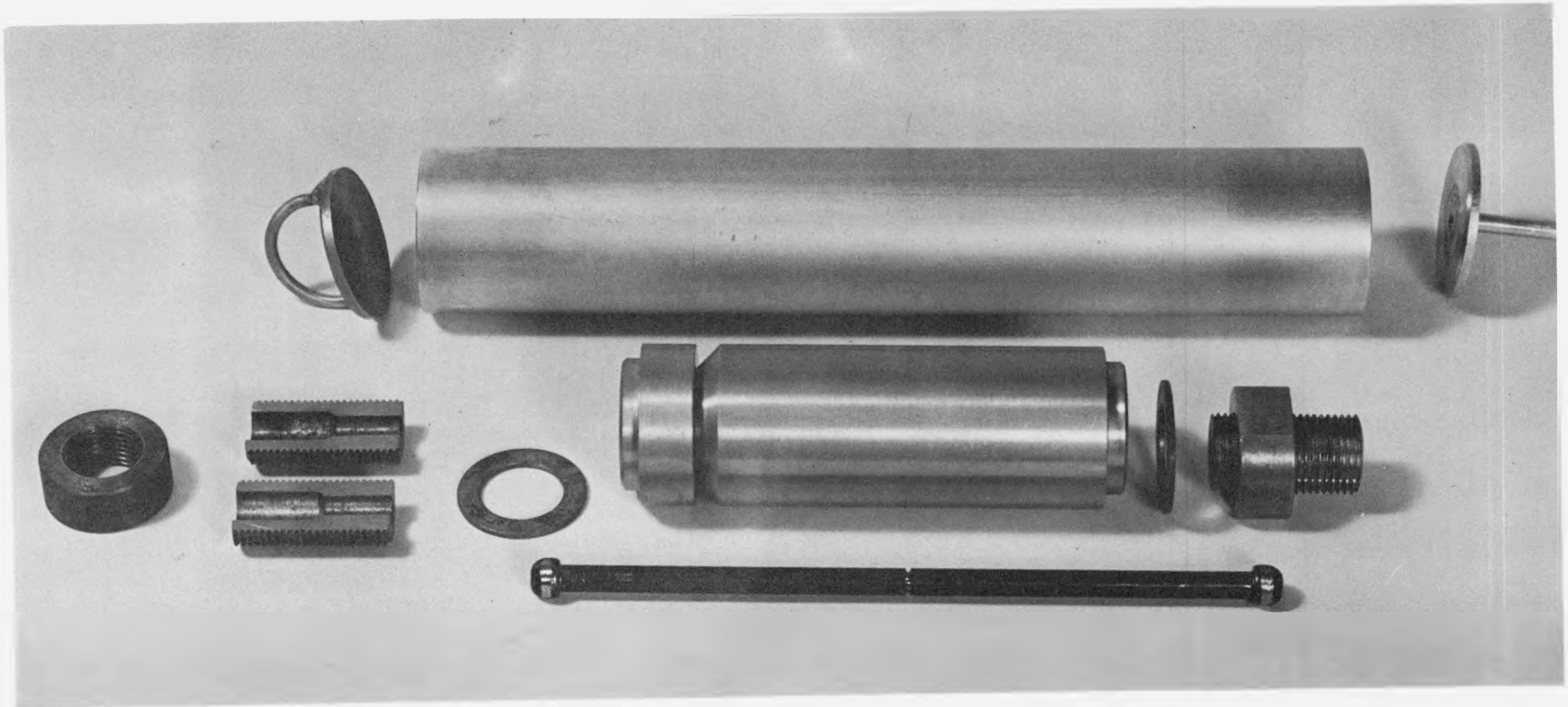


Fig. 4.22. View of disassembled stressing fixture and capsule

Since the TRIGA reactor core is submerged in a pool of water, the stressing fixture was sealed in the aluminum cylinder (see Fig. 4.22). Evacuation for leak checks and atmosphere adjustments were done through the small-diameter tube attached to one end of the capsule. The body of the stressing fixture and the capsule were fabricated of aluminum in order to dissipate the heat developed during irradiation; the specimen temperature stayed below 150 F.

4.6.1.2. Wire Coatings. The coatings applied to the stress-relieved and the Thermalized wire specimens are described in Tables 4.5 and 4.6. The specimens were not precleaned in an acid solution; instead they were thoroughly washed in acetone so that the as-fabricated surface was retained. In this condition, the wire exhibited a thin, tightly adhering, dark oxide film.

The Meta Bond and the Kephos conversion coatings were applied according to the manufacturer's recommendations. Specimens were simply dipped in the desired solution after the notch root had been protected from phosphoric acid attack by a rubber ring. Kephos does not require a rinse, and the residual solution was allowed to drain off while the specimen dried in air. The Meta Bond coated specimens were thoroughly rinsed in tap water, then dipped in the Rustarest solution and allowed to dry in air. Preliminary tests indicated that the Meta Bond procedure would produce coating weights between 250 and 300 mg/sq ft on the wire. The actual weight of the Kephos and Meta Bond phosphate coatings on the specimens was not determined.

The No-Ox-Id CM was liberally applied to form a continuous film approximately 1/32 in. thick, and the Lubriplate autolube grease was similarly applied. The paraffin wax was applied hot with a brush to produce a coating of approximately the same thickness.

4.6.1.3. Capsule Environments. Three of the stress-relieved wire specimens (see Table 4.5) were exposed in individual capsules that had been evacuated

TABLE 4.5

COATINGS APPLIED TO STRESS-RELIEVED WIRE FOR IRRADIATION TESTING

Specimen	Coating	Capsule Environment
1	Control, bare wire	Dry nitrogen
2	No-Ox-Id CM*	Air (59% R.H.)
3	No-Ox-Id CM	Dry nitrogen
4	Autolube	Air (59% R.H.)
5	Paraffin wax	Air (59% R.H.)
6	Paraffin wax	Dry nitrogen

*Trademark of the Dearborn Chemical Division of W. R. Grace & Company.

TABLE 4.6

COATINGS APPLIED TO THERMALIZED WIRE* FOR IRRADIATION TESTING

(Capsule Environment: Air, 50% R.H.)

Specimen	Coating
1	Control, bare wire
2	No-Ox-Id CM†
3	Meta Bond 39 plus Rustarest 452**
4	Kephos†† plus No-Ox-Id CM
5 & 6	Meta Bond plus Rustarest plus No-Ox-Id CM

*Trademark of Richard Johnson & Nephew Ltd.

†Trademark of Dearborn Chemical Division, W. R. Grace & Company.

**Trademarks of IRCO.

††Trademark of Amchem Products, Inc.

and backfilled with air having a 59% relative humidity. This atmosphere was intended to simulate the service condition of a capped prestressing system. The dry-nitrogen environment used on the other three specimens represented a system flushed with nitrogen and capped to retain this environment.

For the second series of tests, in which the Thermalized wire was used, the evacuated capsules were backfilled with ambient air and sealed.

4.6.1.4. Irradiation. Both sets of specimens were exposed to out-of-core irradiation in the GGA TRIGA reactor. The capsules containing the stressed specimens were supported adjacent to the reactor core by a stand placed on the bottom of the pool. The first set was positioned against the core shroud, and the second set was placed 15 cm from the core shroud. In these positions, the specimens received the full spectrum of radiation. Dosimetry in one capsule of the first set of specimens indicated that the dose was 1.7×10^{17} nvt (>1.0 MeV) neutron and 3.88×10^{8} rad (gamma). This dose was achieved in about 8 hr.

For the second set of specimens and before full-power irradiation, a low-power run was made to calibrate the reactor power instruments and provide a relatively low-dose irradiation to the capsules containing dosimetry samples. The dosimetry capsules, which contained an EG&G nickel foil (No. N-972) and a cobalt glass dosimeter (in a neutron shield), were removed after a 20-min irradiation at 190 kW (thermal). The results of this exposure were used to compute the irradiation time required to achieve 1×10^{17} nvt fast-neutron fluence (>1 MeV) and 5×10^{8} rad (gamma) dose.

