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PRESTRESSED CONCRETE PIPE FAILURE JORDAN AQUEDUCT, REACH 3

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16. ABSTRACT

The Bureau of Reclamation conducted failure investigations to identify the cause(s) of a catastrophic rupture of prestressed concrete pipe under impressed current cathodic protection, which occurred on Reach 3 of the Jordan Aqueduct near Salt Lake City, Utah, on August 7, 1984. The multidisciplinary analyses included corrosion, design, petrographic, structural, and metallurgical investigations. From the onset of the failure, the issue was one of reconciling cathodic overprotection and defective (longitudinally cracked) prestressing wire. The report contains a summary of the findings from Reclamation investigations.

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PRESTRESSED CONCRETE PIPE FAILURE JORDAN AQUEDUCT, REACH 3

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CONTENTS

TABLES

FIGURES

CONTENTS—CONTINUED

FIGURES—CONTINUED

Figure | Page

INTRODUCTION

Background

On August 7, 1984, a 66-inch-diameter prestressed concrete cylinder pipe unit abruptly failed on Reach 3 of the Jordan Aqueduct near Salt Lake City, Utah. Reach 3 is part of the 36-mile-long Jordan Aqueduct, which conveys municipal and industrial use water from near the mouth of Provo Canyon to the Salt Lake Valley. Reach 3 consists of 3-1/4 miles of pretensioned concrete cylinder pipe and 2-1/4 miles of prestressed concrete pipe, which traverses both residential and commercial areas (fig. 1). Both pipes were cathodically protected with impressed current systems. The rupture occurred in the prestressed section of the line. This abrupt failure caused rapid and complete loss of pressure which essentially emptied the line, discharging an estimated 5 million gallons of water. The subsequent flood covered a one square city block area of the residential neighborhood adjacent to the break.

The pipeline was constructed under Reclamation (Bureau of Reclamation) Specifications DC-7412. The section that failed was placed and backfilled in September 1981; the cathodic protection system was energized in April 1983. The line was placed into service in July 1984, and the failure occurred 1 month later.

The opinions, findings, and conclusions cited in this report are those of Reclamation personnel. The producer of the prestressed concrete pipe used for Jordan Aqueduct, Reach 3, conducted their own investigation of the failure. Their conclusions do not necessarily agree with those of Reclamation.

Embedded Cylinder Prestressed Concrete Pipe Components and Fabrication

Embedded cylinder prestressed concrete pipe (fig. 2) consists of a mild steel cylinder, which serves as the impermeable membrane, embedded in a concrete core, which is the compression component. The inner core, that portion of the concrete core within the steel cylinder, doubles as the corrosion preventive lining for the steel cylinder. After the core has cured, a cement slurry is applied and high-carbon, high-strength (ASTM A 648) steel prestressing wire is helically wound on its surface at a mean wrapping stress of 75 percent of its specified minimum ultimate tensile strength. In this particular case, two diametrically opposite steel straps (1-1/4 inches wide by 0.03 inch thick) were placed longitudinally on the core surface prior to wrapping. These straps reduce the electronic current return path resistance from the wire, thereby enhancing current collection by wire surfaces. Nonetheless, the electronic resistance along the straps is about 200 times that of its parallel counterpart (steel cylinder) per foot of pipe. A 3/4-inch-thick cement mortar coating over the wire completes the pipe construction and serves to protect the wire from handling damage and corrosion effects.

The pipe uses steel bell-and-spigot joint rings which are gasketed by rubber O-rings to provide the joint seal. The swedge-type anchors, which maintain stress on the wire at the bell and spigot ends, are electrically bonded to the steel joint rings to provide electrical continuity of all metallic components within each pipe unit. Joint bonds are installed after adjacent units of pipe are placed to provide electric continuity across the rubber gaskets. A diaper is then placed around the joint and the annular space is filled with cement grout for external corrosion protection of the joint rings. The internal surfaces of the joints are mortared for internal protection.

Initial Observations

Pipe unit 797, which burst, was designed for 400 feet of head and 10 feet of earth cover. This unit was located 160 feet from a cathodic protection ground bed. Observations of the rupture disclosed that the No. 8-gage (0.162-inch-diameter) prestressing wire (class III) failed near spring line for a length along the pipe of about 7 feet (fig. 3). Wire fractures exhibited cup-and-cone matching surfaces with essentially no macroscopically observable reduction in area (figs. 4 and 5). The 5-1/4-inch-thick core and steel cylinder failed slightly below spring line.

Closer examination after rupture revealed that the wire was cracked along its longitudinal axis (fig. 6). The crack, when forced open, revealed an oxidized layer and dark red deposits on the crack surfaces (figs. 7 and 8).

Unit 797 failed while under a static head of 366 feet. Analyses for transients indicated that operating procedures were not likely the cause for the rupture.

The cathodic protection system for the 2-1/4-mile-long stretch of prestressed pipe consisted of three, essentially equally spaced, semi-deep-well (100-foot), impressed current ground beds (fig. 9). The specified criteria for cathodic protection required a current-applied protective potential of –0.85 volt or more negative as referenced to copper/copper sulfate electrode. Additionally, a polarized (current interrupted) potential of –1.10 volts or less negative was specified to preclude overprotection effects. Thus, the –0.85-volt criterion was effectively removed from ground beds, and the –1.10-volt level became operative adjacent to ground beds.

A potential survey conducted soon after failure revealed a polarized potential of –1.16 volts at the ground bed near the ruptured unit. Following failure, the ruptured pipe exhibited a polarized potential of –0.96 volt. Further, a potential survey of each wire coil with a close electrode disclosed a maximum wire polarized potential of –1.07 volts (fig. 10).

A potential survey conducted 6 months after the burst and after replacement of the ruptured unit showed that the pipeline was protected above the maximum polarized potential criterion at all locations within 200 feet of each of the three ground beds (fig. 11). Polarized potentials as high as –1.24 volts were observed immediately adjacent to the ground beds. In one 600-foot span at the upstream end, protective potentials as low as –0.30 volt were observed. Electronic discontinuity was determined to be the cause for these low potentials.

CONCLUSIONS

Reclamation investigations indicated that the pipeline rupture was caused by the overload of the highly stressed, defective prestressing wire. This conclusion is based upon the following findings:

1. Longitudinal cracks existed in all examined prestressing wire samples.

2. The wire was defective because longitudinal cracks were present in the prestressing wire at the time of pipe manufacturing.

3. The prestressing wire of the ruptured pipe fractured in a ductile manner and the longitudinal cracks were instrumental in the fractures. Inspection of the fractured ends

of the wire from the failed pipe section showed a combination of two types of failure, including a cup and cone ductile failure in combination with a sharp tongue formed by an offset between longitudinal cracks in the wire. This finding indicated the failure was initiated by stress concentrations at the termini of the longitudinal cracks.

4. The high stresses applied to the prestressing wire during the winding operation were also instrumental in the fracture of the prestressing wire. Reclamation testing indicated that the wire was wound at tensile stresses exceeding the specified level.

5. Although the failed pipe section was cathodically protected at polarization potentials above the specified level, no tangible physical evidence was found to indicate excessive cathodic protection resulted in hydrogen embrittlement, fracture of the prestressing wire, and subsequent pipeline failure.

Based on findings from Reclamation's investigations, it is concluded that defective wire was used in the manufacture of the pipe and that it likely was wrapped on the pipe at stresses which exceeded Reclamation specifications. The prestressing load produced stress concentrations at unstable crack termini exposed to the outer side of wire bends and caused the offset, overlapping longitudinal cracks to grow inwardly (toward the center of the wire cross sections), thereby reducing the effective load-carrying area. The situation was likely aggravated by standard pipeline operating procedures, such as valve closings, which could have caused surges and flexing of the highly stressed prestressing wire. As sufficient load-carrying area was removed, instantaneous ductile failure of the wire occurred with little reduction in area observed. The pipe ruptured when sufficient individual wire helices failed such that the pressure could not be contained.

Examination of the wire through several inspection windows along the pipeline revealed defective wire throughout the prestressed section. Therefore, all 2.3 miles were rehabilitated by lining with steel prior to commissioning for service.

FAILURE INVESTIGATIONS

Two units of pipe, No. 797 (the ruptured unit), and an adjacent unit, No. 798, closer to the ground bed, were removed from the pipeline for laboratory investigation and testing. In addition, pipe was uncovered and the mortar coating was removed at eight additional locations along the line to expose inspection windows for wire testing and sampling. Unit 798 was also pressure tested. Hydrostatic testing to 750 feet of head (design head was 400 feet) disclosed no visually apparent distress.

Petrographic Examinations

Petrographic examinations of concrete fragments from the pipe core revealed that the concrete was of satisfactory quality and exhibited no evidence of environmental attack. The mortar was adjudged of fair quality, but perhaps typical of pipe mortar coatings. The only anomalous observation was the presence of some ridges on the concave surfaces of the mortar.

Metallurgical Examinations

Longitudinal cracks. - Although all wire samples exposed by the failure were found to have suffered incipient corrosion from atmospheric and ground-water effects, wires removed from beneath intact mortar were untarnished except where protective potentials below specified criterion were observed.

Initially, the wire from the ruptured unit was found to contain longitudinal cracks. Subsequently, the wire was found to be cracked longitudinally on unit 798, as well as at eight other locations along the line where wire was removed for examination. Cracking was verified either by dye penetrant or, if that technique provided inconclusive results, by subsequent magnetic particle inspection as confirmed by metallographic examination of cut and polished sections.

The cracks normally extended over the length of the examined wire (i.e., 2-foot lengths of wire removed from inspection windows and several coils of wire removed from the pipe circumference of units 797 and 798) in a discontinuous, overlapping pattern. The discontinuous cracks were parallel on the wire surface, but were randomly oriented around the wire circumference with respect to its bending axis. In some cases, the cracks spiraled around the wire circumference and terminated. In such cases, another crack originated diametrically opposite the terminating crack. A large number of wire samples were found wherein the crack ran along a surface defect (die mark). These cracks were very straight for great lengths (i.e., several feet to several coils of wire) (Mote, 1985a). Longitudinal cracking was also observed on the free (unloaded) ends of the wire at the bell anchors of both units 797 and 798.

Because petrographic examinations of the mortar coating had disclosed ridges in the concavity formed by the wire, the coating opposite wider, longitudinal cracks in the wire was closely inspected. In many cases, the surfaces of the concavity exhibited a ridge or imprint of the corresponding longitudinal crack (figs. 12 to 14). X-ray spectral analyses showed the ridge, the smooth surfaces of the concavity, and the fractured mortar surfaces between concavities to be of the same elemental composition. The major constituent was calcium, and moderate amounts of silicon and aluminum were found. No cracking of the mortar was observed beneath the ridges (fig. 15).

In some cases, particles of solid material were seen lodged within longitudinal cracks (figs. 16 to 20). Energy dispersive, elemental x-ray spectral analyses showed the major constituent of the particles to be silicon. The appearance of the particles was that of quartz grains.

Metallographic examinations of the wire's cross section also showed that the longitudinal cracks were radially oriented and varied substantially from a few hundredths of an inch (fig. 21) to a radius or more in depth (fig. 22). On some cross sections, two parallel cracks on the wire surface could be seen to join or nearly join (fig. 23). Longitudinal sectioning exhibited many instances where longitudinal cracks overlapped or joined such that a filament of steel was observed between the cracks (figs. 24 and 25).

When the longitudinally cracked wire was split open by notching at close intervals with bolt cutters, the crack surfaces were found to be covered with an adherent layer of rust. Energy dispersive x-ray analyses of the rust-covered crack surfaces disclosed iron, oxygen, sodium, silicon, potassium, and calcium. X-ray analyses of a wire from the failure site detected only iron on the fracture surface (Mote, 1985a).

Transverse wire fractures. - The intact bell end of unit 797 exhibited many fractured coils (fig. 26) which were largely located over or near one of the bonding straps. This unit was oriented in service such that the bonding straps were at the 3 and 9 o'clock positions. Wire fractures were also noted on unit 798 (fig. 27) when the mortar coating was removed after pressure testing. However, they were fewer in number and randomly located about the pipe circumference. The bonding straps were at the 5 and 11 o'clock positions on this unit in service. No other wire fractures were observed at other locations along the line where windows were opened for wire inspection.

Wire was found to be fractured on the stressed side of the unit 798 bell anchor (fig. 28). The fracture originated at a notch in the wire formed by the swedge-type anchor (fig. 29). The fracture was imprinted in the concavity of the mortar coating opposite the anchor (figs. 30 and 31). Spectral analyses indicated that the imprinted crack, the smooth surfaces formed by the wire and anchor, and the fractured surface of the mortar consisted of calcium and progressively lower amounts of silicon and aluminum.

Field fracture morphology. - All 245 field-fractured coils of wire were sampled from unit 797 both above and below the rupture. Matching resulted in pairing 109 fractures such that the wire on both sides of the fractures could be inspected. Paired fractures from unit 798 were also examined. The examination revealed that all matched fractures occurred at cross sections where a crack terminated and another originated (fig. 32). In addition, fracture morphologies consistent with overload failure were apparent. These fractures were of the ductile cup and cone type in combination with a sharp metal tongue formed by offsetting, overlapping longitudinal cracks (figs. 33 to 35). No areas of typical brittle fracture were observed. Extensive examination of wire surfaces failed to reveal a single secondary transverse crack extending only partially into the wire cross section. Either the wire was totally fractured or only longitudinal cracks were found (Mote, 1985a).

Field Testing

Field testing was conducted to inspect exposed wire as well as to determine the existing *in situ* stress level. Reclamation selected six random locations along Jordan Aqueduct for examination and testing. At each location, the bonding strap was electromagnetically located and the mortar coating was removed to expose the underlying prestressing steel in windows about two feet square. Some of the locations were directly opposite ground beds, and others were midway between so that areas representing a wide range of polarized potentials were evaluated (fig. 9).

