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16. ABSTRACT
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This request was prompted by the criticism from certain suppliers and fabricators that their particular material, system and/or procedure was being discriminated against by the specifications. Two points were especially criticized. These are (1) that no restriction is made as to the placement of wire or strand if water curing is used, but if steam curing is used then the wire or strand can only be placed after steam curing is completed, and (2) that the special restrictions placed against wire and strand do not apply to rod.

The present specification provisions were based on the assumption that post installation corrosion will occur in direct proportion to the amount of corrosion products on the steel at the time of placement. This is not a proven fact but there is sufficient doubt of the claim that all corrosion is arrested by the cement, to make it a prudent assumption. Thus the specifications are as restrictive as can be economically tolerated in the present state of knowledge.

The above two allegations are true but our requirements were established only after careful consideration of all possibilities. The difference of treatment between steam curing and water curing was based on the opinion that water curing was less corrosive than steam curing. Unfortunately, this provision does eliminate the use of certain systems when steam curing is to be used.

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LARRY LOWE

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

A REPORT ON

THE CORROSION OF PRESTRESSING STEEL DURING FABRICATION AND CURING OF POST-TENSIONED CONCRETE.

60-16

DND

January 1960

State of California
Department of Public Works
Division of Highways
Materials and Research Department

January 1960

Lab. Project
Auth. 77-R-6191

Mr. F. W. Panhorst
Assistant State Highway Engineer
Division of Highways
1120 N Street
Sacramento 14, California

Attention: Mr. A. L. Elliott

Dear Sir:

Submitted for your information is:

A REPORT OF

THE CORROSION OF PRESTRESSING STEEL

DURING FABRICATION AND CURING OF

POST-TENSIONED CONCRETE.

Study made by . . . . Structural Materials Section
Under general direction of . . . . J. L. Beaton
Supervised by . . . . H. F. Kuhlman
Field work by . . . . H. F. Kuhlman and L. Lowe
Metallurgical study and report by . . . . C. B. Kendrick
Report prepared by . . . . W. E. Faist and V. M. Sayers

Very truly yours,

F. N. Hveem
Materials and Research Engineer

WEF/CBK/VMS:mw
cc: JWTrask
IOJahlstrom (2)
Bridge Dept. (10)

I. INTRODUCTION

By a letter dated March 23, 1959, the Bridge Department requested that a study be made of the specifications concerning the protection of prestressing steel from corrosion prior to and during construction. The primary purpose was to determine whether the specifications were equitable for all systems and procedures of post-tensioned prestressed concrete.

This request was prompted by the criticism from certain suppliers and fabricators that their particular material, system and/or procedure was being discriminated against by the specifications. Two points were especially criticised. These are (1) that no restriction is made as to the placement of wire or strand if water curing is used, but if steam curing is used then the wire or strand can only be placed after steam curing is completed, and (2) that the special restrictions placed against wire and strand do not apply to rod.

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The above two allegations are true but our requirements were established only after careful consideration of all possibilities. The difference of treatment between steam curing and water curing was based on the opinion that water curing was less corrosive than steam curing. Unfortunately, this provision does eliminate the use of certain systems when steam curing is to be used.

The fact that wire and strand are more closely protected by specifications than is rod is based on the fact that corrosion has less effect percentage-wise in reducing the cross sectional area of a rod than of wire or strand. However, by specifications the rod must still be free of deleterious rust when installed, so it is doubtful that any great disparity exists between our requirements for these three types of prestressing tendons. At least a review of completed projects shows no appreciable imbalance in the use of rods.

The purpose of this study is therefore to determine the relative effect on degree of corrosion of steam curing vs. water curing and whether expedients exist that might allow the use of all post tensioning systems under the same conditions. During the study certain by-product information was also garnered, such as the effect of galvanizing of high strength steel and distribution of and type of corrosion on such steels.

II. SUMMARY AND CONCLUSIONS

Field observations in general seem to indicate little difference between steam curing and water curing insofar as the amount of corrosion on the prestressing steel is concerned. However, in the one control test of this experiment the prestressing steel exposed to water curing was markedly less corroded than was that in concrete subjected to steam curing. The use of vapor phase inhibitors reduced the corrosion products on the steel, both during steam curing and water curing, by as much as 75%. Under steam curing conditions only, the plugging of the ends of the prestressing conduit reduced the corrosion products on wire by about one-half.

A great deal of work has been done recently by various researchers into the effect of galvanizing or plating high strength steels. It has been found that such methods of corrosion protection can result in early failures of high strength steels due to embrittlement. ASTM has specified certain tests to guard against embrittlement, but the safeguards are not fool-proof and cannot guarantee 100% freedom from this defect. This, coupled with the fact that industry has refused to supply galvanized material for prestressing tendons, leads to the conclusion that the galvanizing requirement should be removed from our specifications.

The only circumstance in which a galvanized material should be used is for exterior application. Here only, galvanized wire strand should be used.

The over-all results of this program indicate that while water curing seems to be somewhat less corrosive than is steam curing, nevertheless both can cause corrosion; and no strong evidence has been developed for differentiating between the two methods.

III. RECOMMENDATIONS

It is recommended that the present wording used in the specifications concerning the corrosion protection of prestressing steel be abandoned and that the following wording be substituted:

> Prestressing steel for post-tensioning shall be uncoated high tensile cold drawn wire, uncoated high tensile cold drawn wire strand, or uncoated high tensile alloy bars at the option of the contractor. Whenever a post-tensioning system is used, the prestressing steel shall not be installed in the member until immediately prior to the stressing operation and the tubes shall be grouted within 24 hours after stressing, except that if an approved vapor phase corrosion inhibitor is used properly in the prestressing conduit, and the steel outside the conduit painted with a pre-treatment wash primer conforming to State Specification 52-G52, then the prestressing steel may be installed at the convenience of the contractor. All prestressing steel shall be satisfactorily protected from rust or other corrosion prior to use and shall be free of dirt, rust, oil, grease or other deleterious substances when installed and when tensioned.