The dosimetry results from the 20-min irradiation showed that the No. N-972 foil had received a dose of 5.92×10^{12} nvt (>3 MeV) and 5.61×10^{5} rad (gamma). From these values, it was found, using the recently determined ratio of 1 MeV/3 MeV flux = 3.45, that a 320-hr exposure at 1.5 MW should provide a total dose of 4.2×10^{9} rad (gamma) and 4.48×10^{16} nvt neutron (>3 MeV) or 1.5×10^{17} nvt (>1 MeV). This threshhold flux ratio of 3.45 was determined for a region near the core edge, whereas the samples in this irradiation were 15 cm from the core edge. No determination was made of the ratio at 15 cm, but because the attenuation of neutrons by water increases with increasing energy in this energy region, the ratio would be somewhat lower for the location used for these experiments—approximately 2.5. It was therefore concluded that for a 320-hr irradiation, the sample would receive 1.1×10^{17} nvt (>1 MeV).

Upon completion of the 320-hr, full-power irradiation, a nickel foil (No. N-971) placed in one of the capsules was removed and flux determinations were made. The data indicated an exposure of 5.32×10^{16} nvt (>3 MeV) or 1.33×10^{17} nvt (>1 MeV) using a ratio of 1 MeV/3 MeV = 2.5. Thus, it appears that the capsules received at least 4.2×10^{9} rad (gamma) and 1.3×10^{17} nvt (>1 MeV) neutron fluence.

4.6.2. Results and Discussions

None of the specimens from either set failed during or after the exposure to irradiation. The evidence indicates that the wires are not susceptible to hydrogen embrittlement resulting from the irradiation of the CIC.

4.6.2.1. Sensitivity of Test. The susceptibility of steels to hydrogen embrittlement is usually determined by subjecting notched specimens to either a sustained-load or sustained-strain test. Specimens are usually designed to suit a test-facility limitation or an evaluation of a particular service condition. In sustained-load tests, the stress level increases as a crack develops, thus accelerating failure of the specimen. On the other hand, in sustained-strain tests, the developing crack tends to relieve the stress and may thereby delay the time to failure. With either method, the time to failure is a measure of the susceptibility to embrittlement.

Because of practical considerations associated with the irradiation exposure, it was necessary to use the constant-strain method, although the loads applied axially on the specimens are expressed in terms of stress. Each specimen was loaded to have a stress, based on the notch root area, equivalent to 75% of the ultimate tensile strength of a notched wire. This stress level was an arbitrary selection based on some unreported work to evaluate the susceptibility to hydrogen embrittlement of high-strength aircraft-quality steels. Actually, Elsea and Fletcher, in their review of the work relating to delayed, brittle failure (Ref. 8), concluded that the time to failure depends only slightly on the applied stress so long as the latter is well above the critical level. (The critical level is the stress below which failure is unlikely to ever occur.)

For these tests, the stress-relieved notched specimens were anchored at a load equivalent to a stress of 260 ksi and the Thermalized wire at a load equivalent to a 230-ksi stress. The tensile properties of both types of wire in both the notched and unnotched condition are given in Tables 2.1 and 2.2. It is interesting to note that not only were the notched and unnotched tensile strengths of the stress-relieved wire higher than those of the Thermalized wire, but the notch ratio was higher for the former. Both ratios, being above 1, indicated a relatively low notch sensitivity, and hence a high resistance to failure from transverse defects in the wire. As an example, the results obtained from tests of Thermalized wire notched with 0.004- and 0.001-in. root radii indicated an insignificant decrease in notch ratio for a significant increase in notch acuity.

Notch geometry determined the notch acuity, usually expressed as a stress concentration factor, K_t. Peterson (Ref. 12) developed a family of curves for cylindrical specimens circumferentially notched as well as for other types of notched specimens. From these curves, it was determined that for wires notched with 0.005- and 0.001-in. root radii, the K_t were 5 and 8, respectively. A fatigue-crack front, as the ultimate notch, reportedly has a K_t above 15; on the other hand, according to Federal Specification QQ-P-416A, a specimen notched to have a K_t of 2 and loaded to a stress equivalent to 75% of the tensile yield strength satisfactorily indicates embrittlement. Thus, the wire specimens used for this test were considered sufficiently sensitive to indicate any susceptibility to embrittlement induced by the irradiation products of the CICs.

4.6.2.2. Destressing and Examination. On the chance that significant stress relaxation occurred between stressing and destressing (a period of 3 months for the second set of wires), the load necessary to loosen the body of the stressing fixture was recorded (see Table 4.7). However, these destressing loads are considered only indicative since provisions were not made for their precise measurement. In one instance, the destressing load was less than the stressing load. But because of the high initial stress, this slight relaxation would not have significantly affected the sensitivity of the test.

The fractures of the three specimens that broke under the torque load needed to loosen the anchor nuts and the notches of the first set of specimens were examined microscopically for embrittlement cracks, but none were observed.

The second set of Thermalized-wire specimens was loaded to determine the ultimate strength. These values are shown in Table 4.7. Two were about 10% lower than the average ultimate strength obtained for the control specimens (see Table 2.2).

The Lubriplate autolubricating grease and No-Ox-Id CM changed color and texture during the irradiation. Instead of being a normal amber color, they had become cream-colored and in addition appeared to have softened, as had the paraffin. Such softening has been reported by Bolt and Carroll (Ref. 11), who found that the petroleum greases exhibited

TABLE 4.7

LOADS APPLIED TO STRESS, DESTRESS, AND INDUCE FAILURE IN WIRE SPECIMENS

Spec. No.	Stressing Load (lb)	Destressing Load (lb)	Ultimate Load (lb)	UTS (ksi)
1st Set - Stress-Relieved Wire				
1	6200	8720		
2	6200	9000	(*)	
3	6200	8500		
4	6200	8600		
5	6200		(*)	
6	6200	8200	(*)	
2nd Set - Thermalized Wire				
1	5300	4900	7150	295
2	5200	5800	7150	300
3	5200	5600	7300	307
4	5200	5500	6400	279
5	5200	5700	7050	296
6	5300	5900	6850	284

*Specimen was broken while the anchor nuts were being loosened.

a decrease in gel strength when exposed to doses of gamma radiation below 9 x 10^8 rad. Beyond this range, the grease stiffened until it solidified at some dose above 25 x 10^8 rad. This latter effect was noted on the second set of Thermalized wire. The No-Ox-Id CM became resinous, adhering to the specimens as would a thick coating of varnish.

4.6.2.3. Gas Generation from CICs. A capsule containing 10.76 g of the CIC No-Ox-Id CM was irradiated at the same time as the wire specimens to determine the pressure increase and perform gas analyses. After the capsule was helium leak-checked, it was evacuated and backfilled with ambient air. The pressure was recorded hourly, and gas samples were taken after 70, 165, and 320 hr of exposure.

The first gas analysis indicated that, on a volume basis, the sample was 66% air and 34% hydrogen. The ratio of air to hydrogen may be high, because the gas evolved in the capsule may not have mixed completely with the air in the 35-ft bleed tube but merely have pushed the air into the sampling container. The second analysis indicated that the sample contained 59% nitrogen, 30% hydrogen, 4% oxygen, 7% carbon dioxide, and a trace of carbon monoxide. The nitrogen-oxygen ratio indicates that some oxygen was probably absorbed by the compound to produce acid groups. The final analysis indicated that the sample contained 62% hydrogen, 30% nitrogen, 2% oxygen, 6% methane, and trace amounts of other gases. For the purpose of this test program, sufficient hydrogen appears to have been produced to cause embrittlement of the highly stressed steel.

During the 320-hr irradiation exposure, the pressure in the compound-containing capsule increased to 37 psig at an initial rate of 0.14 psig/hr and a final rate of about 0.12 psig/hr. Since the rate is nearly constant, it seems certain that gas will be generated continuously during the life of a nuclear reactor vessel. Some of this gas may be absorbed by the CIC, but end caps on tendon tubes will require a pressure-relief valve. Since it is not intended that the Fort St. Vrain PCRV tendon tubes will be filled with the compound, in most tubes the gas generated will have free access to the end caps and relief valves.

4.6.3. Conclusion

This test program has demonstrated that the hydrogen produced by irradiating the selected CICs does not cause embrittlement of the stressed tendon wire. Furthermore, any other products which might have resulted from this exposure did not cause degradation of the wire.

5. CONCLUSION

Based on the results of the tests described in this report, the following corrosion-protection system has been prescribed for the Fort St. Vrain PCRV tendons:

1. The wire is coated with Meta Bond plus Rustarest at the wire manufacturer's plant.

2. The coils of wire are spirally wrapped with an HB-VPI paper and then wrapped coils are shipped to the tendon fabricator in sheet-steel containers.

3. During tendon fabrication, the tendons are coated with No-Ox-Id CM CIC.

4. The tendons are shipped to the reactor-vessel site in containers to protect the wires from chemical and mechanical damage.