Inspection windows. - At each inspection window, the exposed, *in situ* wire was subjected to dye penetrant testing to assist in the identification of possible wire irregularities such as longitudinal cracks. Only a limited portion of the wire was visible, however, because the testing was performed *in situ*. If cracks existed along the side of the wire at the mortar interface, they were difficult to identify because of smearing by the dye. Also, cracks on the underside of the wire could not be seen. To confirm the existence of longitudinal cracks, removed wire samples were subjected to magnetic particle inspection and metallographic examination. The dye-penetrant testing, however, showed cracking at stations 1470+00, 1447+00, 1427+00, and 1400+30 and was inconclusive at stations 1396+00 and 1394+60 (table 1).

Stress-relief testing. - Upon completion of the dye testing, stress-relief tests were conducted at each test site adjacent to the inspection window. The in-place testing procedure consisted of attaching a strain gage to the prestressing wire, cutting the wire, and measuring the strain relaxation. Great care was taken to develop a test method which minimized or eliminated torsion, bending, and shock effects. After much experimentation, the following procedure was implemented:

1. Two holes about 2-1/2 inches in diameter were chipped in the mortar coating, one above the other in a line along the circumference of the pipe. The holes were separated by 1 inch of intact mortar coating. A minimum amount of prestressing wire was exposed in the holes for strain gage attachment and most of the wire remained encased in the surrounding mortar (figs. 36 and 37).

2. A strain gage (Ailtech SG-129) was attached to the prestressing wire in one hole while the wire remained stressed around the pipe under *in situ* tension (figs. 38 and 39).

3. A strain indicator was set (Measurements Group P-350 or P-3500) and the initial strain reading was zeroed (fig. 40).

4. The prestressing wire was cut in the second hole to relieve the tension on the wire, and a strain reading was obtained (fig. 41).

5. The mortar bridge separating the two holes was removed (figs. 42 and 43).

6. The wire was held down near the strain gage with a specially fabricated mandrel and a final strain reading was obtained. The mandrel was cut on the same wire radius as that of the pipe and was slotted to prevent damage to the strain gage (fig. 44). In many cases, strain readings obtained in step 4 and step 6 were similar. However, in limited cases, it was apparent that the mortar bridge had restrained the wire (step 4) from becoming totally stress-relieved.

The cut wire then was removed from the pipeline and taken to the laboratory. In the laboratory the wire was straightened, reinstrumented, and tested in tension to produce a stress-strain curve. The field-measured strain was then converted into field stress using the stress-strain curve. Measured field wire stresses ranged from 150,000 to 185,000 lb/in^2 under no-service loads. The field procedure was validated in a controlled laboratory study (Peabody et al., 1986).

Laboratory Testing

Validation of field testing. - The laboratory study consisted of fabricating an aluminum half mandrel with the same radius as the prestressed concrete pipe core (fig. 45). A guide slot was cut into the mandrel so that when a wire sample was placed into the slot, about 20 percent of the wire surface was not in contact with the mandrel. The guide slot was lubricated with oil to minimize the friction between the contact points of the wire and the mandrel. Wire samples, with a length greater than one-half the circumference of the pipe core, were cut from Jordan Aqueduct pipe segments to serve as test specimens. Shorter samples of wire were also cut from the longer samples.

The field testing was validated by simulating the field test on the laboratory half mandrel. A wire sample was loaded on the mandrel in tension to a known measured stress. A strain gage was placed on the wire 4 inches away from the applied load (where friction was negligible), the wire was cut, and strain relaxation was recorded (fig. 46).

The shorter samples of wire which were removed from the longer wire samples prior to mandrel testing were then straightened, instrumented, and tested in tension to failure in a testing machine to produce stress-strain curves. The predicted stress corresponding to the strain relaxation measured by cutting the wire on the mandrel was obtained from the straight wire stress-strain curve. Predicted stress was then compared to the known wire stress measured on the mandrel at the time of stress relieving. The predicted stresses were always lower than the measured stresses, indicating the need for a correction factor (table 2).

The correction factor was determined to be +9 percent. After correction, wire stresses were found to range from 161,000 to 201,000 lb/in^2 for the in-place pipe at the six field test sites. Considering assumptions for stress loss over time resulting from elastic deformation, creep, and shrinkage of the pipe core and subsequent relaxation of the wire when properly wrapped, stress levels at the time of testing should have ranged between 140,000 to 170,000 lb/in^2. The measured values, therefore, exceeded those predicted by design at the time of stress relieving (table 3).

Destructive testing. - Laboratory testing was also conducted on wire from the failure site to verify compliance with the destructive test criteria of ASTM A 648-73 (fig. 47), which was in effect when the pipe was fabricated. During tensioning, the wire was loaded at rates specified in ASTM A 370. After fracture, the ends of the broken specimen were fitted together and the dimensions of the smallest cross section were measured to the nearest 0.001 inch. The area reduction was calculated as the difference between the area after fracture and the initial area, expressed as a percentage of the initial area. Although ASTM A 648-73 did not contain an area reduction criterion and placed no upper limit on the tensile strength, its successor, ASTM A 648-84, required that class III wire achieve a tensile strength ranging from 262,000 to 297,000 lb/in^2 for 8-gage wire and a minimum area reduction of 30 percent. As the data indicate, wire from the failure site (pipe 797) met the tensile strength requirements of both ASTM A 648-73 and ASTM A 648-84, but failed to meet the ASTM A 648-84 area reduction criterion. The mean tensile strength of ten samples was 283 kips/in^2 with a standard deviation of 3.9 kips/in^2 and a coefficient of variation of 1.4 percent. The mean area reduction of the same samples was 13.8 percent with a standard deviation and coefficient of variation of 6.7 and 48.5 percent, respectively (table 4). Wire from pipe 798 also achieved the required tensile strength and exhibited a mean of 288 kips/in^2 with a standard deviation of 2.4 kips/in^2 and a coefficient of variation of 0.8 percent for the ten samples tested. The average reduction in area of three of the ten samples was 10.5 percent with a corresponding standard deviation and coefficient of variation of 1.2 and 11.4 percent, respectively. Many specimens failed at the jaw-wire interface, indicating wire susceptibility to notch effects. The area reduction measurements were not tabulated in these cases (table 4).

In-service wire fractures with further reduced, or no, neck down were reproduced in the Reclamation laboratory by rapidly loading Jordan wire to failure in tension. To perform these tests, specimens were preloaded to about 60 percent of the minimum ultimate tensile strength of the prestressing wire at a rate of 50 kips/in^2/min and rapidly loaded to failure at 1100 kips/in^2/min. One of the fractures (17 percent) occurred in the free length between the jaws and exhibited virtually no neck-down when tested in this manner (fig. 48).

Wire from stations 1499+56 and 1478+44 was also tested to failure in tension. This wire contained severe longitudinal splits visible to the unaided eye but was protected at potentials within criteria while in service. The average reduction in area of 6 samples was 26.5 percent and the corresponding standard deviation and coefficient of variation were 5.9 and 22.1 percent, respectively (table 5). The wire therefore failed to meet the ASTM A 648-84 minimum reduction in area criterion. Also, one specimen failed below the minimum required tensile strength.

Wrap tests were performed by closely wrapping prestressing wire about a mandrel twice the nominal wire diameter. A specimen is considered to have failed if any cracks appear in the wire after the first complete turn. All specimens from unit 797 and unit 798 failed the wrap test (table 4). Wire from unit 797, however, commonly failed the wrap test by breaking whereas wire from unit 798 usually could be wrapped around the test mandrel without breaking. Wire from stations 1499+56 and 1478+44 passed the wrap test (table 5). In many cases, wrap test specimens showed no visible signs of cracking in the wrapping coils, but longitudinal cracks were easily split open on the ends with bolt cutters (fig. 49).

Longitudinal cracks that were not found with the wrap test were often revealed by the bolt cutting test (tables 1, 4, 5). The bolt cutting test was not specified in ASTM A 648-73, but was useful in revealing defects. The test was performed by cutting a wire, rotating the wire 90° about its longitudinal axis, and cutting the wire a second time 3 inches away from the first cut. Cracks that were not identified in the original 3-inch sample were sometimes found with additional cutting at different angles, but not in all cases. Wire which had passed both wrap and bolt cutting tests was found to be cracked longitudinally when inspected microscopically or by magnetic particle techniques.

Hydrogen Embrittlement Exemplar Testing

Almost from the onset of the investigations, explanations for the cause of rupture focused upon the effects of cathodic overprotection that was speculated to have produced wire failure by hydrogen embrittlement. Reclamation conducted several studies to examine this possibility. One study attempted to produce brittle failures of wire in laboratory conditions that were representative of the field environment but more severely stressed and more highly polarized. Wire was tested in simulated concrete (saturated $Ca(OH)_2$) environments (pH = 7 to 12.5), loaded to 90 percent of the minimum ultimate tensile strength of the wire, and locked off. The specimens were cathodically protected, some at polarized potentials near −1300 millivolts, with corresponding cathode current densities up to 35 A/ft^2 (fig. 50). After 5 years of testing under sustained load, no longitudinal cracking or failure attributable to hydrogen embrittlement occurred for the exemplar wire tested. Failures that did occur were determined to be ductile and near the electrolyte/atmosphere interface, where protection was ineffective and active pitting was observed (Mote, 1985b).

In a separate series of tests, hydrogen-induced brittle fractures were produced by cathodically charging wire in a 4-percent solution of sulfuric acid with 50 milligrams of arsenic per liter both before and during stressing. The resulting fractures all exhibited a characteristic ledge or step perpendicular to the longitudinal axis (figs. 51 to 54). Wires tested in this manner also exhibited secondary partial transverse cracking (figs. 55 and 56) (Mote, 1986).

In a third study, bulk hydrogen contents were measured on wire near the failure site after cathodic protection was reestablished to −1210 millivolts for 3 weeks and were compared to the bulk hydrogen contents of laboratory samples of Jordan wire fractured while cathodically charged under load in an acidic environment. Comparisons were also made to the bulk hydrogen content of new wire that was cathodically charged at polarized potentials near −1300 millivolts in a basic environment for over 15 months without failure (Mote, 1987). Wires removed from the Jordan Aqueduct pipeline showed average hydrogen contents of 3.38, 3.08, and 2.26 p/m at stations showing measured potentials of −1210, −980, and −710 millivolts, respectively. Laboratory samples fractured in an acidic environment (4-percent solution of sulfuric acid with 50 milligrams of arsenic per liter) showed hydrogen contents up to 17.6 p/m. In addition, new wire that was tested in a basic solution and held under a sustained load of 70 percent of the minimum tensile strength of the wire for over 15 months without failure exhibited an average hydrogen content of 6.27 p/m.

DISCUSSION

The cause for the pipeline failure became an issue of reconciling the effects of cathodic overprotection and the longitudinal cracks found in the prestressing wire. This issue is addressed below. Conclusions are followed by a summary of the supporting evidence.

Longitudinal cracks existed in all prestressing wire examined.

Longitudinal cracks were found in all examined wire from various locations along the pipeline. The cracks typically ran the entire length of the wire (i.e., 2-foot lengths of wire removed from inspection windows and several coils of wire removed from the pipe circumference of units 797 and 798) in a discontinuous, overlapping, and offsetting pattern, but were randomly oriented around the wire circumference with respect to the bending axis. In some cases, the cracks spiraled around the wire circumference and terminated. Another crack then originated diametrically opposite the terminating crack. A metallurgist concluded that the longitudinal cracks were overstress failures from residual stresses induced during manufacturing and/or the prestressing operation. The cracks varied in depth from a few hundredths of an inch to a radius or more in depth (Mote, 1985a).

The wire was defective because the longitudinal cracks were present in the prestressing wire at the time of pipe manufacturing.

The fractography of characteristic in-service wire fractures, as well as those generated by tensile testing, showed that the longitudinal cracks were a primary material factor in the rupture. Thus, a determination of when the longitudinal cracks existed became relevant. The oxidized surface of the cracks showed that they existed prior to energization of the cathodic protection system because the wire likely did not oxidize in this manner while under cathodic protection in the highly alkaline environment of the mortar coating. The surfaces of the longitudinal cracks in wire from the failure site also contained dark-red deposits. Energy dispersive comparisons between deposits on an in-service field fracture and those on the surface of a longitudinal crack indicated that the longitudinal crack was older than the field fracture. The longitudinal crack surface contained iron, oxygen, sodium, silicon, potassium, and calcium, whereas only iron was detected on the field-fractured surface.

The particles lodged in wider cracks were determined to be largely silicon and appeared to be quartz. The particles are undoubtedly fine grains of sand, which indicates that the cracks existed while the mortar coating was plastic. Although a few particles could have fallen into the longitudinal cracks from gravity effects, Reclamation inspections revealed numerous particles that were lodged and cemented in cracks. Particle impaction could only occur during the pipe manufacturing process when mortar is sprayed on the prestressing wire. Therefore, the impacting or forcing of particles into cracks most likely occurred during the pipe manufacturing process, indicating the existence of cracks at that time.

The inner surface of the mortar coating forms a cast of the surfaces of the prestressing wire. The longitudinal cracks in the wire were found to be embossed on the mortar. The resulting ridge, the smooth surfaces of the concavity formed by the wire, and fractured mortar between concavities exhibited the same composition of a major amount of calcium and moderate quantities of silicon and aluminum, essentially the composition of portland cement. Ridge formation on the mortar surface must have occurred while the mortar was in the plastic state. Because the mortar coating is applied after the pipe core is wrapped with prestressing wire, the presence of the ridges on the concavity of the mortar indicates the defects forming the ridges were present at the time of wrapping and before application of the cathodic protection. The imprints thus add further credence to the conclusion that the wire was cracked while the cement slurry and mortar coating were in a plastic condition.