IV. EXPERIMENTAL PLAN

The investigation as performed included the following:

1. A 15-foot test beam was specially fabricated, using materials and methods typical of State contract work, and the beam and samples of steel were subjected to various cycles of steam and water curing. The steel samples were subsequently examined and tested to determine the effects of the various exposures. The experimental procedures included the following:

   a. Exposures of 3 and 7 days to steam curing.

   b. Three tests under water curing conditions for exposure periods of 14 and 28 days.

   c. One of the prestressing tendons was treated with Shell VPI #250 crystals.

   d. Another was sealed off from the live steam.

2. Observations and tests were made on the following wire specimens.

   a. Wire samples taken from the Paso Robles Overcrossing three years ago. The exposure was 21 days water curing.

   b. Wire (from Basalt Rock Company) that had been under stress for approximately 3 1/2 years in an ungrouted condition.

   c. Wire (exposed to steam) submitted by the Ryerson Steel Company. The exposure period was 18 hours.

   d. Wire units opened, inspected and "lift-off" tests performed on a building lift slab project.

3. Observations from the plant inspectors were obtained and reviewed.

V. CONTROLLED TEST PROCEDURE

General

In order to provide a better means of observing corrosion of prestressing steel (during steam and water curing of post-tensioned concrete members) than is normally possible in the process of routine inspection, a special 15 foot beam was fabricated by inspectors of this Department with the cooperation of the Basalt Rock Company.

Three flexible metal tubes 1 5/8" O.D. were placed in a curved path to simulate the conditions normally encountered in a post-tensioned beam. The test beam was fabricated with the same methods and materials that are used in contract work.

Tarps were draped over the test beam to form the steam chest, and steam was furnished at 140° F. in a saturated condition. After the steam curing test was completed, the test beam was used for the water curing test by being covered with burlap and kept wet with sprinkler hoses to simulate water curing conditions.

In the steam curing tests, 3 different types of prestressing steel were used: 0.276" diameter high tensile wire, 3/8" high tensile 7 wire strand, and 1 1/8" diameter high tensile bar.

In the water curing tests 0.276" diameter wire was used. All of the prestressing steel used was new and the surface finish was smooth and bright prior to exposure.

The curing cycles used were 3 and 7 days exposure to steam and 14 and 28 days exposure to water. In all cases when the curing cycle was complete, the prestressing steel was extracted from the tubes and transported to the laboratory for examination and photographing, every effort being made to obtain photographs of the steel in the condition that it was in at the time the curing cycle was completed.

A metallurgical report was prepared and is included in this report.

Table I of the Appendix is a table listing the prestressing steel covered in this investigation giving the type, amount, and depth of the rust layer. Exhibits II, III, and V are typical micro-photographs of the exposed steel ranging from no corrosion to excessive amounts of corrosion.

Steam Curing Cycles

The initial curing cycle of the test beam was for a 7 day period. The following samples were placed in the tubes at the time the concrete was cast; tube #1 had a bundle of eight 0.276" diameter wires, tube #2 had one 1 1/8" diameter bar, tube #3 had four 3/8", 7 strand cables.

When the steel was withdrawn at the end of the 7 day cycle, all of the samples showed a large amount of corrosion at the ends and a lesser amount approximately 3 feet inside and then a definite line of corrosion at a point where the leach water level was maintained in the curved tube. Exhibits I, III, and IV show the condition of this steel. Exhibit II: A, B, C, D, E, F, and G and Exhibit III: A, B, and C are sections magnified 36 and 110 times, and they show the type of corrosion and the depth to which the corrosion has penetrated.

The second curing cycle was 7 days under steam with an eight wire bundle of 0.276" diameter wire inserted in all three tubes; tube #1 was treated with 1/4 oz. of VPI corrosion inhibitor, tube #2 was sealed to prevent live steam from coming in contact with the wire, and tube #3 was left open to the steam. Wire #1, Exhibit IV-A, is from tube #1 that was treated with VPI Corrosion inhibitor. Wire #2, Exhibit IV-B, is from tube #2 where the ends were sealed from live steam. Wire #3, Exhibit IV-C, was sampled approximately 2 feet from the end of the beam where the tube was left open to the live steam.

The third curing cycle was 3 days under steam. Eight wire bundles of 0.276" diameter wires were inserted in tube #2 and #3 for this test. Tube #2 was sealed from live steam, and tube #3 was open to the steam. Wire #4, Exhibit IV-D, was taken approximately 2 feet from the end of the beam from tube #2 where the ends were sealed from live steam. Wire #5, Exhibit IV-E, was taken approximately 2 feet from the end of the beam where the tube was left open to the live steam.

Wire #11, Exhibit VI-A, shows a specimen that was taken from a group of wires exposed to live steam for 18 hours in an investigation at Ryerson Steel Company in January 1959.

Water Curing Cycles

The first curing cycle was 14 days and the second curing cycle was 28 days of water curing. Eight wire bundles of 0.276" wire were inserted in each tube. The tubes were not flushed out and the leach water from the original curing was allowed to remain in the curve of the tubes. The wires were extracted from tube #2 after 14 days of exposure and are represented by wire #6, Exhibit IV-F, taken approximately 2 feet from the end of the beam. The bundles of wires were extracted from tubes #1 and #3 after 28 days of exposure. Wire #7, Exhibit IV-G, was taken approximately 2 feet from the end of the beam. Wire #8, Exhibit IV-H, was taken approximately 2 feet from the end of the beam. This bundle of wires from tube #1 was treated with VPI corrosion inhibitor.

VI. SPECIFIC OBSERVATIONS

Wire #9, Exhibit IV-I, is from a group of 0.276" diameter wires used to tie together (by post tensioning) a group of precasting molds. These wires had been stressed approximately 3 1/2 years to 175,000 psi in an ungrouted condition. These wires were not subjected to steam; however, over the 3 1/2 years they were subjected to the standard forced warm air curing used on concrete blocks; this involves some moisture but is primarily a dry environment.