5. At installation, the tendons are recoated with No-Ox-Id CM, the tendon tubes having been previously cleaned and coated with the same compound.

6. After the tendon is stressed and the anchor assembly is coated with No-Ox-Id CM, sheet-steel anchor caps are attached to the bearing plates to prevent injurious environments from contact with tendon components.

The continuity of this system is expected to provide complete corrosion protection starting from the time of wire manufacture and continuing during fabrication and installation operations and throughout the life of the reactor vessel.

ACKNOWLEDGMENTS

The author wishes to thank the many people at Gulf General Atomic Incorporated who contributed in some measure to this program and the report. Particular recognition is due the personnel of the capsule, hot cell, metallographic, and mechanical properties laboratories and the TRIGA facility.

APPENDIX A

Bulletin 3222.1

DEARBORN
PROTECTIVE COATING SYSTEMS

NO-OX-ID® CM CASING FILLER - NUCLEAR GRADE

PHYSICAL PROPERTIES

ITEM	RANGE	METHOD
Specific Gravity	0.88 - 0.90	ASTM D-287
Weight Per Gallon	7.35 - 7.50 lbs.	---
Pour Point	110 - 120°F.	ASTM D-97
Flash Point (COC) *	400°F., Minimum	ASTM D-92
Viscosity at 150°F.	130 - 145 SSU **	ASTM D-88
Viscosity at 210°F.	60 - 75 SSU	ASTM D-88

(NOTE: Above 130°F., NO-OX-ID® CM viscosity is virtually identical with that of medium heavy lubricating oil - SAE 30.)

ITEM	RANGE	METHOD
Penetration (Cone) at 77°F.	328 - 367	ASTM D-937
Thermal Conductivity	0.12 BTU/Hr./Ft.^{2}/°F./Ft. Thickness (approx.)	---
Specific Heat (Heat Capacity)	0.51 BTU/lb./°F. (approx.)	---
Shrinkage Factor from 150°F. to 75°F.	3.5 - 4.5%	---

* Cleveland Open Cups

** Seconds Saybolt Universal

RBORN CHEMICAL DIVISION GRACE W. R. GRACE & CO., 375 MERCHANDISE MART, CHICAGO, ILLINOIS 60654
1266
SALES OFFICES IN PRINCIPAL CITIES
IN CANADA, DEARBORN CHEMICAL COMPANY, LTD., 2454 DUNDAS STREET WEST, TORONTO 9
Printed In U.S.A.

APPENDIX B

(COPY)

RICHARD JOHNSON & NEPHEW LTD.

GROUP LABORATORY

Laboratory Report No. GL68/2/80

M.L.S. No. 210

Date Received 7.2.68

Date Reported 5.3.68

Source: Mr. G. Sleigh re Western Concrete Structures.

Subject: Evaluation of the Protective Coating Properties of Metabond 39 - Rustarest 452, under an accelerated corrosion test.

Material: P.S.C. wire .250" dia.

Reference: See Table 1.

Samples:

Summary and Conclusions

Evidence indicates that circulation within the protective tubes was not fully effective in this test, as only very light rusting was apparent on the stripped samples.

The only condition altered from previous tests was the insertion of the chamber lining to further prevent contamination, the lower volume possibly affecting circulation.

The samples freely suspended in the chamber were little affected by the modification.

Examination suggests that the protection given by the Rustarest treatment is more important than that between Metabond and Kephos treatments, bearing in mind that the Metabond was Laboratory controlled and had a much higher effective coating weight than the production applied Kephos coating.

A further test is now in progress to evaluate the relative merits of Metabond - Rustarest and Kephos - Rustarest coatings.

Introduction.

A series of coated samples were tested in order to evaluate the corrosion resistance properties of Metabond - Rustarest protective surface coating, as applied by Western Concrete Structures, under an accelerated humidity test.

Test Conditions.

Solution	Tap water.
Atomizing nozzle air pressure	12 psi.
Humidity	100% throughout test.
Temperature	63 - 71°F.

Sample Preparation.

The samples for Metabond - Rustarest coating were approx. 10" long and prepared as follows:

a) Stripping.

1) 5 mins immersion 20% Caustic soda solution at 175°F.
11) 5 mins immersion 10% hydrochloric acid at room temperature (1% Rhodine inhibited.)

b) Cleaning.

10 minutes immersion in a 2% boiling detergent solution.

c) Rinse.

5 minutes immersion in a cold tap water overflow rinse

d) Phosphate Coating (Metabond).

5 mins immersion at 190°F in a solution of:

2.6 ozs MetaBond 39)
3.4 ozs Metabond 164) per U.S. gallon of water.

e) Rinse.

Overflow rinse in cold tap water for 5 mins.

f) Corrosion Protection (Rustarest).

Short dip in a solution of 1 quart Rustarest 452 per gallon water at 150°F.

g) Air dry.

Stripping was necessary to remove the Kephos coating already present on the wire.

Samples were also retained at the phosphate coated stage to evaluate this stage of treatment.

The samples were then varnished at both ends in order to prevent end corrosion effects.

Samples in each condition of surface coating were both free suspended and suspended in open ended tubes in the fog chamber, the latter protection to prevent direct contact with water.

Further samples of Kephos production coating and plain non-coated wire were incorporated into the test.

The full list of test samples is given in Table 1.

TEST PROCEDURE.

The test samples were suspended in the fog chamber which had recently been modified to incorporate a perspex liner to further prevent contamination.

After testing, the samples were inserted into tubes, which had a dessicant in the base, and sealed.

VISUAL EXAMINATION.

The samples were evaluated by the method used by Western Concrete Structures on previously despatched specimens, i.e., the degree of corrosion was evaluated subjectively, using a scale of 100, where 0 represents the least and 100 the most corroded specimen.

The results of the evaluation are shown in Table 11.

RESULTS.

Tube Protected.

Evidence suggests that some interference with circulation within the tubes has occurred as only very light rusting was present, even on the stripped samples.

The only variable altered from previous tests was the insertion of the perspex liner within the fog chamber.

Free Suspended.

These samples appeared relatively unaffected by the chamber modification and a plot of test duration (vertical axis) v. surface rust evaluation (horizontal axis) for the various coatings is shown in Graph 1.

COATING WEIGHTS. mgs/sq.ft.

	Kephos Coat.	Non-coated	Metabond 39.
Total coat.	360.0	148.0	933
Lime soap.	43.0	15.6	
Rustarest			446.0
Free lime	47.2	15.6	
Zinc phosphate	4.7	Nil	334.0
Iron phosphate	88.7	Nil	153.0
Sodium as Na.	23.2	--	
Dirt by diff.	153.2	116.8	

TABLE 1. TEST SAMPLES.