The condition of the mortar under the embossed ridges provides further evidence. No cracking was found. Because the mortar is a brittle (strain intolerant) material, radial cracks in the mortar should be evident if wire cracking occurred after the mortar coating had hardened.

Discontinuity of the ridge was also an important revelation. Ridges can form as a result of wire die marks, although wire with die marks serious enough to result in the formation of ridges would not comply with specifications (ASTM A 648-73, sec. 9.1) for use in pipe production. Die marks occur as die defects are etched onto the wire during drawing. If a ridge attributable to a die mark was formed on the wire, the pattern would be straight and continuous because it is a reflection of a consistent defect on the die surfaces. The longitudinal crack defect on the prestressing wire, however, exhibited a characteristic discontinuous offsetting and overlapping pattern. If mortar was sprayed upon cracked wire during pipe manufacturing and ridge formation occurred at that time, the discontinuous offsetting pattern should also be observed on the concavity of the hardened mortar coating. Reclamation investigations have revealed this phenomenon when ridges in the concavity of the mortar were related to longitudinal wire cracks. Both ridges that were straight and formed by straight preexisting longitudinal cracks in the wire, and ridges that were offset and formed by preexisting offsetting longitudinal cracks in the wire, were observed. Metallurgists also have related ridges in the mortar concavity to longitudinal cracks in the wire (Mote, 1985a), (Klodt, 1985).

The random orientation of longitudinal cracks about the wire circumference with respect to its axis of bending also showed they were not related to die marks from the drawing process. Longitudinal cracking of newly manufactured wire would most likely occur at the outermost fiber of the bend as it was wrapped on the original wire spool. To determine if the wire is cracked on the surface adjacent to the concrete core, however, the wire must be removed from the pipe. When removed, the wire assumes a different curvature and orientation which is not representative of wire as wrapped on the pipe. Observations regarding the orientation of longitudinal cracks with respect to the curvature of the wire would then most likely be valid for the wire orientation on the wire spool and not around the pipe. Such observations indicated that the longitudinal cracks were likely present at the time of wrapping because they were randomly oriented with respect to the curvature of the wire on the pipe.

The most important observation regarding this matter is that longitudinal cracks were found on the unstressed side of wire anchors. Longitudinal cracks in the unstressed wire would once again indicate that cracks were present at time of wrapping.

Reclamation specifications required that the prestressing wire conform to the requirements of ASTM A 648-73, "Standard Specification for Steel Wire, Hard Drawn for Prestressing Concrete Pipe." Section 9.1 states "The surface of the wire as received shall be smooth and free from cross checking or torn surface. No serious die marks, scratches, pits, or seams may be present." Reclamation, in its examination, concluded that the wire contained longitudinal cracks at the time of pipe manufacturing and therefore did not meet these specifications.

Specifications also required conformance to two destructive tests specified in ASTM A 648-73, namely the tensile and wrap tests. Numerous tensile tests conducted by Reclamation on longitudinally cracked Jordan wire yielded only one sample which failed below the minimum tensile strength requirement of 262,000 lb/in^2.

Reclamation tests have raised doubts regarding the effectiveness of the wrapping test in revealing the longitudinal crack. The effectiveness of the test is dependent upon the orientation of the crack with respect to the direction of bending. Reclamation performed a wrap test by closely wrapping prestressing wire about a mandrel twice the specified wire diameter. When the crack was oriented on the inside or side of a wrap, the wire usually did not split open. When the crack was oriented toward the outer side of the wrap, diametrically opposite the wire-mandrel interface, the crack usually split open. The greater the length of a crack, the more probable the failure during wrap testing because chances were greater that the cracks would be critically oriented.

Reclamation tests showed that if a wire is cracked in the longitudinal direction on one side of a wire, chances are reduced for the defect to be oriented toward the outside of a wrap, and a defective specimen will generally pass the wrap test. In many cases, wrap test specimens showed no visible signs of cracking in the wrapping coils, but longitudinal cracks were easily split open on the ends with bolt cutters. If a wire is cracked in the longitudinal direction in more than one location around the wire circumference, however, chances become progressively greater for a defect to be exposed in proportion to the number of crack locations.

Reclamation tests also demonstrated that the depth and surface area of the crack are important considerations once a wrap test defect is exposed. If the depth was shallow, the crack was forced open, but the wire could still be wrapped around the test mandrel without breaking. If the crack was deep, however, and extended over a large surface area, the wire usually broke during winding.

In the majority of cases of cracked wire tested along Jordan Aqueduct, the specimens could be wound around the test mandrel after a defect was exposed without breaking. For the wire at the failure site, however, this was generally not true because most of the wire failed the wrap test by breaking. The cracks were very deep, extending about halfway through the wire, and the offsets and overlaps were also more closely concentrated throughout the wire length and about the wire circumference. Wire from the failure site therefore likely failed the wrapping test the majority of the time because it was more severely cracked over a larger surface area.

The bolt cutting test often revealed longitudinal cracks that were not found with the wrap test. ASTM A 648-73 did not specify the bolt cutting test, but the test was useful in revealing defects. However, some wire which passed both the wrap and the bolt cutting tests was found to be cracked longitudinally when inspected microscopically or by magnetic particle techniques.

Reclamation testing demonstrated that cracked wire could easily have been wound around Jordan pipe during manufacturing. Even if longitudinally cracked defective wire passed the destructive ASTM A 648-73 quality control tests prior to use in pipe production, defects probably would not have been identified without careful and continuous visual inspection as required by section 9.1. The tensile and wrap test results of most longitudinally cracked wire indicate it was both sufficiently strong and ductile to be wrapped on the pipe core during manufacturing without breaking.

A wire manufacturer's mill certificate and letter submitted to Reclamation both indicated that some wire supplied to the pipe manufacturer in 1981 met the ASTM A 648-73 criteria for chemical composition, tensile strength, and wrap test, as well as more stringent self-imposed quality control tests prior to being shipped to the pipe manufacturer for use in pipe production. However, no determination can be made whether the mill certificate relates specifically to the wire used in the production of some of the Jordan pipe, all of the Jordan pipe, or if it is only an example of the pipe manufacturer's general requirements. In addition, the mill certificate only implies conformance to the chemical, wrap, and tensile requirements of ASTM A 648-73, and does not provide additional supporting data to verify the claim that the wire met even more stringent self-imposed quality control guidelines. For instance, no data were provided to show that the wire was subjected to a more severe wrap test requiring it to be bent around a test mandrel in three planes at 120° intervals. The only data provided appeared on a document showing a "2d" and an "OK" implying that the wrap test passed the ASTM A 648-73 criterion requiring it to be closely wound around a test mandrel twice the specified wire diameter. Further, the mill certificate disclaimer states, "No warranty is expressed or implied other than those set forth above." In other words, the manufacturer apparently only warrants the ASTM A 648-73 criteria.

The prestressing wire of the ruptured pipe fractured in a ductile manner, and the longitudinal cracks were instrumental in the fractures.

Field-fractured wire from the failure site was sampled above and below the break, and matched pairs were examined microscopically. In every case, transverse wire fractures occurred at the termini of the longitudinal crack segments. These locations are characterized by a circumferential offset between the longitudinal cracks. The transverse fracture surface contained both a sharp metal tongue formed by the offset between the ends of the longitudinal cracks and a cup and cone failure surface. The cup and cone failure surfaces were characteristic of a ductile failure mode, typical of overloaded wire conditions, but little load was carried in the portion of the fracture affected by the defect, namely the metal tongue. When Reclamation tested wire from the failure site in tension in the laboratory, the field fracture morphology was commonly reproduced, i.e., the failure occurred at the termini of offsetting longitudinal cracks, resulting in a cup and cone fracture with a corresponding metal tongue. The fracture morphology, therefore, exhibited the uneven and overstressed conditions of defective wire.

Fractured wire from the failure site also commonly exhibited little to no reduction in area at the fracture cross-section. The lack of reduction in area could have resulted from several effects, including stress concentrations from wire defects (longitudinal cracks), high strain or rapid loading rates, restraint of the wire, compound triaxial stresses, and wire embrittlement.

Laboratory uniaxial tension testing demonstrated that wire failure will always occur at a location influenced by stress concentrations from the wire defects (i.e., at the termini of offsetting longitudinal cracks). Small reductions in area will also be produced because reduction in area measurements are made at the fracture point, where the characteristic metal tongue carries little load. Although the wire fails in a ductile manner, the longitudinal cracks prohibit the load from being carried uniformly in all areas of the fracture, and cracked wire cannot neck down normally. As a result, the neck down of nonhomogeneous cracked wire is less than that of homogeneous wire. The offsetting longitudinal cracks therefore contribute to the small reductions in area for the Jordan wire.

The rate of loading also influences the neck down characteristics of the wire. The faster the loading rate, the smaller the reduction in area. When Jordan wire was rapidly strained to failure in uniaxial tension in the laboratory, wire fractures with little to no area reductions were obtained (Mote, 1985a). Fractures with essentially no measurable neck down were commonly produced. Fracture morphology of such samples was virtually indistinguishable from those found at the failure site. One sample exhibited no measurable neckdown when tested in uniaxial tension in accordance with the loading rates specified in ASTM A 370. The wire sample was obtained from unit 797, the ruptured pipe, and was tested about 7 years after the pipe failure occurred.

The standard uniaxial tensile test does not simulate the restraint of the wire on the pipe by friction of the surrounding mortar or the role of compound triaxial stresses in limiting the neck down capabilities of the wire. Unit 798 was pressure tested to 750 feet of head with no visually apparent failure. However, upon removal of the mortar coating, many wire fractures were found with features identical to those from unit 797 and exhibited little to no neck down. Whether these fractures (other than the one at the bell anchor) occurred before or after pressure testing is not known. However, the pipe does not exhibit outward signs of distress, even though individual prestressing wire coils have fractured.

A preponderance of wire fractures along the bonding straps on the intact bell end of unit 797 was also noted. No such tendency was noted on unit 798, where fewer and more randomly located fractures were observed. Other units along the line where the wire was partially exposed at the bonding straps disclosed no wire fractures. Unit 797 was oriented in service such that the bonding straps were located at pipe spring line, whereas on unit 798, the bonding straps were located near the crown and invert. Spring line is an area of high tensile stress concentration at the wire level on the pipe circumference. The foregoing indicates that the 0.03-inch-thick bonding strap performed as a stress riser for the wire at this already highly stressed area.

Wire embrittlement caused by excessive cathodic protection was ruled out as a probable cause of the no neck-down fractures. A loss in wire ductility caused by an embrittling effect also would have likely been accompanied by a microscopically visible brittle fracture of the prestressing wire at the failure site, which was not the case. It was also possible to determine the area reduction of longitudinally cracked wire that was cathodically protected within criteria where reduced potential for wire embrittlement existed. Such a determination was necessary because comparing neck-down of crack-free exemplar wire to that of longitudinally cracked Jordan wire is not appropriate because the detrimental influence of the longitudinal crack would not be known and equivalent materials would not be compared. Wire from stations 1499+56 and 1478+44, which contained severe splits visible to the unaided eye, was therefore tested. The observation that this wire was severely split even though it was protected within criteria once again substantiated that high pipe polarization potentials were not related to the longitudinal cracking. As before, the wire failed to meet the ASTM A 648-84 minimum reduction in area criterion, again indicating that the offsetting longitudinal cracks contributed to the small area reductions as opposed to hydrogen embrittlement from excessive cathodic protection.

The high stresses that were applied to the prestressing wire during the winding operation were also instrumental in the fractures of the prestressing wire.

Field testing to determine the existing stress level of the prestressing wire at six locations along Jordan Aqueduct yielded *in situ* stresses ranging from 148,000 to 184,000 lb/in^2. With the laboratory correction of 9 percent, pipe stresses were found to range from 161,000 to 201,000 lb/in^2. Taking into account assumptions for stress loss over time resulting from elastic deformation, creep, and shrinkage of the pipe core and subsequent relaxation of the wire when properly wrapped, stress levels at the time of testing should have ranged from 140,000 to 170,000 lb/in^2. The measured values therefore exceeded design values predicted at the time of stress relieving.

Regression analysis of the corrected field measurements that were projected back to the time of manufacturing by application of design assumptions for stress loss caused by elastic deformation, creep, and shrinkage of the pipe core and subsequent relaxation of the wire indicated that the pipe was wound at stress levels in the 200,000 to 250,000 lb/in^2 range. Although Reclamation specifications permitted instantaneous load fluctuations outside a range of plus and minus 10 percent of the mean wrapping stress during wrapping, it is most unlikely that the particular coils selected for testing were only those on which the load excursions above tolerance occurred. These projections therefore indicated the wire was overstressed during pipe manufacturing and exceeded the specified wrapping limitations (177,000 to 216,000 lb/in^2).

The 1974 Standard Specification for Embedded Cylinder Prestressed Concrete Pipe required that the tension in the prestressing wire be recorded with a calibrated measuring device. The load calibration of the prestressing machine should have been verified by proof of calibration of the dynamometer used to adjust the prestressing load of the specific machine used to wrap Jordan pipe. Quality control procedures required certification of the dynamometer calibration by an independent laboratory with calibration equipment certified by the National Institute of Standards and Technology. Although requested, no such certification was produced by the pipe manufacturer, and the calibration of the prestressing machine used in the production of Jordan pipe has never been verified.