Wire #10, Exhibit VI-B, is a 0.250" diameter wire extracted from the Paso Robles Overcrossing approximately 3 years ago. These girders were cast in place and water cured for 21 days. The wire had not been in the structure for more than 30 days total and was removed 21 days after the concrete was cast but before being stressed. It therefore appears that most of the corrosion should be considered as occurring during the water cure.

VII. GENERAL OBSERVATIONS

In addition to the tests and observations performed for this particular project, limited observations have been made of prestressing steel (placed in compliance with current specifications) that has been in service for up to 5 years. In these few observations by visual inspection, corrosion has been found. However, in no case has it progressed to the extent that it affected structural adequacy of the member.

Although these limited field observations did not show any signs of structural failure, the tests and observations of the project covered by this report show that a corrosion problem does exist and that our specifications, rather than being too restrictive, may need to be modified to reduce still further the possibility of corrosion during the curing period. Further studies of the possibility of continued corrosion of prestressing steel after grouting are apparently needed.

Our Los Angeles area inspectors have noted little difference in visual corrosion products as the result of water curing vs. steam curing. However, they point out that they have little experience with water curing.

Our San Francisco area inspectors also have noted little difference between the two methods. They further point out that under either method when the steel is moved out of the beam after curing that the majority of rust is on the steel exposed at the ends, the enclosed steel usually having only a light coating of powder rust.

Observations that have been made on prestressed lift slabs used in State building construction show that the quality of concrete and grout fill associated with prestressed construction should be carefully controlled. Any excessive shrinking will allow moisture to come in contact with the steel.

In one building in the San Francisco area, the grout fill capping the prestressing anchorage system was chipped away and the anchorage systems exposed in four locations. In all four locations the entire stressing anchorage assembly and bearing plate had a red rust coating. There was very little pitting that was visible to the naked eye. The rusting seemed to be of a general nature covering all of the steel in the area. This building had been in service approximately 2 years at the time the anchorage systems were exposed.

Exhibit VII-A and B are photographs of 1 1/8" diameter post-tensioned, post grouted stressing steel removed from a bridge girder that had been in service for approximately 5 years. The grouting tube has been removed, exposing the incomplete grout fill in the tube. A small amount of rusting has occurred and shows as a dark contrast in the grout.

VIII. METALLURGICAL STUDY

A. INTRODUCTION

Prestressing steels which had been previously subjected to a variety of concrete curing processes, were inspected to determine the extent of the corrosion due to these processes. Those steels considered were a 1 1/8" high tensile stress rod, a 3/8", 7 wire strand, and nine 0.276" high tensile wires, and two 1/4" high tensile wires.

B. PROCEDURE

1. Specimen Preparation

In order that the oxides on the surface of the steels would be held intact against the surface during the finishing process, the steels were surrounded by a hard epoxy mixture. A cross-sectional cut was taken across the specimen. These cross-sections were then ground and lapped so that they could be inspected microscopically.

2. Metallographic Techniques

The metallograph was used for microscopic inspection and for the micro-photographing.

In order to show the fraction of the oxides which exhibit the "rust" color, the samples were examined through cross-polarizers with a red filter. In this way, the "rust" color is distinguishable from the remaining material, while the black and gray oxides also remain distinguishable from the original steel.

The specimens were inspected directly through the microscope to obtain a general illustration of each specimen, but measurements of the depth of the rust layer were taken from the photographs.

3. Visual Inspection

Prior to the preparation of the samples for microscopic inspection, the steels were inspected directly to determine the approximate surface area which was corroded.

C. DISCUSSION

1. Determining the Extent of Corrosion

The extent of corrosion would depend on the depth of the corroded pits and how much of the surface area is oxidized. The percentage of surface area corroded is a visual approximation. The measurement of depth of pits in the corroded areas did not lend itself to rapidity of study, so it was decided to use the thickness of oxide layer. While this does not present a completely true picture, it is considered sufficiently accurate for the present purpose. So as an expedient in order that the thickness of the oxide layer might be quantitatively compared, the following criterion was used:

$$\text{Depth of rust layer } (\%) = \frac{\text{Thickness of rust layer}}{\text{bar (or wire) radius}} \times 100$$

2. Recognition of Corrosion

There are a number of ferritic oxide products which may be present. Examples are FeO, Fe_2O_3, Fe_3O_4, and Fe_2O_3 hydrates. Those most common are the Fe_2O_3 hydrates which have the characteristic red rust color, Fe_2O_3 which appears gray or black, and FeO which appears black.

It is presumed that FeO and Fe_3O_4 are removed prior to or by the cold drawing operation; and since these oxides are not formed below 560° C, they are not likely to be reformed on the wire in any significant quantity during or after the draw. Thus oxides which appeared rust colored were presumed to be hydrated forms of Fe_2O_3. Those oxides which appeared black or gray and occurred as thick masses which extended irregularly into the section of the wire were assumed to be Fe_2O_3 produced by corrosion of the wire, but those which appeared in a thin even black layer over a smooth, apparently undamaged wire surface were assumed to be remnants of a scale formed during the drawing process.

It was observed that in many locations on the circumference, there existed a relatively smooth surface; whereas in other localities a rough, irregular surface was observed. Initially, the problem was to decide whether (1) the irregular surface was an indication of corrosion, or (2) these irregular surfaces were introduced by the cutting and grinding process required to prepare the specimen. To find the answer, a test was made on an uncorroded bar. It was subjected to the same preparation as the actual samples. The smooth surfaces remained intact, indicating no damage by the process. This same bar was then subjected to a very strong etch and still no noticeable damage was done. From these tests, it was concluded that the irregular surfaces could only be due to corrosion.