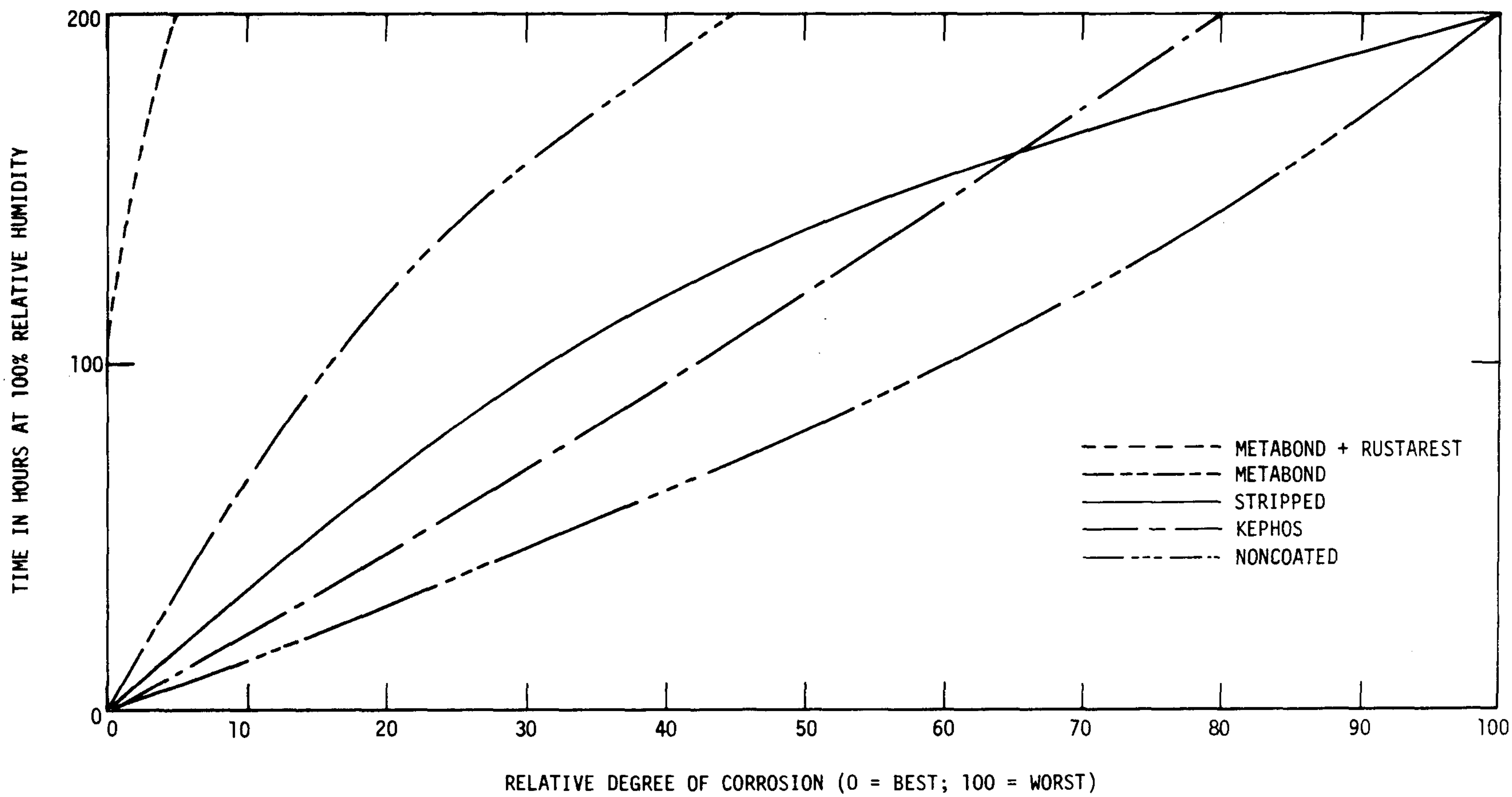
Tube Protected.

	No. of samples tested at: 100 hours.	200 hours.
Stripped	2	2
Metabond treated	1	1
Metabond and Rustarest treated	2	2
Free Suspended.		
Stripped	1	1
Metabond treated	1	1
Metabond and Rustarest treated	1	1
Kephos coated (production sample)	1	1
Non-coated (production sample)	1	1

TABLE 11.

Tube Protected.	Rust evaluation at test duration of: 100 hours.	200 hours.
Stripped	*	*
Metabond treated	0	0
Metabond and Rustarest treated	0	0
Free Suspended.		
Stripped	40	100
Metabond treated	20	45
Metabond - Rustarest treated	0	5
Kephos coated (production sample)	50	80
Non-coated (production sample)	70	100

GRAPH NO. 1 - FREE SUSPENDED SAMPLES



APPENDIX C

(COPY)

Laboratory Report No. GL68/3/69
M.L.S. No. 265
Date Received 28.2.68
Date Reported 25.3.68

RICHARD JOHNSON & NEPHEW LTD.

GROUP LABORATORY

Source: Mr. G. Sleigh re Western Concrete.

Subject: Evaluation of the protective coating properties of Metabond 39-Rustarest 452 and Kephos-Rustarest 452 under an accelerated corrosion test.

Material: P.S.C. wire .276'' dia.

Reference: Laboratory report No. GL68/3/80.

Samples: See Table 1.

Summary and Conclusions

Equal rust protection was given by Kephos-Rustarest and Metabond-Rustarest treatments, as neither showed evidence of rusting during or after the test.

Evidence showed that Rustarest was the important rust inhibiting treatment, as all such treated specimens showed negligible rusting, irrespective of whether any prior treatment was present.

Further samples showed that the protection given by the production applied Kephos coating was superior to a laboratory applied, production simulated, Metabond coating given a 10 second dip, but slightly inferior to a Metabond coating produced by a 5 minute dip as applied by Western Concrete Structures.

INTRODUCTION

During a previous experiment, Report No. GL68/2/80, evidence indicated that the protection given by the Rustarest treatment on Metabond coated wire, was more important than the difference between Metabond and Kephos treatments.

A series of samples were, therefore, tested in order to determine the relative merits of Metabond-Rustarest and Kephos-Rustarest coatings.

TEST CONDITIONS.

Solution	Tap water.
Atomizing nozzle air pressure	12 psi.
Humidity	100% throughout test.
Temperature	66 - 72°F.

SAMPLE PREPARATION.

The samples were approximately 10" long and the Metabond-Rustarest coatings were prepared as in the previous test, i.e.:

a) Stripping.

1. 5 mins. immersion 20% caustic soda soln. at 175°F.
2. 5 mins. immersion 10% hydrochloric acid at room temperature (1% Rhodine inhibited).

b) Cleaning.

10 minutes immersion in a 2% boiling detergent solution.

c) Rinse.

5 minutes immersion in a cold tap water overflow rinse.

d) Phosphate Coating (Metabond)

5 minutes immersion at 190°F in a solution of:

2.6 ozs Metabond 39)
3.4 ozs Metabond 164) per U.S. gallon of water.

Further samples were prepared using a 10 seconds immersion to simulate production coating.

e) Rinse.

As stage (c).

f) Corrosion Protection (Rustarest).

Short dip in a 25% v/v solution of Rustarest 452 at 150°F. Production coated Kephos samples were prepared from this stage.

g) Air Dry.

Stripping was necessary to remove Kephos coating already present on the wire before Metabond coating could be applied.

Samples were also retained in various stages of treatment and stripped -Rustarest treated, in order to evaluate them independently.

The samples were then varnished at both ends in order to prevent end corrosion effects.

Samples in each condition of surface coating were both free suspended and suspended in open ended tubes in the fog chamber. The latter protection to prevent direct contact with water.

The full list of test samples is given in Table 1.

TEST PROCEDURE.

The test samples were suspended in the fog chamber and the maximum and minimum temperature and humidity were read at regular intervals.

After testing, the samples were inserted into tubes which had a dessicant in the base, and sealed.

VISUAL EXAMINATION.

The samples were displayed against a white background and the degree of corrosion was evaluated subjectively, using a scale of 100, where 0 represented the least and 100 the most surface corroded specimens.

This was the method used by Western Concrete to evaluate the first set of corrosion samples.

The results of the evaluation are shown on Table 11.

RESULTS.

Tube Protected Samples.

Examination showed that the Rustarest treated samples showed no visible signs of rusting irrespective of prior treatment.

Free Suspended Samples.

Except for the Metabond 10 second dips + Rustarest sample,which showed slight rusting (5% estimated), none of the Rustarest treated samples showed visible evidence of rusting irrespective of prior treatment.

The free suspended samples without Rustarest showed a greater degree of rusting than their corresponding tube protected coating, probably due to contact with atomised droplets in the chamber.

COATING WEIGHTS mgs/ sq.ft.

	Kephos Coat.	Metabond 10 sec. dip.	Metabond 5 min. dip.
Total coat.	706.62	576.9	933.0
Rustarest	443.0	467.0	446.0
Iron phosphate	61.13	50.8	153.0
Zinc phosphate	Nil	59.1	334.0
Free lime	18.08		
Borax	5.21		
Fatty acid	44.50		
Iron oxide	80.10		
Dirt	54.60		

TABLE 1.