The fracture on the bell anchor of unit 798 is also indicative of high wire stresses. At the ends of the pipe, the wire is wrapped at about half the nominal stress. Nevertheless, the wire fractured at this location. The fracture originated at a notch in the wire formed by the swedge-type anchor and is indicative of the notch sensitivity of the high-strength prestressing wire. The fracture and corresponding longitudinal crack were imprinted on the mortar coating opposite the anchor when the slurry and mortar were plastic at the time of pipe manufacture. Spectral analysis showed that the imprinted crack, the smooth surfaces formed by the wire and anchor, and the fractured surface of the mortar were of the same elemental composition. The failure exhibited no reduction in area.

Reclamation specifications also required that records be kept to verify the proper wire tension during prestressing. Records of wire prestressing showing the dynamic load fluctuations during the wrapping process should have also been produced. Quality control procedures required that records be kept up to date, properly labeled, and sent to quality control. Records should have been kept on charts in the recording device throughout the duration of pipe manufacturing. Although no calibration or prestressing records were submitted for Jordan pipe, prestressing records of pipe made for another customer on the same day were submitted as proof of calibration of the prestressing machine used to produce Jordan pipe. These records only indicated the load measured by the load cell during the production of a pipe for the other customer. If the load was not adjusted to the calibrated dynamometer prior to manufacturing, the prestressing records are meaningless because the accuracy of the load cannot be determined.

Additional reasons exist to question the load used in Jordan pipe production. The pipe manufacturer produced pipe wrapped with 6-gage wire (0.192-in diameter) in the same time period in which Jordan pipe was manufactured. The Jordan Aqueduct pipe, however, was made with 8-gage wire (0.162-in diameter). In Reclamation specifications, the prestressing wire is required to be wound at 75 percent of its minimum ultimate tensile strength plus or minus 10 percent. For 6-gage wire, the mean wrapping stress required for prestressing would be 0.75 x 252,000 = 189,000 lb/in^2, and the corresponding tensile load would be 5,470 pounds. When switching from producing pipe with 6-gage wire to pipe with 8-gage wire, the operator of the machine must adjust the load from 5,470 to 4,050 pounds to stress the 8-gage wire to 75 percent of its minimum ultimate tensile strength. The operator should also document this adjustment. Without the verification of prestressing records, especially in these circumstances, the 5,470-pound load appropriate for 6-gage wire could have been used to wrap 8-gage prestressing wire around the Reclamation pipe, which would have resulted in a wrapping stress of 265,000 lb/in^2. The wire would then have been dangerously overstressed, exceeding the specification wrapping limitations (177,000 to 216,000 lb/in^2) and the required minimum tensile strength of the wire (262,000 lb/in^2). If the prestressing machine was out of calibration, the prestressing load could have been even higher.

Although the failed pipe section was cathodically protected at polarization potentials above the specified level, no tangible evidence was found to indicate that excessive cathodic protection resulted in hydrogen embrittlement, fracture of the prestressing wire, and subsequent pipeline failure.

Examination and testing have shown that longitudinal cracks were present in the prestressing wire at the time of pipe manufacture and that no demonstrated loss of ductility occurred because of wire embrittlement from an external cathodic source. It is also well known throughout the wire industry that longitudinal cracks can and do develop during the wire manufacturing process (Klodt, 1984 and 1985).

The longitudinal splits were not related to high pipe polarization levels because virtually all wire examined along Jordan Aqueduct contained offsetting longitudinal crack segments which ran the entire length of the removed wire, regardless of the polarized pipe potential. Severe splits visible to the unaided eye were apparent when wire from stations 1499+56 and 1478+44 was examined. Pipe polarization potentials at these stations, however, were within specifications and reduced potential for wire embrittlement existed. Longitudinal cracks were also observed at station 1394+60, where no cathodic protection was being provided. The observation that wire was split even though it was protected within criteria or not protected at all further substantiated that high pipe polarization potentials were not related to the longitudinal cracking.

Also, area reduction measurements that were performed at the fracture cross-section of these longitudinally cracked samples tested to failure produced mean values less than those required in ASTM A 648-84 for uncracked homogeneous wire, as did those from the failure site. Because samples protected above and within criteria exhibited unacceptable ductility, the comparison indicates that effects from the offsetting longitudinal cracks likely contributed to the small area reductions, as opposed to effects from excessive cathodic protection.

Hydrogen embrittlement by excessive cathodic protection can be substantiated only if the following claims can be proven:

1. Atomic hydrogen is produced at the reinforcing wire by high cathodic protection potentials with corresponding current densities which can realistically be applied by the system.

2. The atomic hydrogen so produced survives long enough in the highly alkaline environment to diffuse into the wire.

3. The absorbed hydrogen produces a specific embrittlement effect in the wire, which then adversely affects the strength of the wire.

4. Wire from the failed Jordan Aqueduct pipe exhibits the specific effect of strength loss (i.e., fracture) under sustained load from hydrogen embrittlement effects.

Although grosser degrees of wire embrittlement result in a reduction of wire ductility, the most insidious manifestation of hydrogen embrittlement is that of fracture of the steel under a sustained load that is appreciably less than the tensile strength. Strength loss as opposed to ductility loss is the key issue of the wire failure.

The properties of ductility and strength are required to initially wrap the wire around the pipe core. Thereafter, wire strength is the controlling property. If the level of cathodic protection used on Jordan Aqueduct can be shown capable of producing an embrittlement effect on the wire in an alkaline environment, then the next step is to show that the hydrogen embrittlement is severe enough to produce a loss in tensile strength under a sustained load which is appreciably less than the original tensile strength of the wire. The preceding step would indicate whether hydrogen could be produced in an alkaline environment by higher levels of cathodic protection and if the hydrogen could diffuse into the wire, resulting in a loss of strength.

Reclamation performed this type of laboratory test in which longitudinally cracked samples from the failure site, as well as new homogenous samples, were immersed in an alkaline environment, loaded to 90 percent of the minimum ultimate tensile strength, and locked off. The wire relaxed such that stresses near 70 percent were continuously sustained. No attempt was made to sustain the alkaline pH (12.5), and the solution acidified toward a pH of 7 and lower with time. As previously mentioned, the specimens were cathodically protected, some at polarized potentials near −1300 millivolts, with corresponding cathode current densities of up to about 35 A/ft^2. Current densities of this magnitude are unheard of in practice. Typically, current densities of 200 $\mu A/ft^2$ are required to achieve adequate protection for this type of environment. The maximum theoretical average current density available within the span between the two rectifiers adjacent to the failure site was 400 $\mu A/ft^2$. After 5 years of Reclamation testing, no failures attributable to hydrogen embrittlement occurred in the exemplar wire tested.

Furthermore, examination of fractures from Jordan Aqueduct and wire failed through induced hydrogen embrittlement has shown that the fracture morphologies are completely different (Mote, 1986). Hydrogen-induced fractures all exhibited a characteristic ledge or step perpendicular to the longitudinal axis and secondary partial transverse cracking. The testing demonstrated that hydrogen-induced fractures will occur when excessive external cathodic charging is applied to prestressing wire in an acidic environment. Atomic hydrogen will then diffuse from the outer surface of the wire into the lattice, where it will propagate or advance cracks. As cracks propagate, the load carrying area will be removed and the wire will fail. Evidence of the path so traveled will remain on the fracture surface and will be characterized by a ledge or step transverse to the longitudinal axis. In addition, characteristic secondary partial transverse cracking will occur where cracks have not reached the critical size necessary for wire fracturing. Nothing resembling this fractography was evident on any examined field-fractured wire. Instead, features of a cup and cone failure, typical of tensile overload, were observed on every wire examined.

Bulk hydrogen contents were also measured on wire near the failure site after cathodic protection was reestablished to −1210 millivolts for 3 weeks and compared to the bulk hydrogen contents of laboratory samples of Jordan wire that fractured while cathodically charging under load in an acidic environment (Mote, 1987). The measured concentration of hydrogen in the laboratory-fractured wires was significantly higher than that found in the wires removed from the Jordan pipeline. The lowest hydrogen content found in the laboratory-fractured samples was also greater than the highest value found on specimens removed from the pipeline. In addition, the bulk hydrogen content of a new wire that was cathodically charged at a polarized potential near −1300 millivolts in a basic environment for over 15 months without failure was greater than the bulk hydrogen contents measured on the Jordan pipeline. Although the new wire exhibited a hydrogen content of 6.27 p/m, the material was not embrittled based on results of strength/ductility tests. It is also interesting to note that although a wide range of hydrogen contents existed (probably because of the structural defects or longitudinal cracks within the wire), each of the samples that fractured in the acidic environment while under load exhibited hydrogen contents greater than 11.79 p/m at some location within the specimen.

The pipe was determined to be overprotected at all locations within 200 feet of each cathodic protection ground bed where polarized potentials as high as −1.25 volts were observed. At the rupture, polarized potentials of wire coils with close electrodes were found to be a maximum −1.07 volts. The potential of either the steel cylinder or prestressing wire is essentially impracticable to determine because the two are electronically shorted. Thus, a potential measurement reflects a composite condition (mixed potential) of the two components. Although cathodic polarization effects would tend to equalize the two potentials, considering the grossly different current return path electronic resistances (two orders of magnitude), the wire likely was not polarized to potentials sufficiently high to generate hydrogen under the highly alkaline conditions provided by cement mortar.

The pipe rupture was likely caused by the overload of the highly stressed, longitudinally cracked prestressing wire.

All in-service wire fractures examined displayed morphology consistent with tensile overload failures. Loss in wire ductility caused by an embrittling effect from excessive cathodic protection would likely have been accompanied by a microscopically visible brittle fracture of the prestressing wire at the failure site, which was not the case. The characteristic fractography of the in-service failures bore no resemblance to exemplar fractures resulting from laboratory embrittlement. Additionally, secondary transverse cracking typical for stress corrosion and hydrogen embrittlement was nonexistent on surfaces of in-service fractured wire.

With the exception of one sample, all wires removed from the pipeline and tested to failure were found to meet the requirement for minimum tensile strength. The failed pipe section ruptured while statically loaded and in service. The pipeline had been under earth load for 3 years, cathodically protected for about 15 months, and pressurized for 1 month before failure occurred. Thus, a delayed static failure mechanism is suggested. The common potential causes for this mode of failure are corrosion, stress corrosion cracking, hydrogen embrittlement, and structural defects. No tangible evidence supported the first three causes as probable reasons for the failure.

The observation that failures occurred at the termini of longitudinal cracks showed that stress concentrations at crack tips, along with geometry, played a major role in the rupture. The termini are cross sections of stress concentrations. Wrapping the wire around the core imposes torsional, bending, and axial stresses. The stresses on the wire cross section are compression and tension. The tensile stress, tending to separate the wire, results from Poisson's effect. The forces could then open or close the crack, depending on the orientation of the longitudinal cracks about the wire circumference with respect to the bending axis. Thus, if the cracks were oriented about the wire circumference with respect to the bending axis such that the surfaces were exposed to the outer side of a wire bend, the sustained prestressing force would have produced stress concentrations at the unstable crack tips, causing cracks to propagate inward. The situation could have been aggravated by standard pipeline operating procedures, such as valve closings, which would have caused surges and flexing of the highly stressed prestressing wire. When cracks were offset or overlapping on the surface, they propagated toward the center of the wire cross section until they met and effectively removed a sector of load carrying cross-sectional area (fig. 57). As sufficient load-carrying area was removed, instantaneous ductile failure of a wire occurred with little reduction in area observed. When enough individual wires failed, a pipe section would rupture.

Reclamation dye-penetrant testing indicated that longitudinal cracks were located toward the outer side of the bend on the failed pipe section. It is also known that the pipe section ruptured near spring line. Many transverse wire fractures also occurred along the bonding strap for cathodic protection, which in this particular case was also located at spring line, an area of high stress concentration. Other pipe units along the line, however, were partially exposed at the bonding straps not located at spring line, and no wire fractures were observed. The foregoing indicates the bonding strap acted as another stress riser, assisting crack growth and increasing the probability of pipe rupture in this particular case.

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Table 1. - Results of tests for longitudinal cracking.

Station (ft)	Polarized potential (volts)	Dye penetrant inspection	Bolt cutting test	Magnetic particle inspection	Metallographic inspection
1394+60	−0.50	Inconclusive	Pass	Cracks	Cracks[1]
1396+00	−0.32	Inconclusive	Pass	Cracks	Cracks
1400+30	−0.85	Cracks	Fail	-	-
1427+00	−1.23	Cracks	Fail	-	-
1447+00	−0.94	Cracks	Fail	-	-
1470+00	−1.00	Cracks	Fail	-	-

[1] See figure 21.

Table 2. - Validation of field method of testing by laboratory mandrel tests

Specimen identification	Wire stress (kips/in^2)		Indicated field error (percent)
	Field method	Lab. mandrel test	
Unit 797 - wire 1	200	213	−6
Unit 707 - wire 1A	191	198	−4
Unit 797 - wire 1B	205	227	−10
Unit 798 - wire 3A	184	198	−7
Unit 798 - wire 5A	206	233	−12
Unit 798 - wire 5B	170	193	−12
New wire 1	196	219	−11
New wire 1A	186	209	−11
New wire 1B	184	190	−3
			Mean −9

Table 3. - Summary of Jordan Aqueduct field testing.