D. RESULTS

(See Table I)

E. CONCLUSION

The corrosion on the strand wire and the 1 1/8" stress rod was fairly heavy. Among the 0.276" prestressing wires, wire numbers 6, 7, and 8 were not corroded to any noticeable degree. Wires 1, 2, and 5 were slightly corroded, and wires 3, 4, and 9 were heavily corroded.

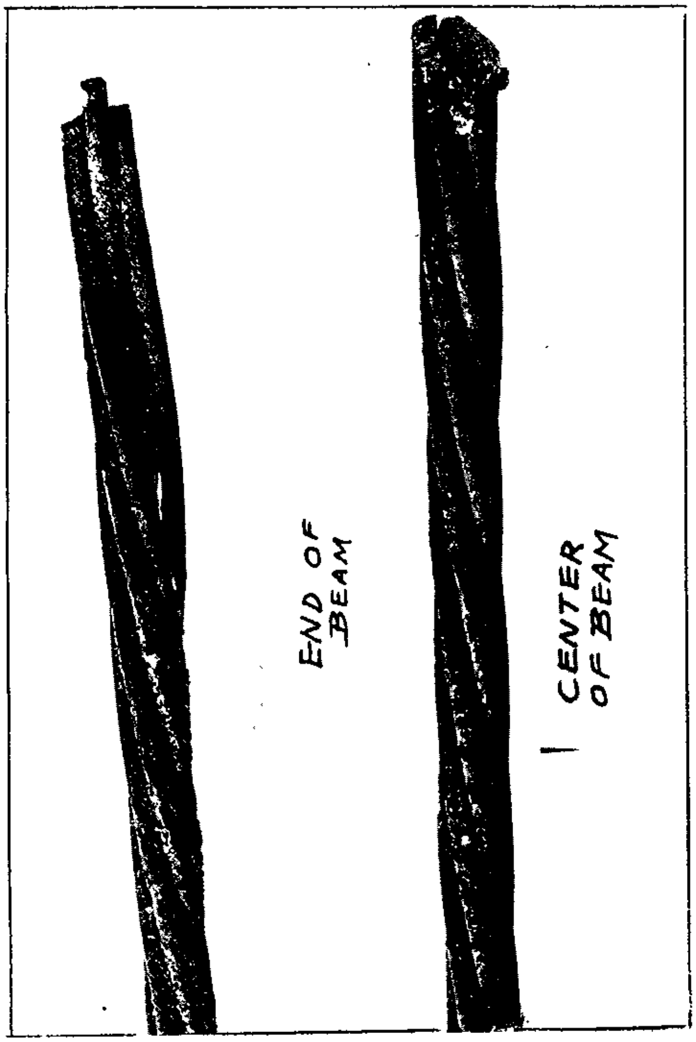
TABLE I

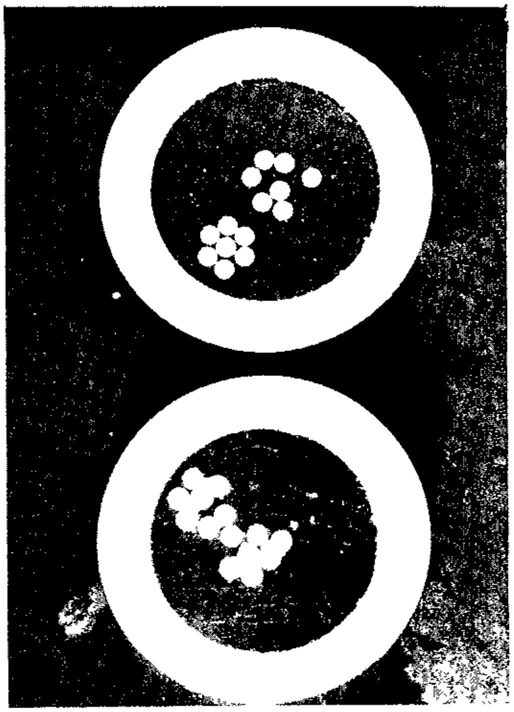
EXTENT OF CORROSION

Specimen (See Photographs)	% Surface Area Rusted	Limits of DRL *	Average Depth of Rust Layer (Mils)	Comments
Strand Wire	20 - 40	0 - 9	4.0	Each strand is similar in extent of rusting. Oxides favor one side.
1 1/8" rod	30 - 50	0 - 5	2.5	Uniform rusting with exception of spots of 5 DRL *.
0.276" Prestress Wires				
#1	3 - 7	0 - 3	2.0	Infrequent spots of rust.
#2	20 - 30	0 - 3	2.0	Frequent spots of rust. Oxides generally on one side.
#3	70 - 90	0 - 4	3.0	Heavy corrosion throughout. Uniformly distributed.
#4	35 - 45	0 - 1.5	1.0	Thin rust coat favoring one side.
#5	50 - 60	0 - 0.8	0.5	Thin rust coat.
#6	less than 1	0 - 0.4	0.2	Thin and spotty rust. Very infrequent
#7	less than 1	0 - 0.4	0.2	Thin and spotty rust, very infrequent.
#8	less than 1	0 - 0.5	0.2	Thin and spotty rust, very infrequent.
#9	70 - 90	0 - 4	3.0	Very heavy layers of rust, uniformly distributed.