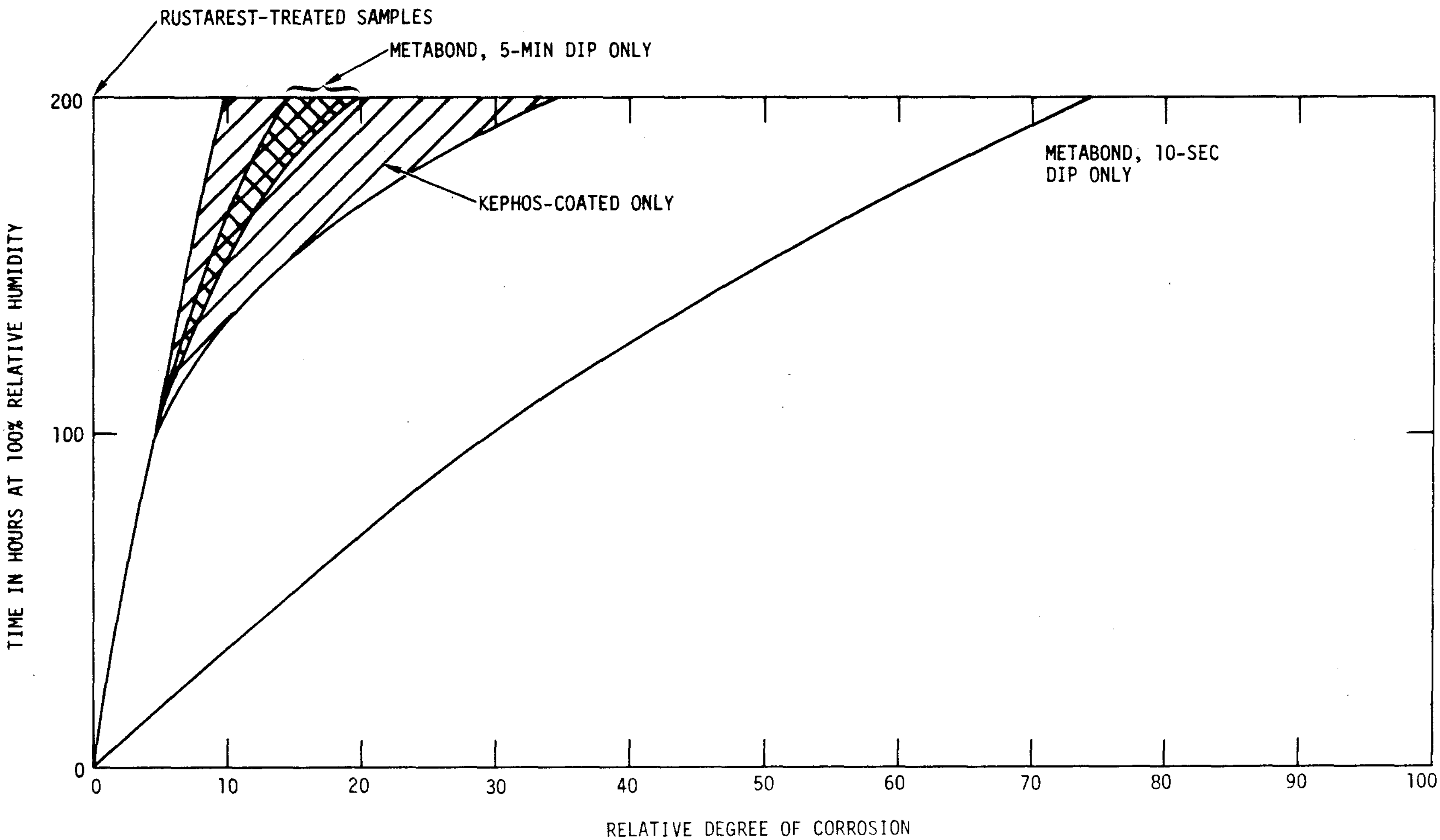
Tube Protected	No. of samples tested at: 100 hours.	200 hours.
Stripped	1	1
Stripped + Rustarest	1	1
Metabond 10 sec. dip	1	1
Metabond 10 sec. dip + Rustarest	1	1
Metabond 5 min. dip	2	2
Metabond 5 min. dip + Rustarest	2	2
Kephos production coated.	2	2
Kephos production coated + Rustarest	2	2
Free Suspended.		
Stripped	1	1
Stripped + Rustarest	1	1
Metabond 10 sec. dip	1	1
Metabond 10 sec. dip + Rustarest	1	1
Metabond 5 min. dip	2	2
Metabond 5 min. dip + Rustarest	2	2
Kephos production coated	2	2
Kephos production coated + Rustarest	2	2

TABLE 11.

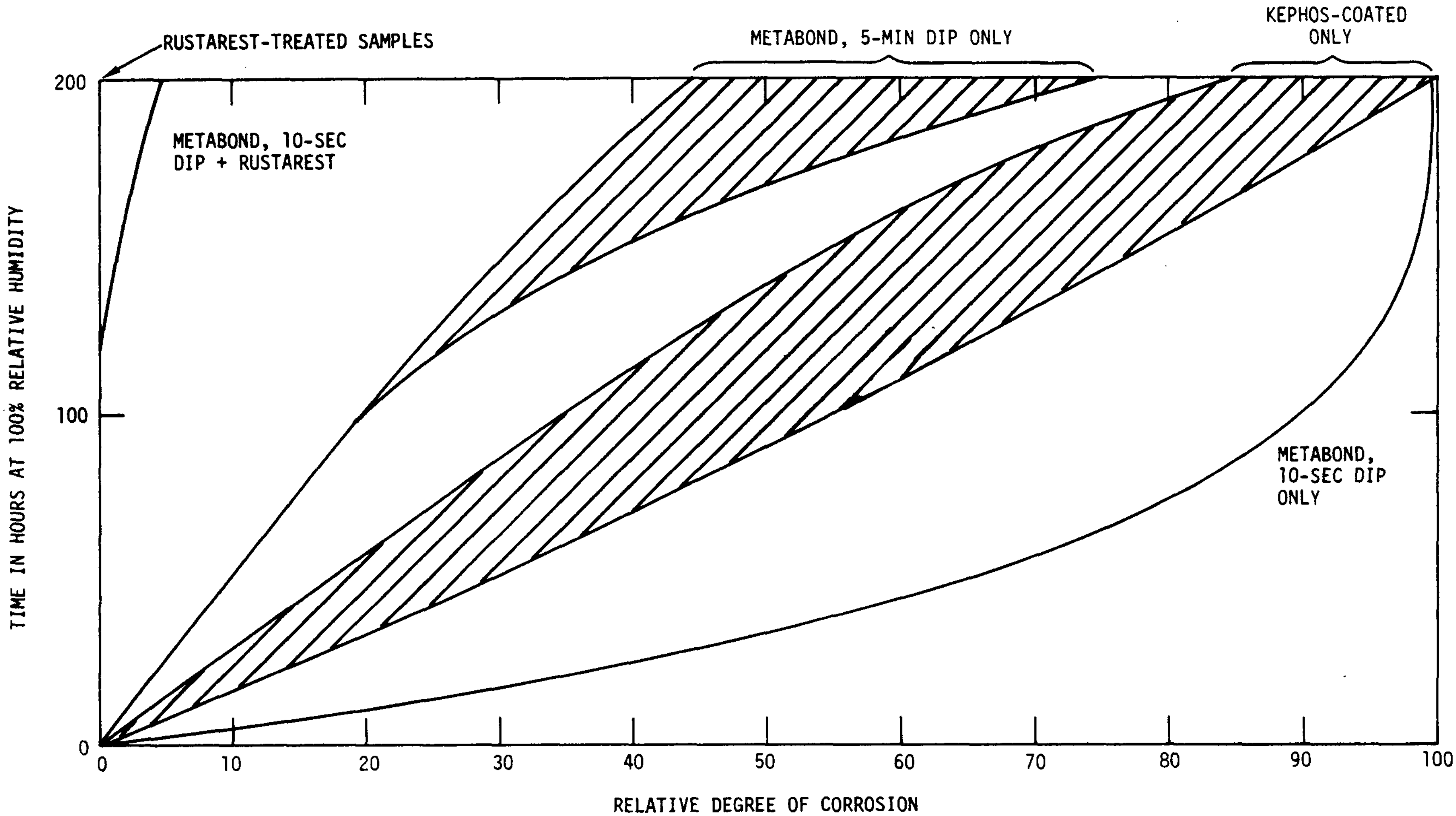
Tube Protected	Rust evaluation at test duration of: 100 hours.	200 hours.
Stripped	80	80
Metabond, 10 sec. dip	30	75
Metabond 5 min. dip	5, 5	15, 20
Kephos coated	5, 5	10, 35
Stripped and Rustarest	0	0
Metabond, 10 sec. dip + Rustarest	0	0
Metabond, 5 min dip + Rustarest	0	0
Kephos coated + Rustarest	0	0
Free Suspended.		
Stripped	100	100
Metabond 10 sec. dip	90	100
Metabond 5 min dip	20, 20	45, 75
Kephos coated	35, 55	85, 100
Stripped and Rustarest	0	0
Metabond 10 sec. dip + Rustarest	0	5
Metabond 5 min. dip + Rustarest	0	0
Kephos coated + Rustarest	0	0

These results are presented in graphical form in Graphs 1 and 11.