	Expected stress range (lb/in^2)	Station 1394+60		Station 1396+00		Station 1400+30		Station 1427+00		Station 1447+00		Station 1470+00	
		Strain (10^{-6} in/in)	Calculated stress (lb/in^2)	Strain (10^{-6} in/in)	Calculated stress (lb/in^2)	Strain (10^{-6} in/in)	Calculated stress (lb/in^2)	Strain (10^{-6} in/in)	Calculated stress (lb/in^2)	Strain (10^{-6} in/in)	Calculated stress (lb/in^2)	Strain (10^{-6} in/in)	Calculated stress (lb/in^2)
Field stresses (lb/in^2)	140,000	6,530	184,000	5,440	-	6,135	166,000	5,950	170,000	5,875†	165,000†	5,580	162,000†
	to	6,290	177,000	6,150	174,000	6,220	170,000	5,600	162,000	-	-	5,060	148,000†
	170,000	6,380	180,000	6,420	177,000	6,350	174,000	5,820	165,000	-	-	-	-
		4,900	-	6,560	178,000	6,230	172,000	-	-	-	-	-	-
Estimated wrapping stress range (lb/in^2)*	177,000 to 216,000	220,000 to 230,000*		218,000 to 223,000*		208,000 to 218,000*		203,000 to 213,000*		206,000*		185,000 to 203,000*	
Laboratory corrected field stress range (lb/in^2)**	140,000 to 170,000	193,000 to 201,000**		190,000 to 194,000**		181,000 to 190,000**		177,000 to 185,000**		180,000**		161,000 to 177,000**	
Estimated corrected wrapping stress range (lb/in^2)***	177,000 to 216,000	241,000 to 251,000***		237,000 to 243,000***		226,000 to 238,000***		221,000 to 232,000***		225,000***		202,000 to 221,000***	
Polarized potential (volts)****	-	−0.50		−0.32		−0.85		−1.23		−0.94		−1.00	

Notes:

1. Required mean wrapping stress = 196,500 lb/in^2.
2. Allowable wrapping stress range = 177,000 lb/in^2 to 216,000 lb/in^2.
3. Expected stress range at time of testing = 140,000 lb/in^2 to 170,000 lb/in^2.
4. Stress data rounded to nearest 1,000 lb/in^2.
5. All stress measurements include the area of the strain gages in the cross-sectional area calculation.
6. All stresses calculated from stress-strain curves of actual *in situ* field tested wire unless noted.

† Representative stress-strain curves from *in situ* wire on the same pipe segment.

* Field stress increased 25 percent to account for wire stress losses over time due to elastic deformation, creep and shrinkage of pipe core, and relaxation of the wire. Factor obtained from John Thurston, design engineer in the Water Conveyance Branch. No laboratory corrections are applied.

** Laboratory tests indicate the calculated field stress should be increased an average of 9 percent.

*** Laboratory corrected field stress increased 25 percent to account for wire stress losses over time due to elastic deformation, creep and shrinkage of pipe core, and relaxation of the wire. Factor obtained from John Thurston, a design engineer in the Water Conveyance Branch. Laboratory corrections are applied.

**** Relative to copper/copper sulfate electrode reference with current interrupted.

Table 4. - Results of tension, wrap, and bolt cutting tests.

Specimen No.	Slowly strained[1]				Rapidly strained[2]
	Wire diameter (in)	Diameter after test (in)	Area reduction (%)[3]	Tensile strength (kips/in^2)	Tensile strength (kips/in^2)
		Wire from unit 797			
1	0.163	0.150	15.3	284	285
2	0.163	0.156	8.4	283	288
3	0.163	0.154	10.7	287	289
4	0.163	0.155	9.6	281	292
5	0.163	0.145	20.9	284	291
6	0.163	0.150	15.3	285	292
7	0.163	0.143	23.0	286	290
8	0.163	0.159	4.8	273	282
9	0.163	0.157	7.2	282	290
10	0.163	0.143	23.0	285	291
11	-	-	-	-	290
Sample Size	-	-	10	10	11
Mean	-	-	13.8	283	289
Std. Deviation	-	-	6.7	3.9	3.1
Var. Co. (%)	-	-	48.5	1.4	1.1
Wrap test - failed		Bolt cutting test - failed			

[1] All specimens loaded at 50 kips/in^2/min.
[2] All wire preloaded to 160 kips/in^2 and rapidly loaded to failure.
[3] Many specimens failed in the jaws such that it was not possible to determine area reduction.

Note: Minimum tensile strength requirement for class III, gage 8 prestressing wire = 262 kips/in^2.

Table 4. - Results of tension, wrap, and bolt cutting tests (continued).

Specimen No.	Slowly strained[1]				Rapidly strained[2]
	Wire diameter (in)	Diameter after test (in)	Area reduction (%)[3]	Tensile strength (kips/in^2)	Tensile strength (kips/in^2)
		Wire from unit 798			
1	0.162	0.145	10.5	286	290
2	0.162	0.143	11.7	284	290
3	0.162	-	-	291	289
4	0.162	-	-	287	282
5	0.162	0.147	9.3	288	285
6	0.162	-	-	287	290
7	0.162	-	-	292	-
8	0.162	-	-	288	-
9	0.162	-	-	288	-
10	0.162	-	-	290	-
Sample Size	-	-	3	10	6
Mean	-	-	10.5	288	288
Std Deviation	-	-	1.2	2.4	3.4
Var. Co. (%)	-	-	11.4	0.8	1.2
Wrap test - failed		Bolt cutting test - failed			

[1] All specimens loaded at 50 kips/in^2/min.
[2] All wire preloaded to 160 kips/in^2 and rapidly loaded to failure.
[3] Many specimens failed in the jaws such that it was not possible to determine area reduction.

Note: Minimum tensile strength requirement for class III, gage 8 prestressing wire = 262 kips/in^2.

Table 5. - Prestressing wire tests from Jordan Aqueduct, Reach 3, where cathodic protection polarized potentials were measured within specifications.*

Specimen No.	Diameter of wire (in)	Diameter after test (in)	Area** reduction (%)	Tensile strength (lb/in^2)	Wrap test	Bolt cutting test
1478+44 No. 1	0.164	-	-	270,300	Passed	Failed
1478+44 No. 2	0.164	-	-	267,100	Passed	Failed
1478+44 No. 3	0.164	0.137	30.2	266,100	Passed	Failed
1478+44 No. 4	0.164	-	-	279,900	Passed	Failed
1478+44 No. 5	0.164	0.143	24.0	282,000	Passed	Failed
1478+44 No. 6	0.164	-	-	284,200	Passed	Passed***
1499+56 No. 1	0.164	0.133	34.2	271,400	Passed	Passed
1499+56 No. 2	0.164	0.147	19.7	267,100	Passed	Failed
1499+56 No. 3	0.164	0.137	30.2	269,300	Passed	Passed
1499+56 No. 4	0.164	0.146	20.8	256,500****	Passed	Passed
Mean	-	-	26.5	271,390	-	-
Standard deviation	-	-	5.9	8,440	-	
Coefficient of var. (%)	-	-	22.1	3.1	-	-

* All specimens loaded at 50,000 $lb/in^2/min$.

** Several specimens failed in the jaws of the testing machine. Therefore, it was not possible to determine the area reduction of these specimens.

*** Specimen passed the bolt cutting test; however, a crack was found on the specimen after the test with additional cutting of original 3-inch sample.

**** Specimen failed below the minimum tensile strength requirement of 262,000 lb/in^2 for class III, 8-gage prestressing wire.

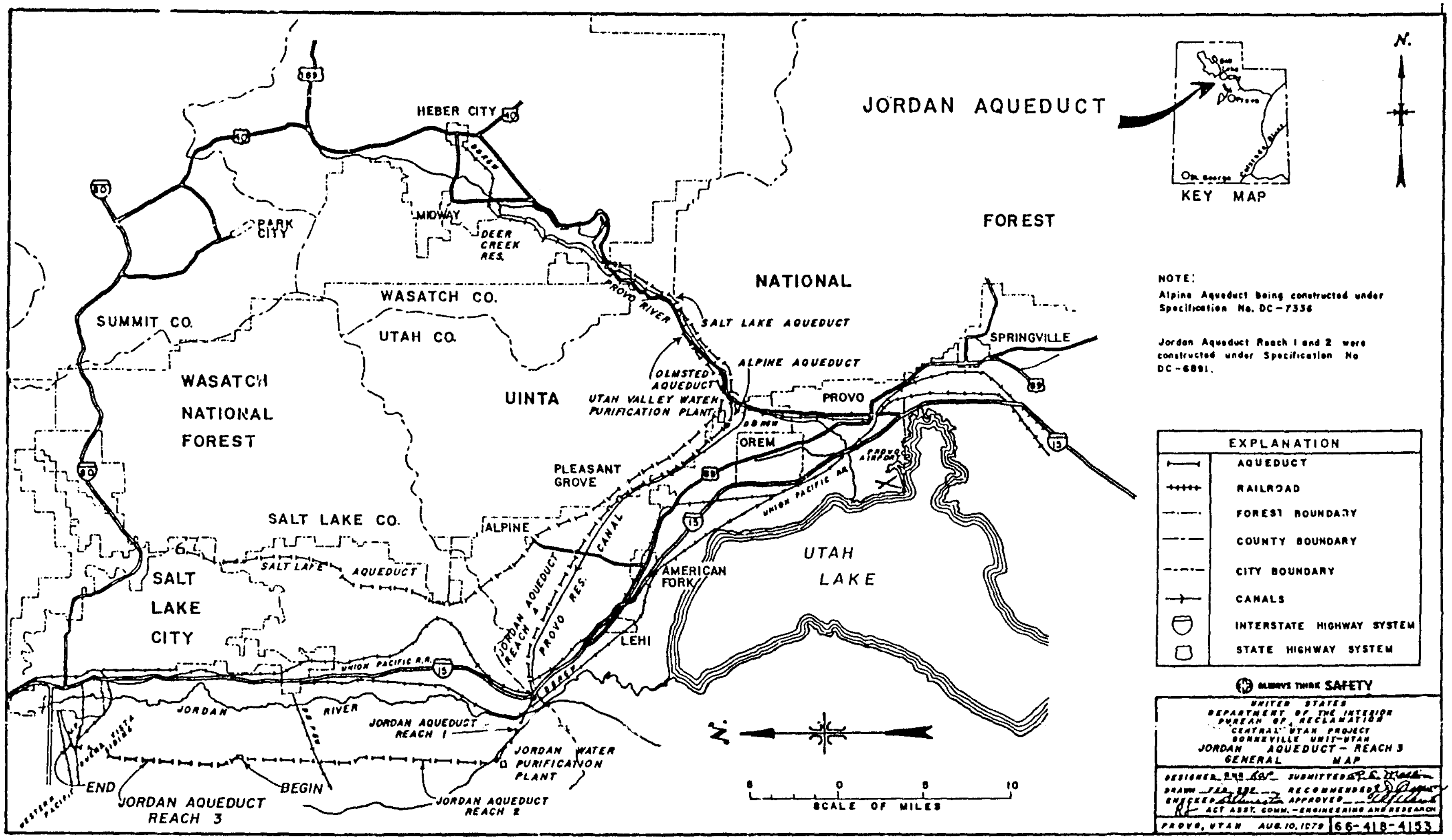


Figure 1. - Location map, Jordan Aqueduct.

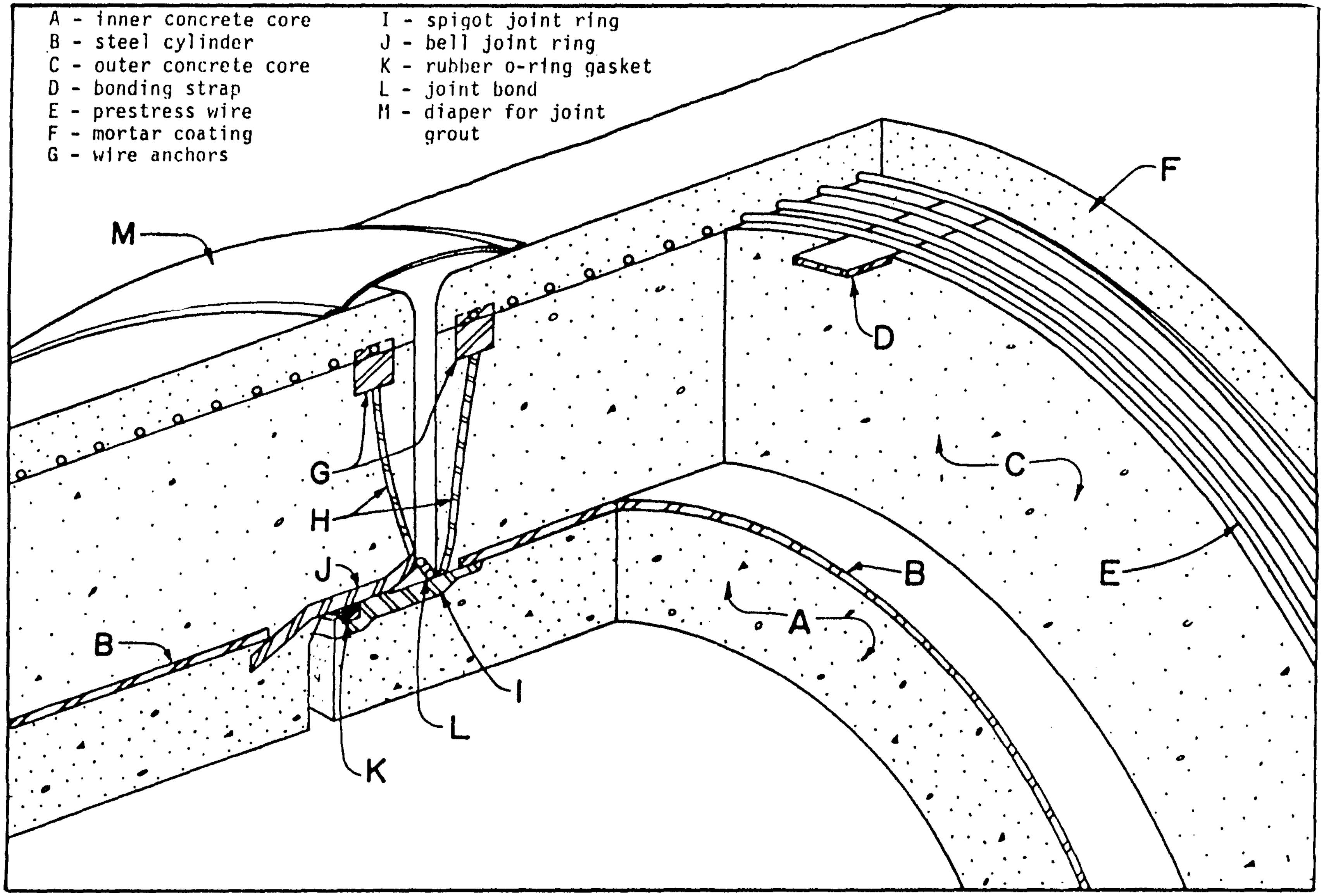


Figure 2. - Schematic drawing of embedded cylinder prestressed concrete pipe.