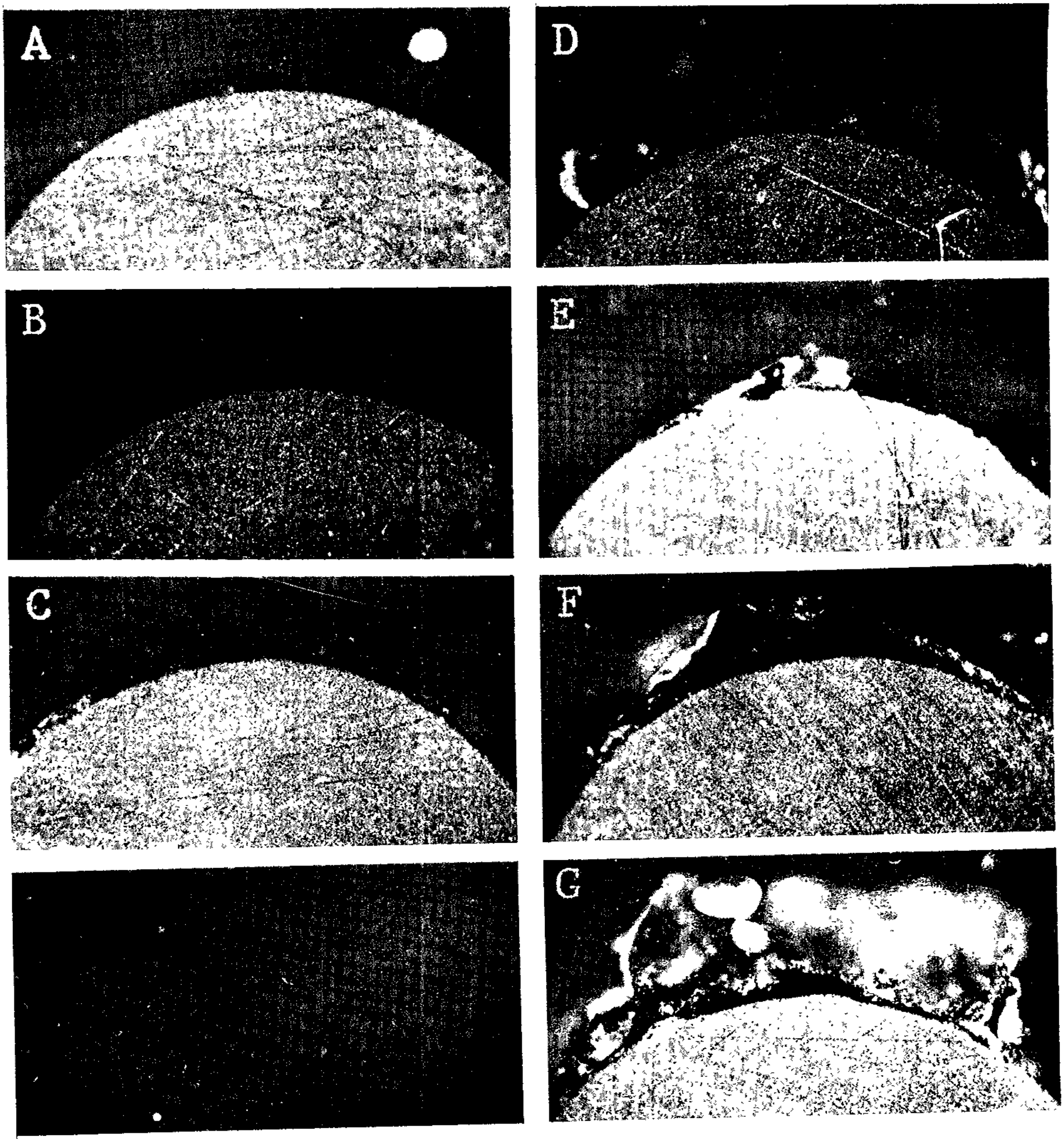
* DRL = Depth of Rust Layer. Expressed as % of radius.

3/8" 7 Wire Strand





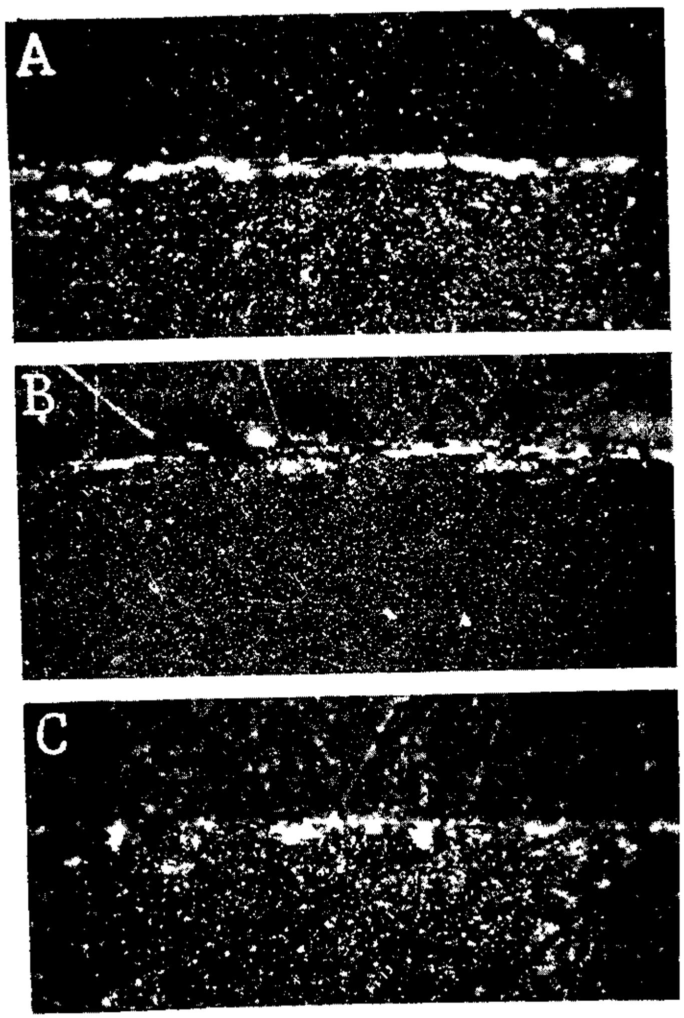
The above left specimen shows heavy corrosion. Each strand was corroded mainly on the outer surface with little corrosion on the inside. The picture on the right shows the mounting used to hold the specimen for microscopic inspection. Four different cross-sectional cuts were made across the same wire strand specimen.