GRAPH I - TUBE PROTECTED



GRAPH II - FREE SUSPENDED



APPENDIX D

PRESTRESSING SYSTEMS*

The Magnel system uses wedge type anchorage and wires, with a jacking frame for stressing.

The Freyssinet system uses cone anchorage, cable, or conduits containing several wires, and special jacks for prestressing.

The CCL system uses a cone anchorage, cables, and twin jacks.

The Lee McCall system uses steel rods anchored with wedges or threaded nuts on a distribution plate. A special jack is used for prestressing. This system is used more for vertical than for horizontal prestressing.

The BBRV system uses cables, buttonhead anchorages, and special jacks.

The Chalos system uses steel tendons cast in the tank wall in the tensioned condition and released subsequently to compress the concrete.

The Preload system uses a steel wire cold drawn and wrapped spirally around a concrete shell. A continuous winding machine applies a tension of approximately 140,000 psi to the wire. One layer of wire may be covered with mortar and another layer of wire drawn and wrapped outside it.

Crom and BBR systems resemble the Preload system in many respects. There are differences in the methods whereby wire tension is obtained, and in other details.

---

*Taken from Cornet, I., "Corrosion of Prestressed Concrete Tanks," <u>Mater. Protect.</u> <u>3</u>, 91 (January 1964).

In the Magnel, Freyssinet, CCL, Lee McCall, and Chalos systems the rod, tendon, or cable is generally cast into the concrete wall. Hewett, Preload, Crom, and BBR systems use rods, tendons, or wires in tension outside a concrete cylinder wall; a protective cover of sprayed concrete or mortar can be applied on the outside, but this cover is not in compression.

Preload, BBR, and Crom wire wrapped tanks are probably most numerous. The East Bay Municipal Utility District has in service tanks prestressed by the Hewett, Preload, Crom, and Freyssinet systems.

APPENDIX E

GENERAL EFFECTS OF RADIATION ON ORGANICS*

Radiation changes organic substances by two main routes - cross linking (or polymerization) and scission (cleavage). Hydrogen is evolved, and reactive sites formed in the residual organic molecule may lead to side reactions, depending on the molecular structure involved.

Crosslinking is manifested in liquids by viscosity increase; in solids by increased hardness and brittleness. Cleavage (the formation of lower-molecular-weight materials) results in less viscous liquids and softened (or even semifluid) solids.

Molecular structure is the largest factor influencing radiation stability, which varies 1,000-fold among organics. The most stable compounds contain aromatic rings; least stable are those having nonaromatic unsaturation.

The use of additives to protect less resistant materials is now widespread. Additives are most effective in the least stable materials, but even there rarely increase the radiation dose required for a given effect by more than a factor of 10.

In general, the gross effects of radiation, in the absence of time-dependent factors such as oxidation, depend only on dose and are independent of dose rate. Theoretically, very high dose rates should produce different behavior; but this has not yet been clearly established by experiment. There is recent convincing evidence that neutrons are more damaging than electrons, but most prior information supports the "equal-energy-equal-damage" concept regardless of the type of radiation.

---

*Taken from Carroll, J. G., and R. O. Bolt, "Radiation Effects on Organic Materials," Nucleonics 18, 78 (September 1960).

Radiation does not change all properties of an organic material to the same degree. Thus, the critical property must be specified in considering the useful life of a given material. In any event, the longest lives will generally be obtained with compounds rich in aromatics and with radiation exposures in inert atmospheres at moderate temperatures.

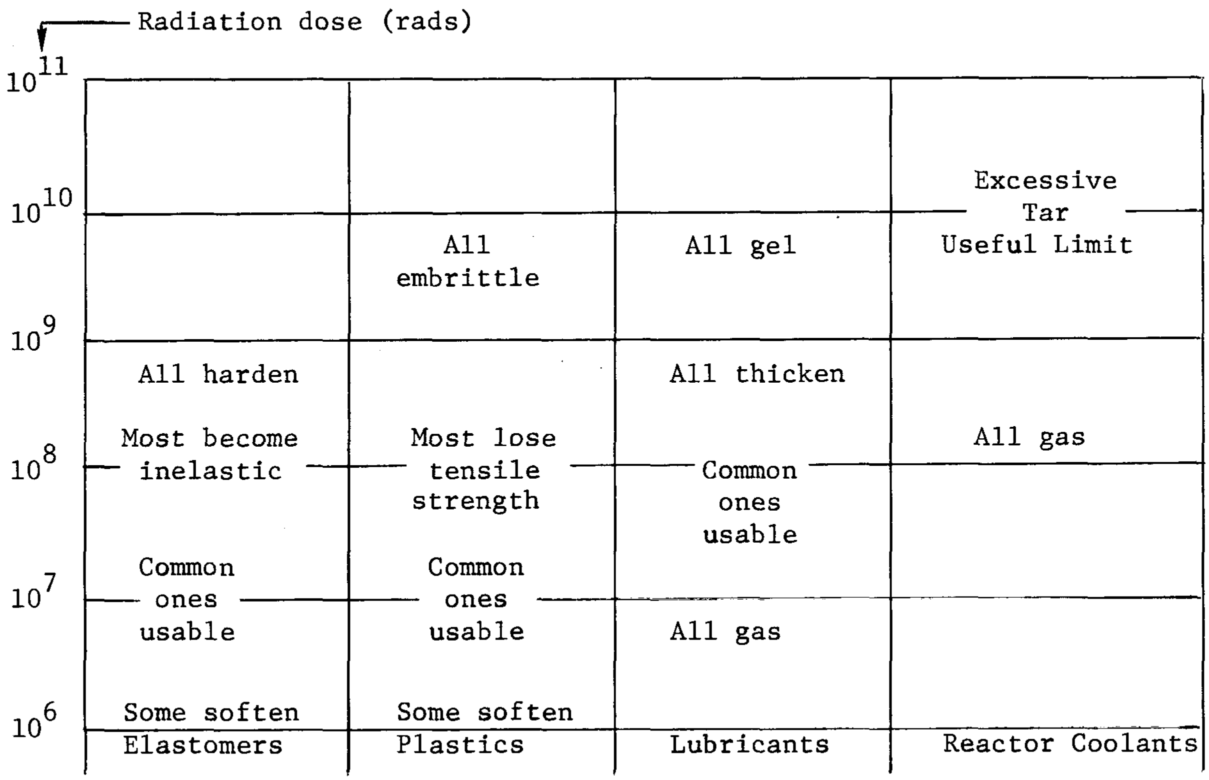


FIG. 1 RELATIVE SENSITIVITY of organic materials to radiation (10^3 rads are lethal to man; most metals and ceramics are usable above 10^{12} rads)

APPENDIX F

(COPY)

RADIATION EFFECTS ON GREASE IN PCRV

by

D. M. J. Compton

The question you raised was of the effects of 10^{10} rads, over thirty years, on the grease you propose to use to protect the tendons in a reactor pressure vessel, and in particular whether corrosive materials can be formed that would attack the steel.

Without knowing the composition of the grease, other than paraffin with inhibitors, etc., it is difficult to give more than a general answer, but the main predictions are:

1. Initially, at $\sim 10^6$ rads, the gelling agents in the grease may break down and the viscosity may decrease, so that it may flake. At $\sim 10^7 - 10^8$ rads the viscosity will increase again and by $10^9 - 10^{10}$ rads the grease will be essentially coke.

2. Hydrogen and small amounts of other gases (chiefly methane) are evolved. Extrapolating from low dose values, about 500 ml of gas will be evolved per gram of grease during the 10^{10} rad dose. The hydrogen is molecular, but is initially atomic and the possibility of attack by the atomic hydrogen cannot be excluded.

3. Rust inhibitors in greases have been shown to fail after $< 10^8$ rads.

4. If air is present, oxidation will be serious, particularly over this long time span (oxidation at higher dose rates is usually limited by the access of oxygen to the oil or grease).

   Oxidation forms substantial quantities of organic acids, e.g., oils markedly increase in neutralization number. These organic acids can corrode certain types of steel.

5. Acids are also formed from non-paraffin components of the oil. Particularly serious are phosphates, which yield strong acids, and any halogen (fluorine, chlorine) compounds also do so. Any additives of these types should be avoided.

6. All of these effects get worse with increasing temperature.

7. It thus seems that there may be a problem. If you allow ingress of air, acids may be formed. If you make a truly hermetic seal, the gas pressure may build up to alarming values (although it is doubtful if such a seal can be made in concrete).