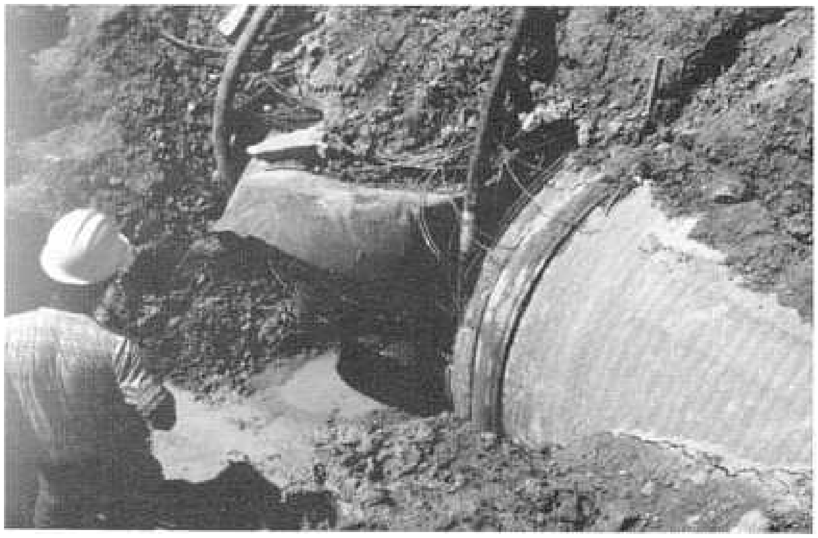


Figure 3. Burst pipe unit 797, station 1428+60.

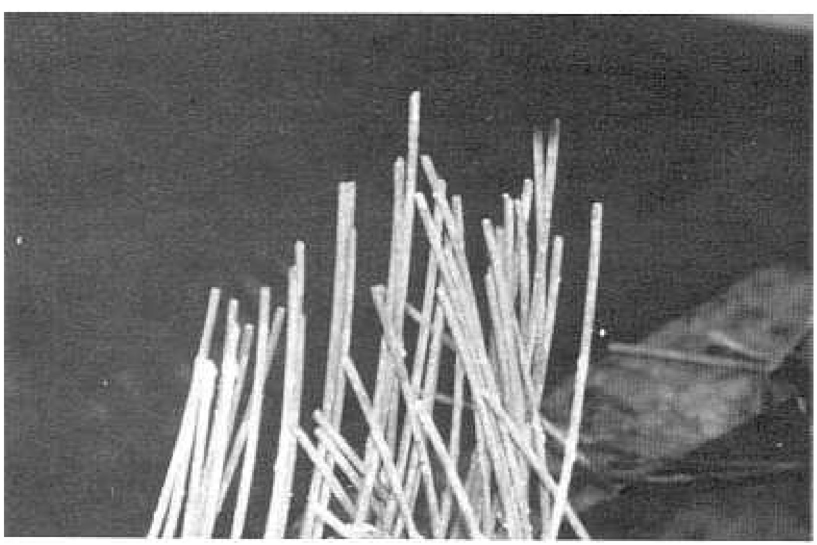


Figure 4. Fractured ends of prestressing wire at rupture.

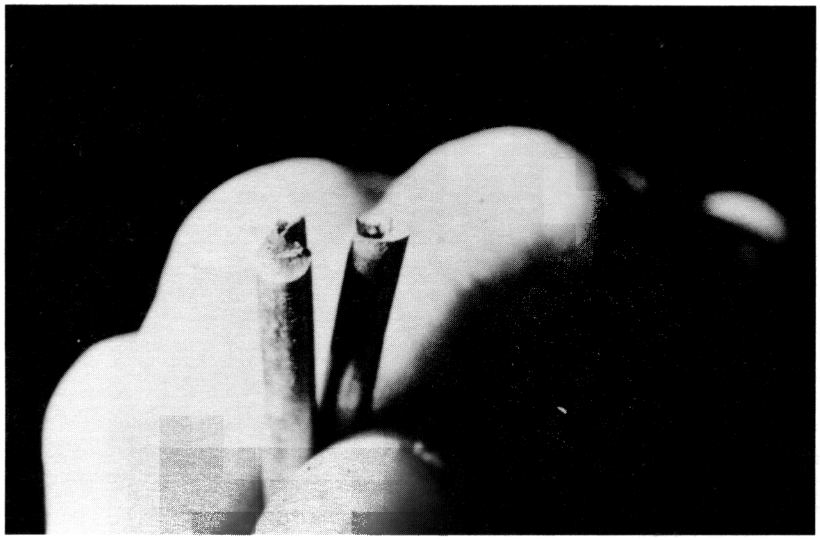


Figure 5. - Characteristic cup and cone fracture.

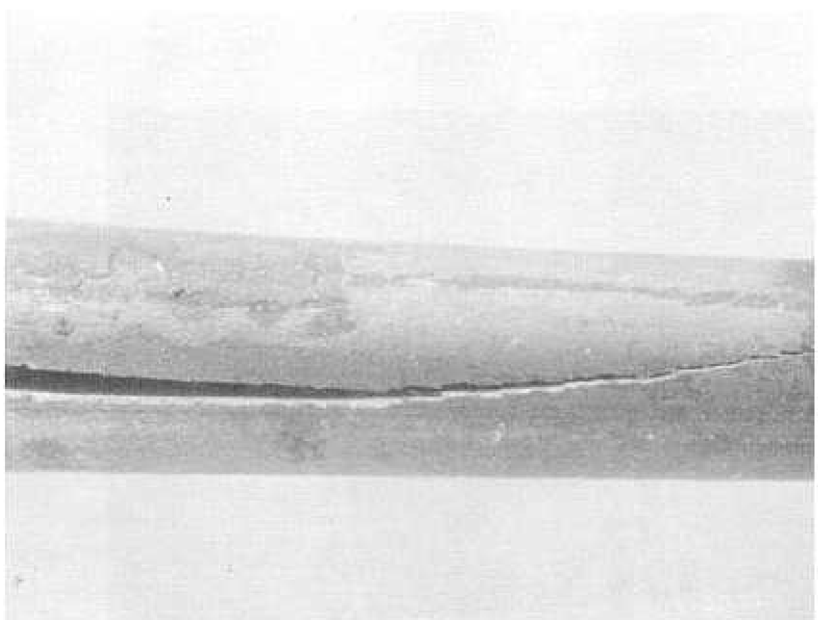


Figure 6. - Longitudinal crack along surface of prestressing wire, about 9X.

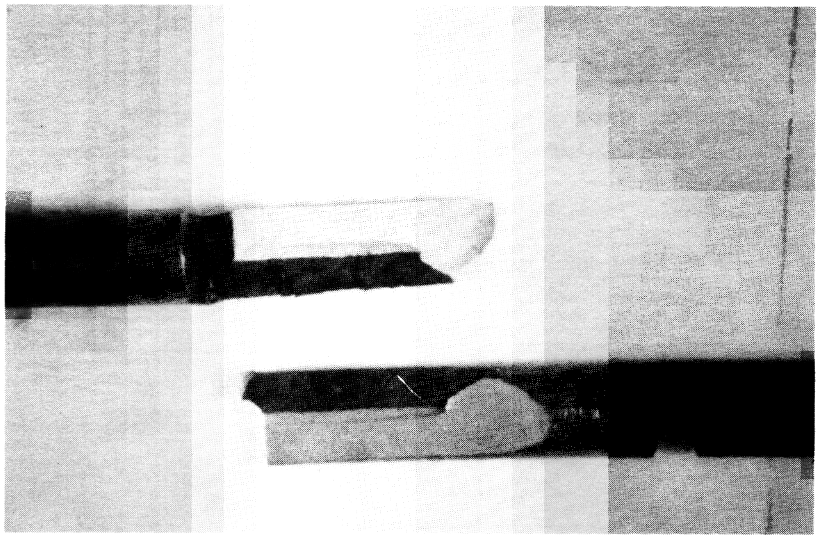


Figure 7. - Wire after forcing to split open. Dark surface is oxidized; light surface is freshly fractured, about 3X.

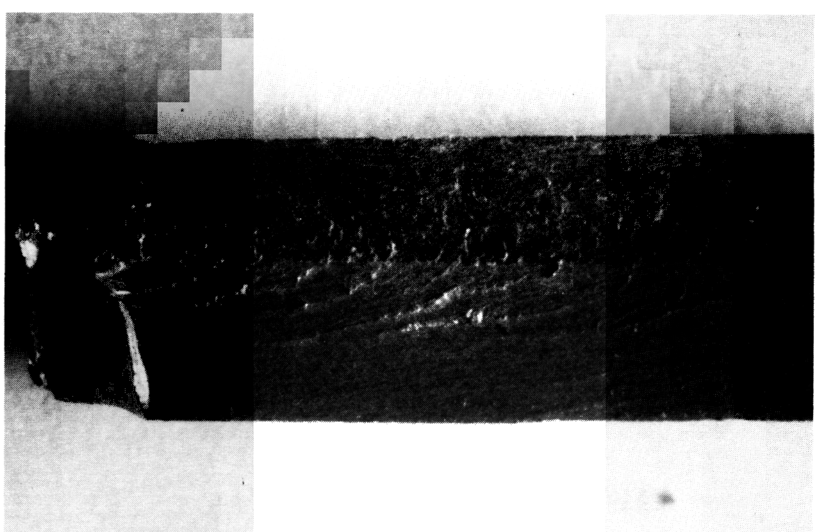
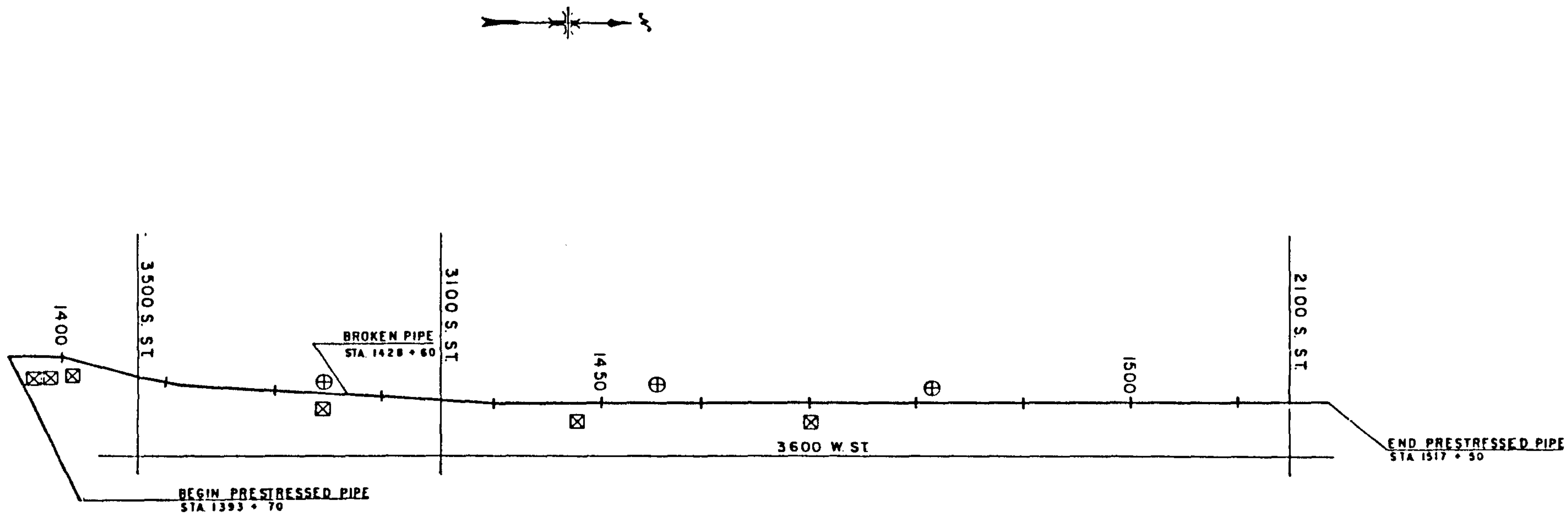


Figure 8. - Magnified view of wire after splitting, about 9X.



LEGEND ⊠

STATION	COATING REMOVAL
1394 + 60	1
1396 + 00	2
1400 + 30	3
1427 + 00	4
1447 + 00	5
1470 + 00	6

LEGEND ⊕

STATION	RECTIFIER NUMBER
1427 + 00	4
1456 + 00	5
1482 + 00	6

STATION	STRUCTURE
1435 + 08	20" Turnout, Blowoff, Manhole
1437 + 35	Air valve, Manhole
1451 + 00	Blowoff, Manhole
1454 + 10	Air valve, Manhole
1463 + 55	Blowoff, Manhole
1466 + 82	Air valve, Manhole
1488 + 00	Blowoff, Manhole, Taper
1491 + 10	Air valve, Manhole
1513 + 44	Valve, Manhole
1517 + 00	Terminal Structure

JORDAN AQUEDUCT
REACH 3
EMBEDDED CYLINDER PRESTRESSED PIPE

Figure 9. - Schematic of prestressed concrete pipe section showing location of pipe rupture and the three cathodic protection ground beds, as well as the wire strain gaging test sites.