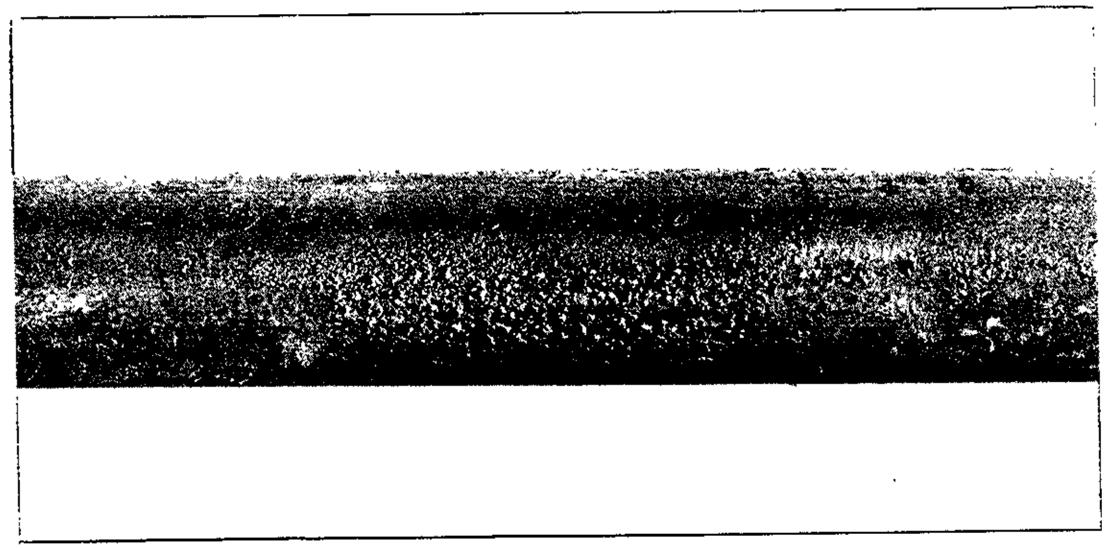


<u>3/8" Wire Strand</u> - 36 Diameters

The above are typical examples of the surface from a cross-sectional view. The white and black layers on the circumference of the wire are oxides. The white spots in the epoxy above the wire are either bubbles or foreign material embedded in the epoxy. Figures A and B exhibit no corrosion. Figure C exhibits mild corrosion. Figures D and E exhibit moderate corrosion. Figures F and G exhibit heavy rusting.

Exhibit III





1 1/8" High-Tensile Rod

Above is the specimen in actual size showing corrosion on its surface. In general the rusting is heavy and uniformly distributed with the exception of concentrations as exhibited in the lower middle of the bar.

To the left are cross-section photographs of the above bar at approximately 110 diameters. The bright white band across the middle is oxide and the occasional black patches below the band are black oxides. Above the band is the base metal. The shiny white spots in the epoxy and in the base metal are embedded impurities and not iron oxide.

0.276" High Tensile Wire

A - Infrequent spots of rust in the form of pits.

B - Frequent spots of rust generally on one side in the form of pits.

C - Heavy rusting throughout, uniformly distributed.

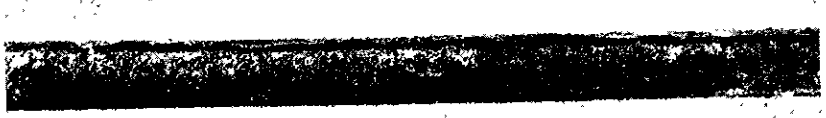
D - Thin rust coat favoring one side.

E - Thin oxide coat, some pitting.

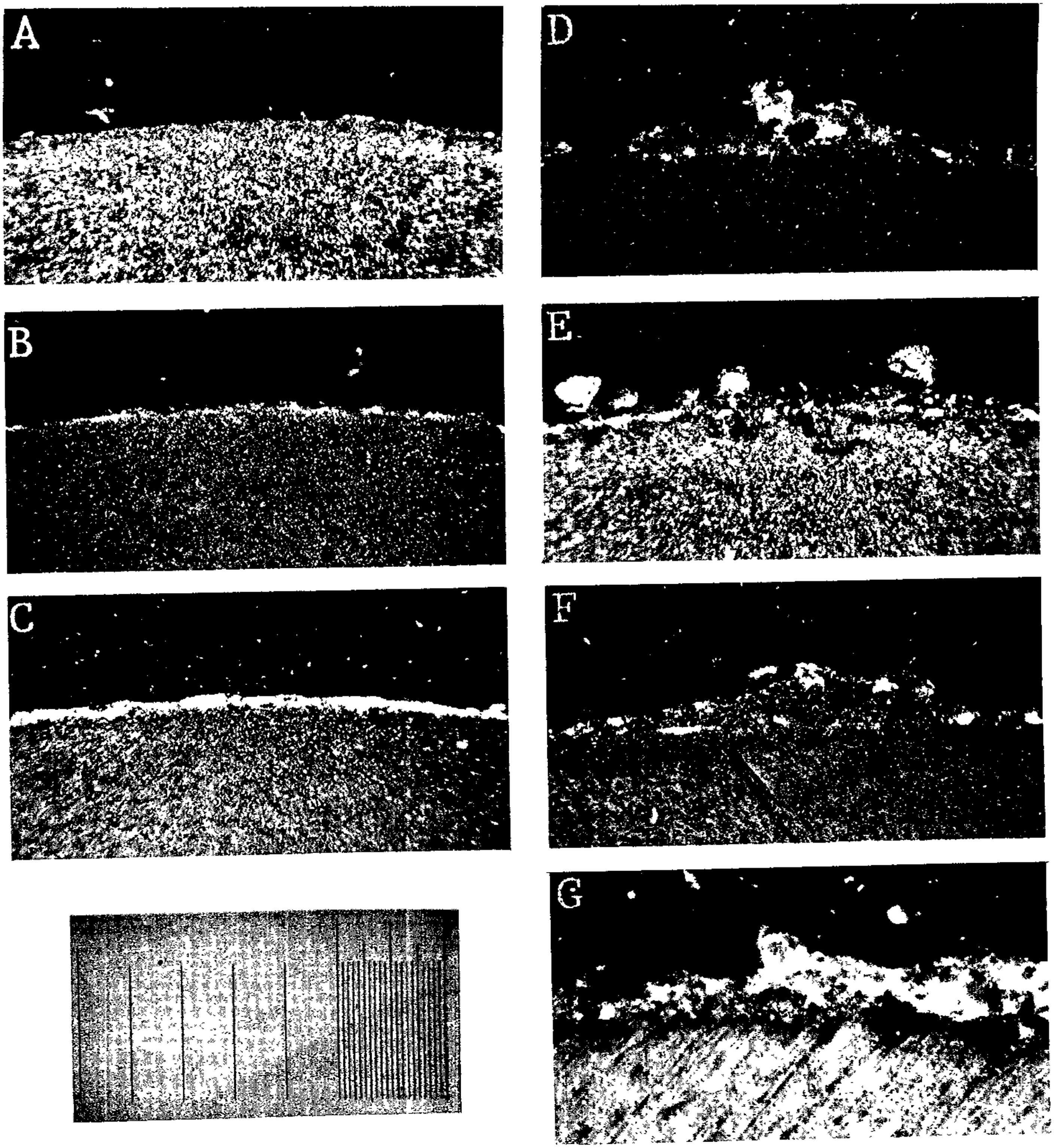
F - Clean, with the exception of a few traces of rust in spots.