APPENDIX G

CORROSION PROTECTION OF REACTOR PRESTRESSING SYSTEM*

There are two distinct phases of corrosion protection, namely:

a) Temporary protection of all the steel products from the moment of their manufacture through transit and storage on site until the final corrosion protection is applied after stressing the vessel.

b) Final corrosion protection to be effective for the life of the vessel.

The temporary corrosion protection should cover a period of up to one year, while the final protection must last 30 years. For observation and possible restressing during the life of the vessel the cables must not be grouted. The use of galvanized wire, without additional corrosion protection, can give rise to hydrogen embrittlement and therefore, this method is unsuitable.

TEMPORARY CORROSION PROTECTION

Steel Ducts

The outside surface of the ducts is not protected, but loose rust, if any, is removed from them before casting into concrete. The inside surface is treated with a wax compound M.D. 858/3 by the manufacturer. On site, the ducts are stored in a closed building with their ends closed by weather proof hessian covers. They are supported clear of the ground. Before, or soon after, being built into the vessel their inner surface is coated with Rustilo 43 (petroleum oil and lime soap). On the vessel the duct ends are kept closed by waterproof caps. This treatment may be omitted if the environmental conditions are not unduly severe.

*Taylor Woodrow Construction Ltd., unpublished data.

Wire

The wire is phosphated with Kephos 235 and waxed by electrostatic spray or emulsion at the manufacturers works. Cerabrit BD 706, (water soluble wax), or Ferromede D/26M5, waxes would be suitable. The wire is stored clear of the ground in a closed building on site. With the Wylfa 36 strand system a Castrol S200 grease is applied during manufacture. A corresponding treatment might be required for the wires of the BBRV tendon using a lower viscosity material. This treatment would provide additional corrosion protection and reduces friction during stressing.

The Anchorages

The anchorages are supplied with a protective coating of Ensis Fluid 256 (a petroleum wax plus lanolin and resin) and packed in wooden boxes. They are stored in the same boxes clear of the ground in a closed building.

FINAL CORROSION PROTECTION

This protection is applied immediately after stressing the tendons.

Ducts and Tendons

As the ducts are placed in position the mating surfaces of the couplings are liberally covered with Evomastic RD 290, and the joints bandaged with a waterproof tape. It is important to ensure that all the joints are made watertight.

The longitudinal and hoop ducts are fitted at one end with a side injection tube through which a small quantity of a vapor phase inhibitor (V.P.I.) is poured after sealing the anchorages. The V.P.I. is placed in the top cap through injection tubes at both ends of the duct. The bottom cap ducts, which have a central drain and injection tubes at both ends, have a different treatment. Immediately after concreting the duct is protected by a V.P.I. Before inserting the tendon this material is drained off and the duct dried out with hot air. After stressing and scaling the anchorages, petroleum jelly Astrolan FD 361 (petro jelly + V.P.I.) is pumped in to fill these ducts completely. Finally, the injection tubes are plugged.

Anchorages

Immediately after stressing the anchorages are sprayed all over with Evomastic RD.290 (bitumen with asbestos fibers). Then the cylindrical surface of the chocks and the nut are wrapped with a fabric followed by another coat of RD.290. A waterproof cap over the anchorage is then fixed with a circlip round the bottom of the chocks.

LIST OF MATERIALS FOR CORROSION PROTECTION

A list of the materials, used in this section, for corrosion protection is as follows:

1. MD.858/3, a hydrocarbon wax with lanolin soap and solvent.
   Supplier: Astor Boisselier & Lawrence Ltd.

2. Rustilo 43, a temporary corrosion protective made from petroleum oil, lime soaps and anti-corrosion agents.
   Supplier: Castrol Limited, London, W. I.

3. Kephos 235, a phosphate coating deposited from a non-aqueous solution.
   Supplier: I.C.I. Limited, Paint Division, Slough, Bucks.
   (in U.S. - Amchem)

4. Cerabrit BD 706, a synthetic wax which can be emulsified in water.
Supplier: Bush Beach & Segner Bayley Limited, London, E.C. 3.

5. Ferromede D/26 M5, an aqueous dispersion of a synthetic wax for deposition by dipping, spraying or coating.
Supplier: Sunbeam Anti-Corrosives Limited, West Molesey, Surrey.

6. Ensis Fluid 256, a petroleum wax with lanolin and resin in a solvent.
Supplier: Shell Mex & B. P. Limited, London, W.C.2.

7. C.C., cyclohexylammonium carbonate, vapor phase inhibitor.
Supplier: Any supplier.

8. Astrolan FD 361, a petroleum jelly with V.P.I. with non-slump properties at 50°C.
Supplier: Astor Boisselier & Lawrence Limited, West Drayton.

9. Evomastic RD.290, a non-slump plasticized bitumen compound with asbestos fibers.
Supplier: Evode Limited, Stafford.

ANNOTATED BIBLIOGRAPHY

Armson, F. J., T. Cahill, and E. H. Parkinson, "The Development of the Kephos and Wax Coating Process for the Corrosion Protection of Stabilized Prestressing Wire," GKN Group Research Laboratory Report No. 780, 1965.

1. Corrosion tests conducted on samples of stabilized strand using five environments are discussed.

2. This report is principally concerned with the use of Kephos/wax coating for stabilized strand.

3. It is concluded that a satisfactory level of corrosion protection of the strand has been achieved by the production application of a Kephos/wax coating.

Bate, S. C. C., and R. H. Corson, "Effect of Temperature on Prestressing Wires," in Conference on Prestressed Concrete Pressure Vessels, Institute of Civil Engineers, London, March 1967 (Group 21, Paper D).

1. Drawn steel wire has not exhibited evidence of stress corrosion.

2. Hydrogen embrittlement has been observed to occur in notched wire in the presence of zinc and hydrogen sulfide. In unnotched wire, hydrogen embrittlement has not occurred.

Blake, D., and I. O. Gordon, "Initial Corrosion Protection of the Wylfa Nuclear Reactor Prestressing System," International Research and Development Company, unpublished data.

1. An assessment of the initial corrosion-protection procedure for the Wylfa nuclear reactor prestressing system is presented.

Cahill, T., "Wire and Strand for Prestressed Concrete," Wire Industry (Feb.-Mar. 1965).

1. Where rusting is uniform, there is little danger of failure through loss of strength; wire stored in the open for 3 months showed tensile losses of only 2%.

2. During poor storage, partially immersed in water, where pitting occurs, 50% losses in strength have been reported after a few weeks.

3. Zinc-coated wire may fail by hydrogen embrittlement.

4. Stress-corrosion cracking has been observed only in boiling nitrate solutions.

Chen Pang Tan, "Prestressed Concrete in Nuclear Pressure Vessels, A Bibliography of Current Literature," USAEC Report ORNL-TM-1675, Rev. 1, Oak Ridge National Laboratory, 1969.

Cornet, I., "Corrosion of Prestressed Concrete Tanks," Mater. Protect. 3, 91 (Jan. 1964).

1. Case histories of known corrosion problems are described.

2. Fundamentals of corrosion indicate that iron has little tendency to liberate hydrogen if the solution pH is above 6; above pH 13, corrosion occurs through the formation of soluble hypoferrites instead of an insoluble ferrous hydroxide film.

3. Cured concrete normally is alkaline in reaction (pH about 9.5 to 12.5), and protects steel.

4. Potential shifts making steel more anodic may result from differential aeratron cells and differential concentration cells; in poor-quality concrete, both may cause corrosion of prestressing steel.

Everling, W. O., "Stress Corrosion in High Tensile Wire," Wire Wire Prod. 30, 316 (1955).

1. Cracks propagate transaxially in oil-tempered wire and semiaxially in cold-drawn wire.

2. All samples were brittle in nitrate solutions.

Gilchrist, J. D., "Stress Corrosion Cracking of High Tension Steel Wire," Concrete Construc. Eng. 60, 18 (Nov. 1965).

1. "Steels in which carbides appear as pearlite, that is in well-developed lamellar formation, were found to be immune to such cracking while steels in which carbides appear as discrete particles, 'particulate carbides,' were generally susceptible to such cracking in appropriate conditions."

2. Susceptible steels crack in aqueous nitrate solutions and sulphates, sulfites, and sulfrides. Chlorides cause cracking only under alkaline conditions.

Gilchrist, J. D., "The Stress Corrosion Cracking of High Tensile Steel Wire," Royal College, Science and Technology, J. Metallurgical Club No. 13 (1960-61).