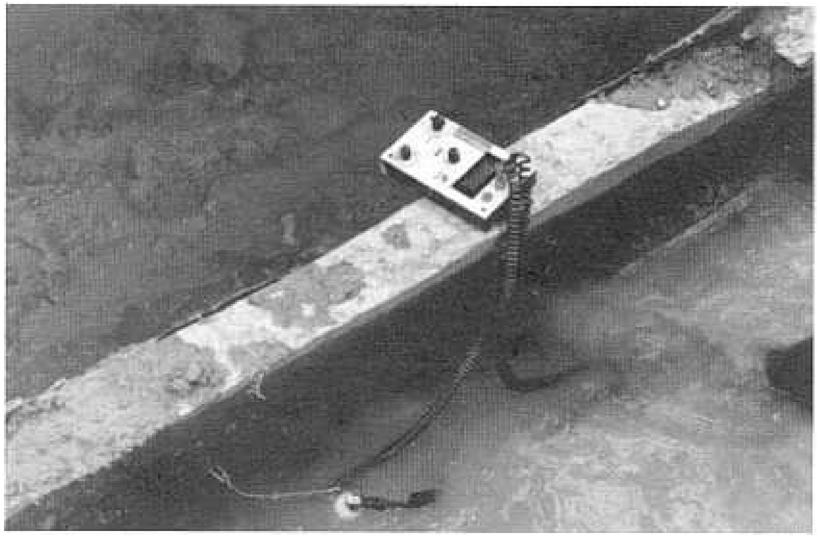


Figure 10. Testing for polarized potential of individual wire coils with reference to the coil under test.

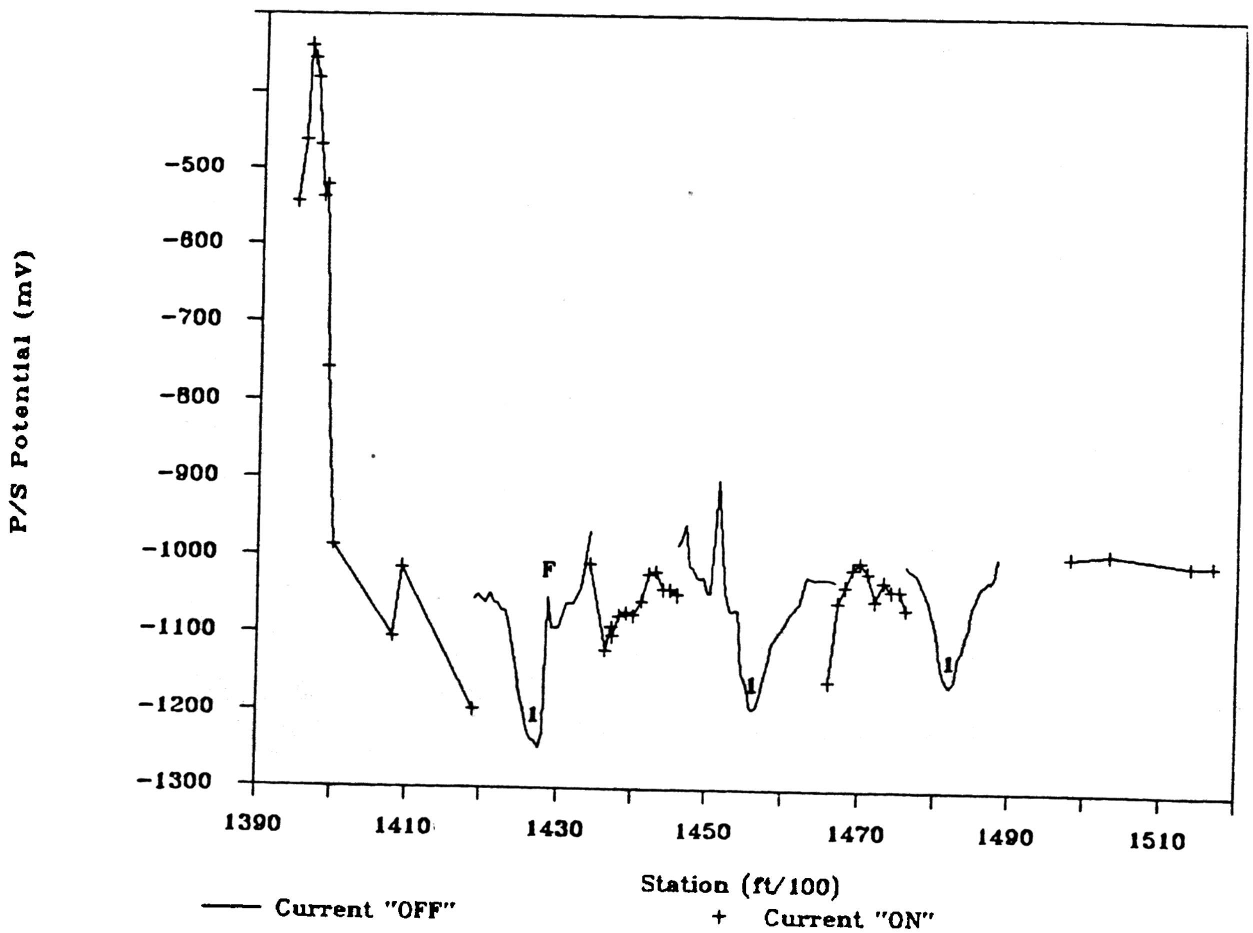


Figure 11 Potential survey, February 25-March 1985.

Figure 12. - Mortar coating opposite the prestressing wire. Note line in center of the middle concavity, about 2.5X.

Figure 13. - Magnified view of ridge in concavity, about 30X.

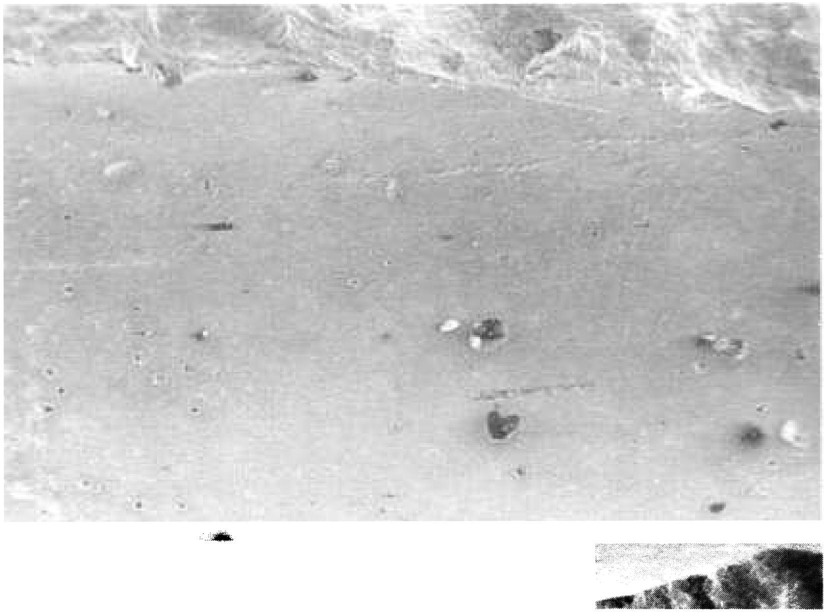


Figure 14. - Offsetting ridges in mortar concavity.

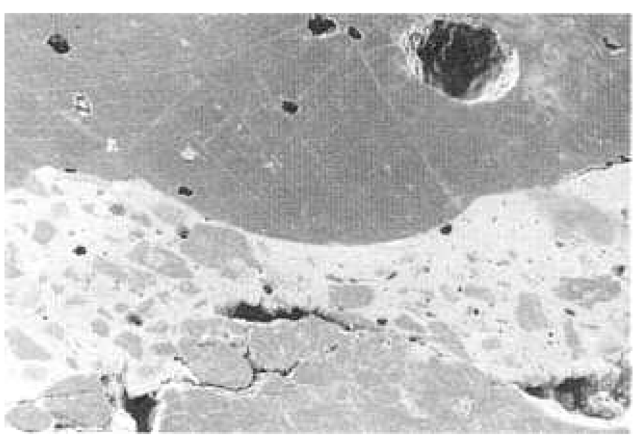


Figure 15. - Cross section of mortar coating concavity after encapsulating in plastic. No voids in mortar and no cracking of the mortar beneath ridge, about 14X.

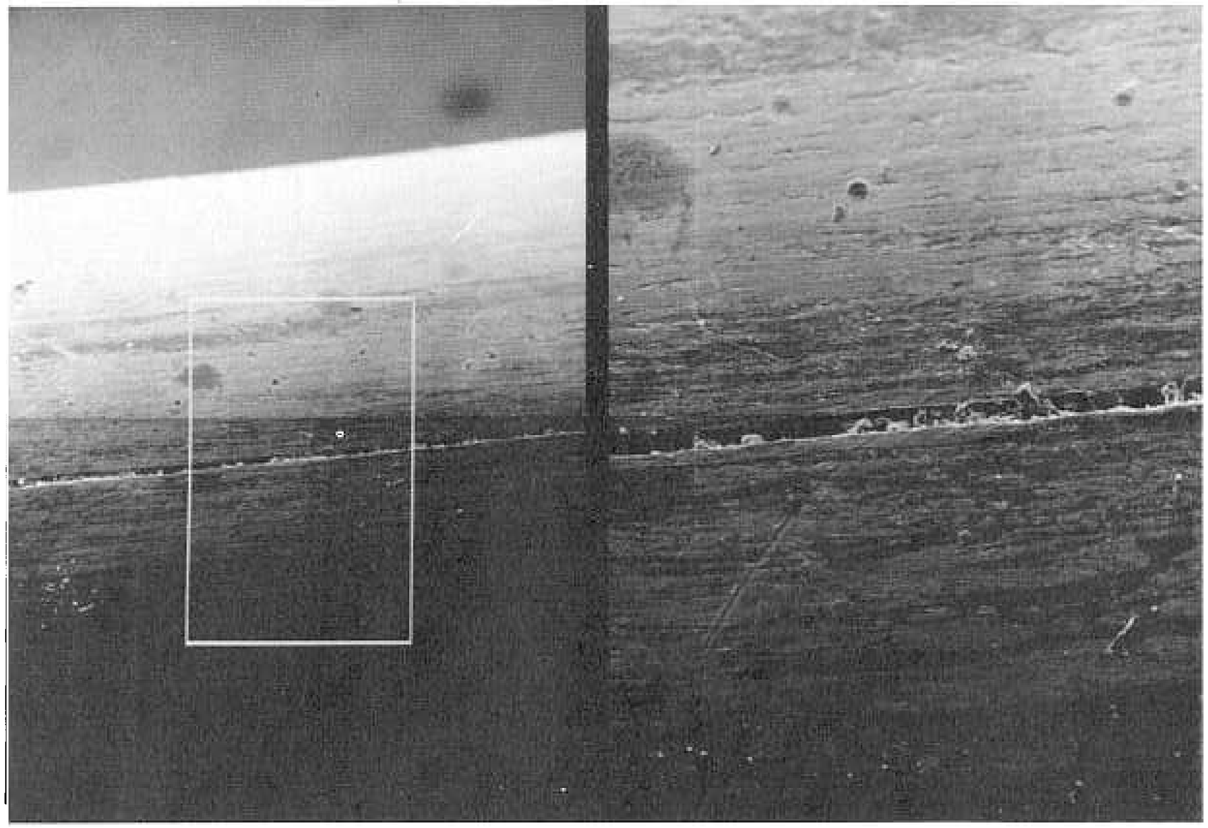


Figure 16. - Particles lodged within longitudinal cracks. Right photo is enlargement of area on left photo bordered in white. Crack is about 25 micrometers wide.

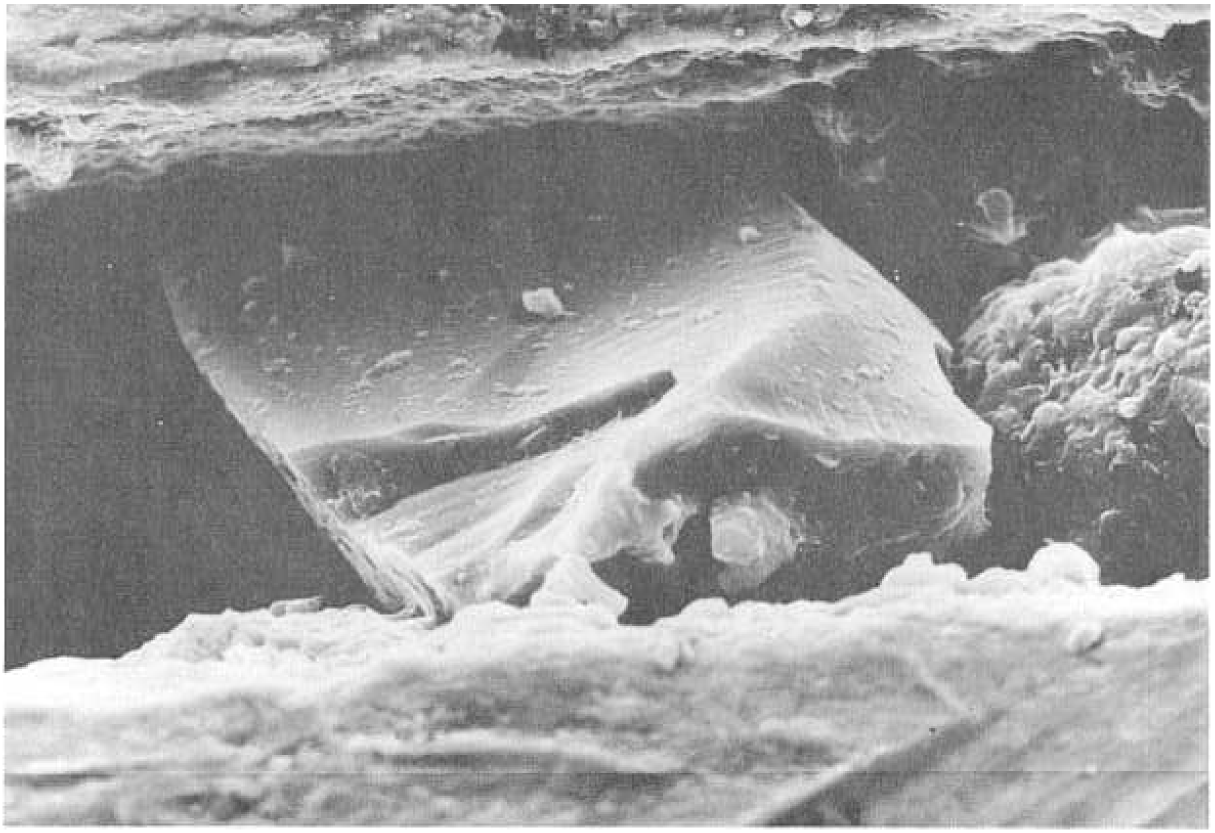


Figure 17. - Further enlargement of particles within the 25-micrometer-wide crack.