G - Clean, with the exception of a few traces of rust in spots.

H - Clean, with the exception of a few traces of rust in spots.



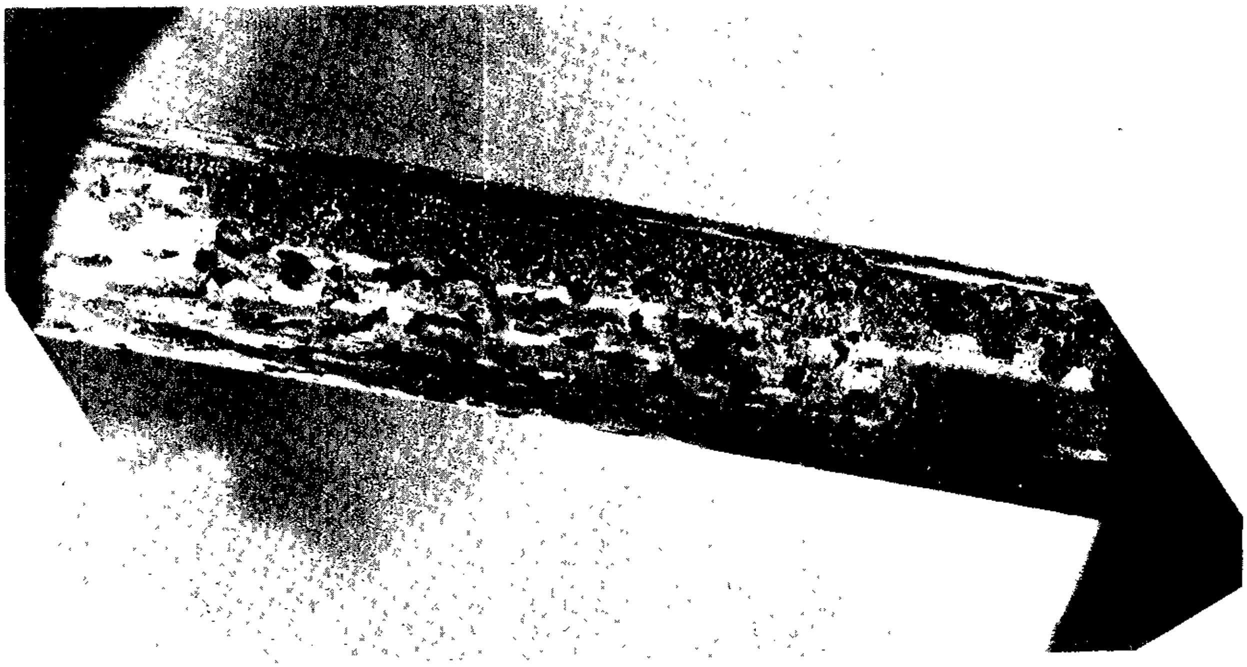
I - Very heavy layer of oxides, uniformly distributed with extensive pitting.