1. Mild steel is attacked by complex liquors containing ammonia, cyanides, and sulfides. Nitrate cracking depends on the form and distribution of carbides; spheroidized cementite in the grain boundaries is the worst condition.

2. It is concluded that stress-corrosion cracks form in areas where the structure contains fine spheroidal carbide, whether this is bainite or sorbite, and not in pearlitic or coarsely spheroidized structures.

3. The paper cites Radeher and Grafen (Stahl Eisen 76 (11), 1616 (1956)) to the effect that cracking of mild steel with NaOH (caustic embrittlement) occurs in a critical range (15% to 33%) and at a suitable oxygen content.

Godfrey, Howard J., "Corrosion Tests on Prestressed Concrete Wire and Strand," PCI J. 5, 45 (1960).

1. Prestressed-concrete beams were exposed to an industrial atmosphere for 3 yr. In a beam without calcium chloride in the concrete, the strand was free of rust and showed no loss of strength or elongation. In a beam with calcium chloride in the concrete, the strand was rusted and pitted and showed a 5% loss of tensile strength and a 60% loss in elongation.

Klodt, D. T., "A Study of Corrosion of Prestressing Steel - Effect of Stress, Metallurgical Structure and Environment," Paper No. 75, presented at the NACE Conference, Cleveland, Ohio, 1968.

1. This paper is principally concerned with the effect of a hydrogen sulfide environment.

2. As-received, mechanically polished, and electrolytically polished surface finishes exhibited a comparable propensity for failure in an H_2S environment.

3. Experiments showed that in high-pH chloride solutions, free oxygen bubbles need not adhere to the steel surface to initiate corrosion; an oxygen concentration cell is sufficient.

4. Imperfect galvanized coatings could result in cracking of the steel in an H_2S atmosphere.

Leonhardt, F., Prestressed Concrete, 2nd ed., W. Ernst, Berlin, 1964, pp. 41, 191.

1. Hydrogen embrittlement and stress-corrosion cracking are discussed.

2. A protective measure for the wire during shipments and prior to grouting is suggested.

Libert, Y., and A. Hache, "Contribution to the Study of the Stress Corrosion of High Strength Steel Wires," 8th Colloque de Metallurgies (June 1964). Stress-corrosion, delayed failures, fatigue-corrosion and relations between these phenomena, Centre d'Etudes Nuclaires, Saclay, 1965, p. 81.

1. Stress corrosion of prestressing wire occurred on site (prior to installation).

2. Removal of surface layer by grinding improved the behavior of wire, as did hot galvanizing.

Monfore, G. E., and G. J. Verbeck, "Corrosion of Prestressed Wire in Concrete," J. Am. Concrete Inst. 32, 491 (1960-61).

1. "Hot-rolled tempered" steel wire reportedly failed while the wire was still in coils.

2. Oil-tempered wire was by far the most susceptible to stress corrosion cracking.

3. Calcium chloride (1.5 to 3.0 wt-%) was the primary source of corrosion in shotcrete-mortar pipe.

4. Under normal conditions, steel does not corrode when embedded in concrete.

5. Hard-drawn wire of one manufacturer was somewhat more susceptible to longitudinal cracking than another manufacturer's hard-drawn wire.

Reinhard, F. M., Twenty-year Atmospheric Corrosion Investigation of Zinc-Coated and Uncoated Wire and Wire Products, American Society for Testing and Materials, Philadelphia, 1961 (ASTM, STP-290).

1. The serviceability of zinc coatings is discussed.

Roberts, M. H., "Effect of Calcium Chloride on the Durability of Pretensioned Wire in Prestressed Concrete," Mag. Concrete Res. 14, 42 (1962).

1. "There is very little corrosion at all ages for ordinary Portland cement without calcium chloride."

2. With 2% $CaCl_2$, corrosion after 6 months was very slight; with 5%, it was appreciably greater.

3. Corrosion was more marked in sulfate-resisting Portland cement containing 2% and 5% $CaCl_2$.

4. Steam curing and storing at 100 F and 93% RH for up to 18 months resulted in very little corrosion of steel embedded in Portland cement. If chlorides were present, the corrosion was more severe.

Simnad, M., Gulf General Atomic Incorporated, "Corrosion Protection and Lubrication Systems for the Prestressing System of the PSC-PCRV," unpublished data.

Simnad, M., Gulf General Atomic Incorporated, "PSC Prestressing System Corrosion Protection: Proposal to use Aluminum Tube Cladding with Magnaform Processing," unpublished data.

Spare, Gordon T., "Prestressing Wires - Stress-Relaxation and Stress-Corrosion Up to Date," Wire Wire Prod. 29, 1421 (1954).

1. This article is a general review.

2. It describes a free-loop test of the susceptibility of wire to stress-corrosion cracking. The test showed the high susceptibility of heat-treated wire, which failed in 1 hr, and the low susceptibility of cold-drawn wire, which had not failed after 1000 hr.

"A Method of Corrosion - Proofing and Lubricating Cables," Civil Eng. Publ. Works Rev. 60 (Mar. 1965).

1. This article describes Cosmic Wax 64 sprayed as powder on previously heated strand. Any damage to coating seems to be self-healing. Prephosphating is recommended. Cosmic Wax 64 was on the Wylfa nuclear power station.

"Corrosion and Concrete," Concrete Construct. 9 (2) (1965).

1. High-alumina cement concrete does not attack aluminum and lead.

2. Aluminum, lead, zinc, cadmium, and glass corrode in concrete. Copper corrodes if chlorides are present.

"Corrosion Problems with Prestressed Concrete (RILEM-FIP-IABSE Report)," J. Am. Concrete Inst. 63, NLII (Oct. 1966).

1. Cold-drawn wire exhibits a higher degree of safety than heat-treated wire.

2. Nitrates cause intercrystalline stress corrosion.

3. H_2S causes hydrogen embrittlement. It attacks steel, producing atomic hydrogen, which enters the steel before recombining to form molecular hydrogen. H_2S is the most dangerous aggressive agent in relation to prestressing wire.

"Specification for Steel Wire for Prestressed Concrete," British Standards Institution Report BS-2691:1963.

REFERENCES

1. Szilard, Rudolph, "Corrosion and Corrosion Protection of Tendons in Prestressed Concrete Bridges," ACI J. 66, 42 (1969).

2. Johnson, B. G., "Method of Test for Hydrogen Embrittlement Due to Electrolytic Cadmium Plating," Symposium on Materials for Aircraft, Missiles, and Space Vehicles, American Society for Testing and Materials, Philadelphia, 1963, p. 82 (ASTM STP No. 345).

3. Chow, G. S., and J. Hildebrand, "Small-Scale Tendon Friction Tests," USAEC Informal Report GAMD-9379, Gulf General Atomic Incorporated, 1969.

4. Shreir, L. L., Corrosion, v. II, George Newnes Ltd., London, 1963, p. 16.19.

5. Monahan, E. C., "A Field Study of Sea Spray and Its Relationship to Low Elevation Wind Speed - Preliminary Results," Thesis, Woods Hole Oceanographic Institution, August 1965.

6. Armson, F. J., T. Cahill, and E. H. Parkinson, "Development of Kephos and Wax Coating for the Corrosion Protection of Stabilized Prestressing Wire," GKN Group Research Laboratory Report No. 780, 1965.

7. Northup, T. E., G. S. Chow, and J. F. Hildebrand, "Testing Large Tendons for a Nuclear Reactor Vessel," USAEC Report GA-9155, Gulf General Atomic Incorporated, 1968.

8. Elsea, A. R., and E. E. Fletcher, "Hydrogen-Induced, Delayed, Brittle Failures of High-Strength Steels," Battelle Memorial Institute, Defense Metals Information Center, Report DMIC-196, 1964.

9. Frohmberg, R. P., W. J. Barnett, and A. R. Troiano, "Delayed Failure and Hydrogen Embrittlement in Steel," Trans. Am. Soc. Metals 47, 892 (1955).

10. Sachs, K., and G. D. Branch, "Delayed Failure of Prestressing Wire," GKN Group Research Laboratory Report No. 673, 1962.

11. Bolt, R. O., and J. G. Carroll (eds.), Radiation Effects on Organic Materials, Academic Press, New York, 1963, chap. 2 & 9.

12. Peterson, R. E., Stress-Concentration Design Factors, John Wiley & Sons, Inc., New York, 1953.