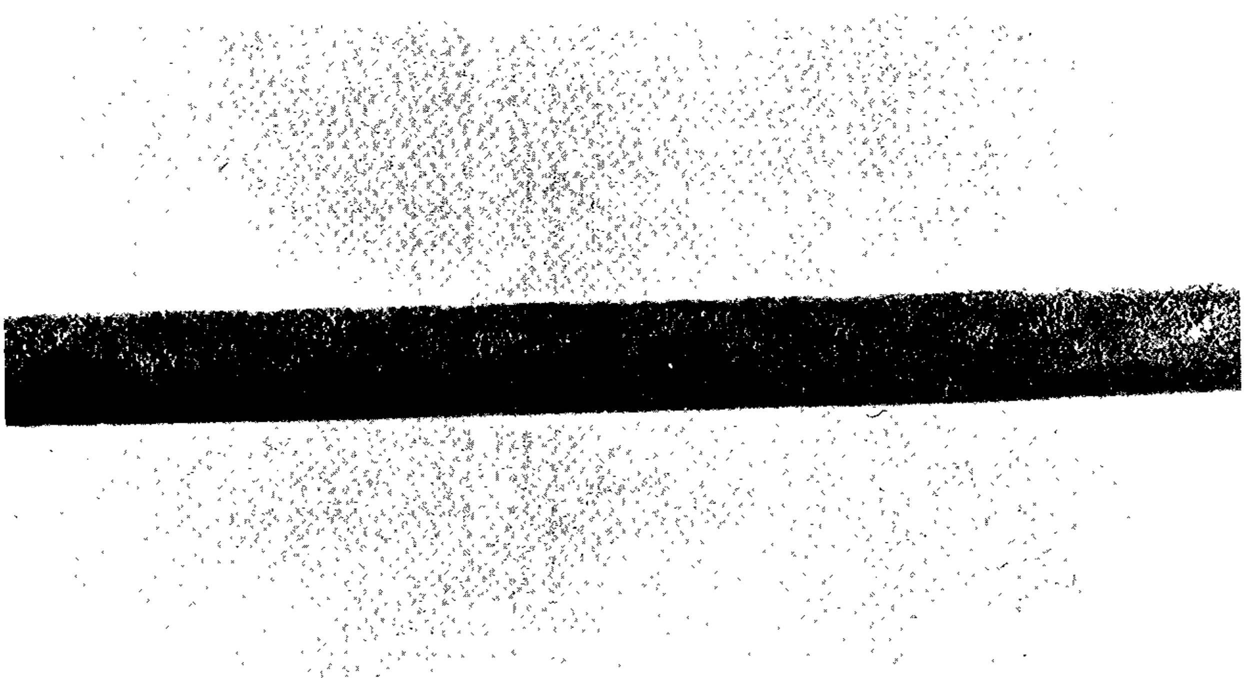
0.276" Wire at 130 Diameters

Figures A, B, and C - Exhibit negligible, light, and mild corrosion respectively. Figures D, E, F, and G - Exhibit heavy corrosion.

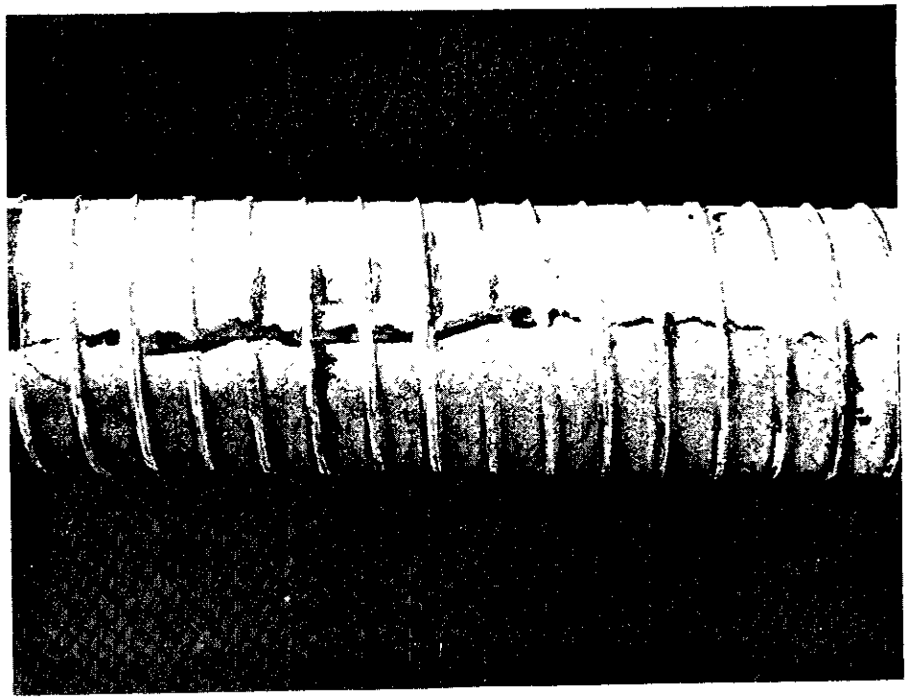
The above are typical examples of the surface from a cross sectional view. The black region in the top portion of each picture is the epoxy plastic which surrounds the wires. The bright specks in the plastic are either bubbles or foreign material which was lodged in during the grinding and lapping process. The oxides are plainly seen between the plastic and the base metal. They show up white, dark gray, or black depending on the type of oxide.



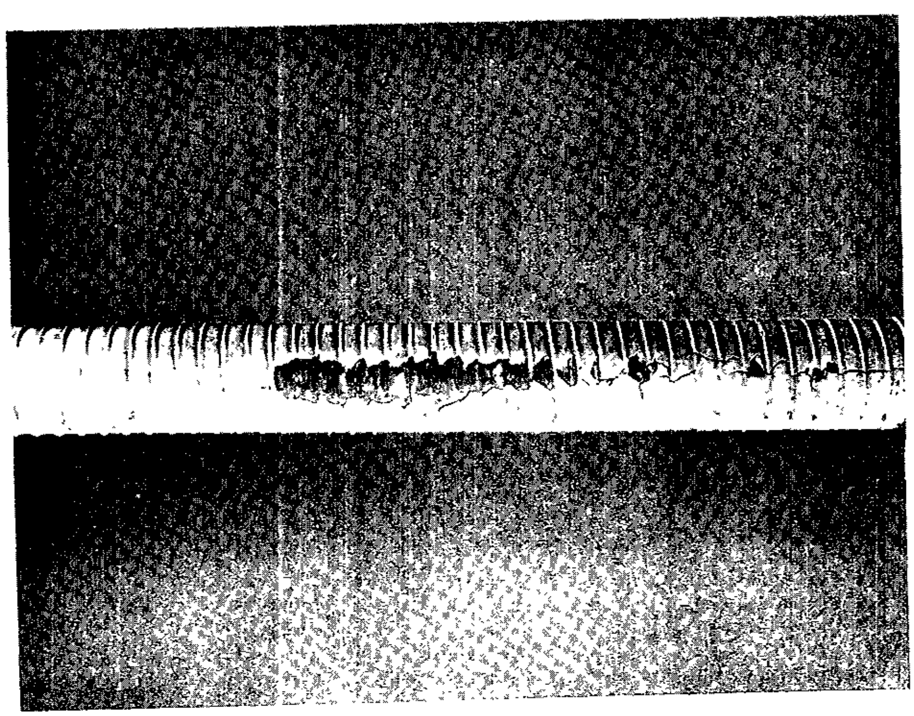
A



B



A



B