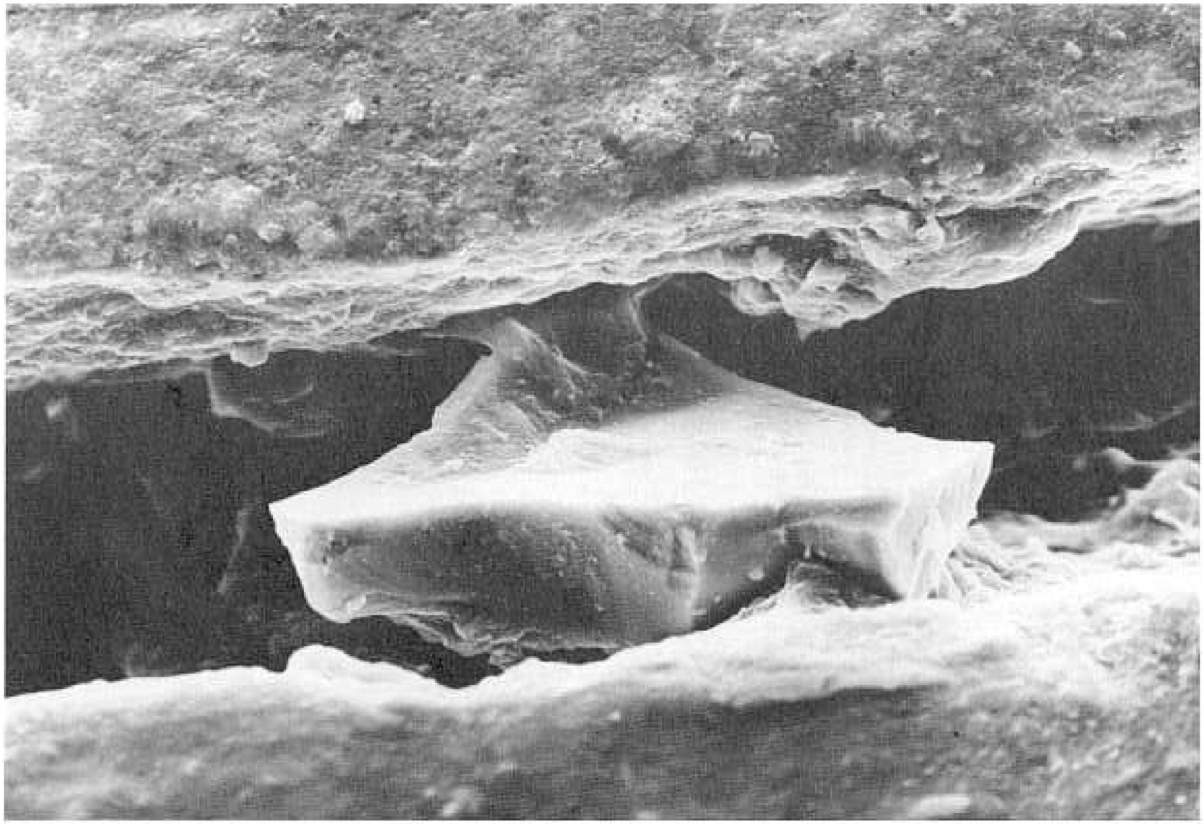


Figure 18. - Magnified view of particle in 22-micrometer-wide crack.

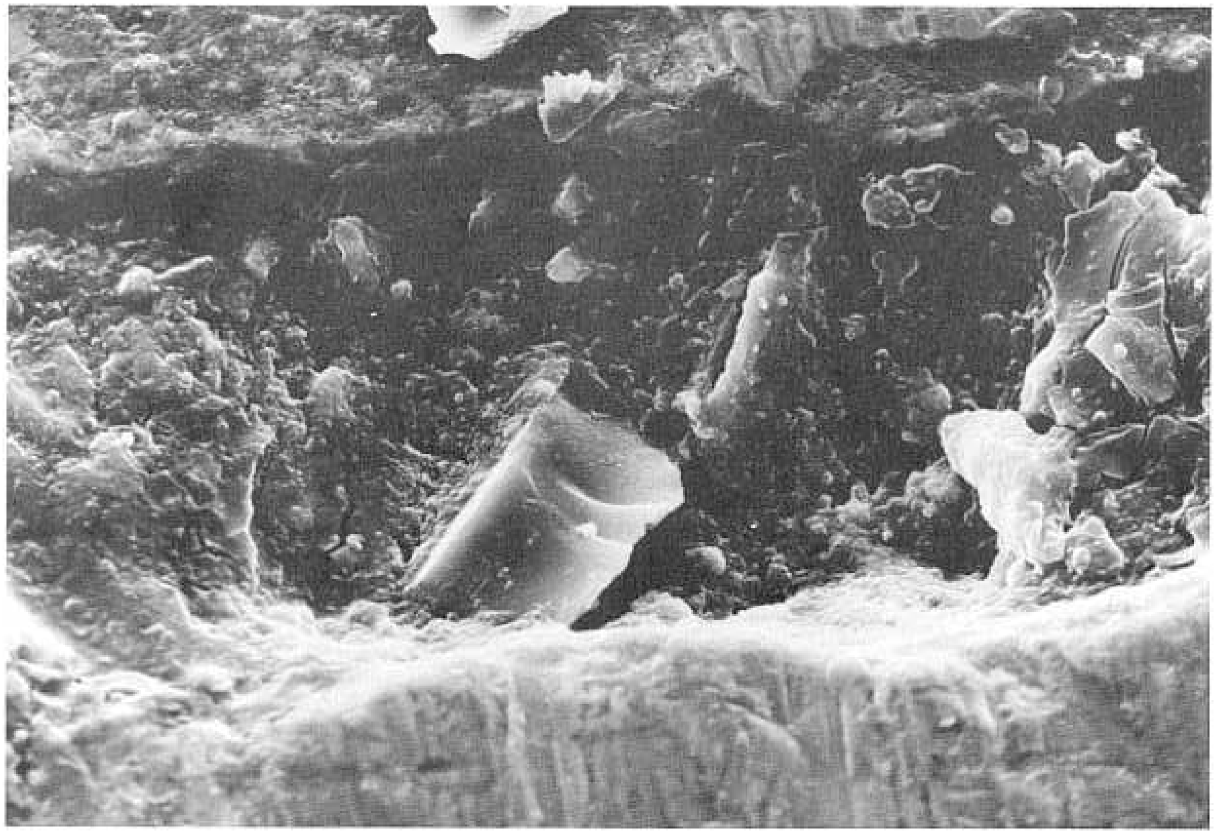


Figure 19. - Particles embedded in 27-micrometer-wide crack.

a. Magnification - 510X.

b. Magnification - 870X.

Figure 20. - Particles that have been lodged or impacted within longitudinal cracks.

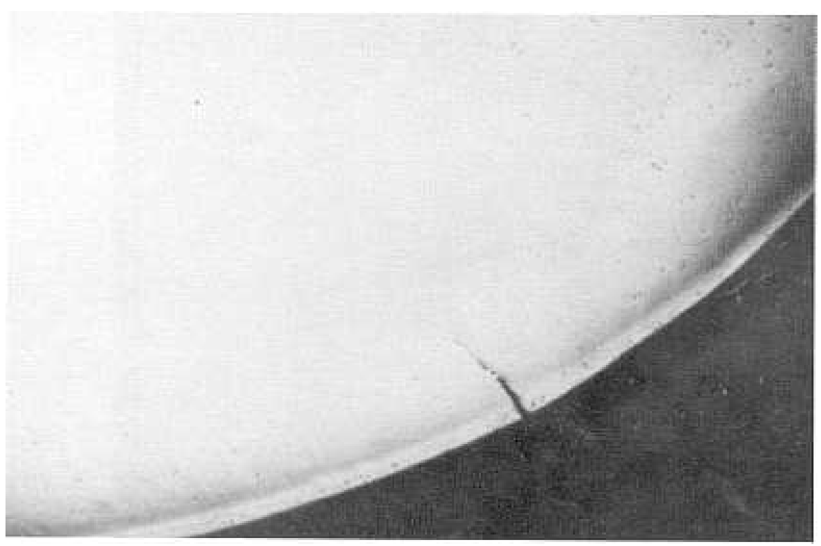


Figure 21. - Photomicrograph of wire cross section. Crack is 0.01 inches deep, about 80X.

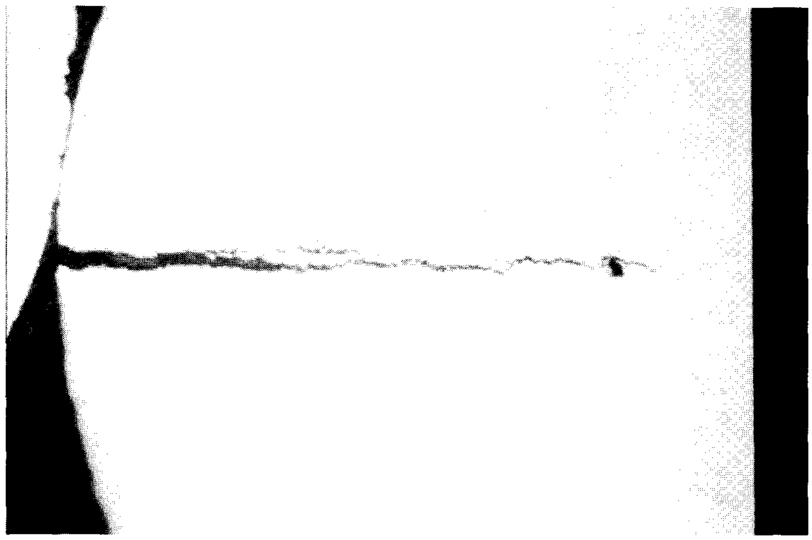


Figure 22. - Photomicrograph of wire cross section. Crack is 0.09 inches deep, about 35X.

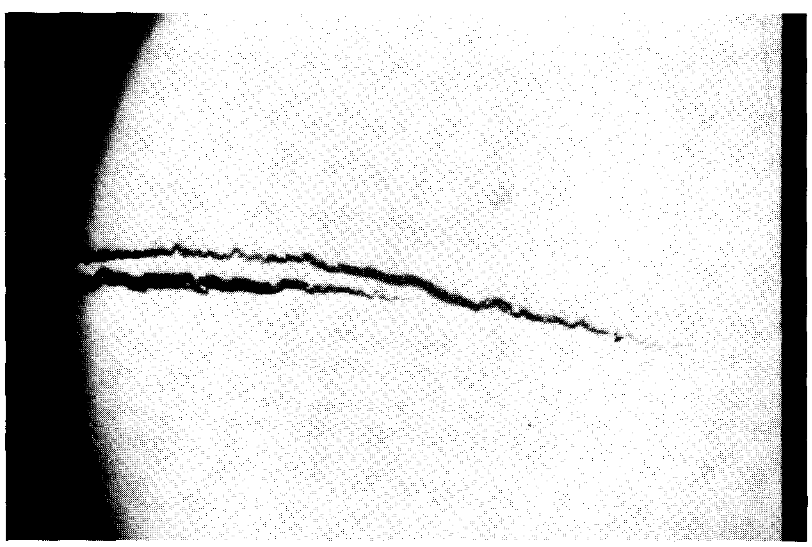


Figure 23. - Two longitudinal cracks have not quite joined in this cross section, about 35X.

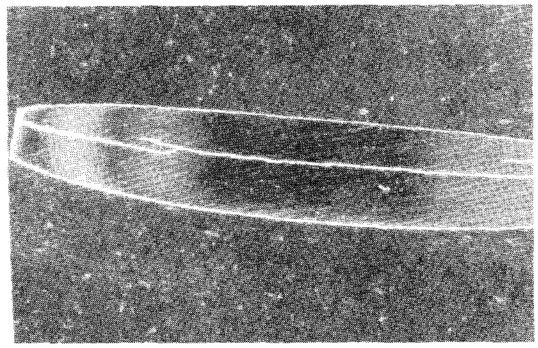


Figure 24. - Photomacrograph of a short length of wire after mounting in plastic and grinding to slight depth. Note overlapping and offsetting longitudinal cracks, about 3X.

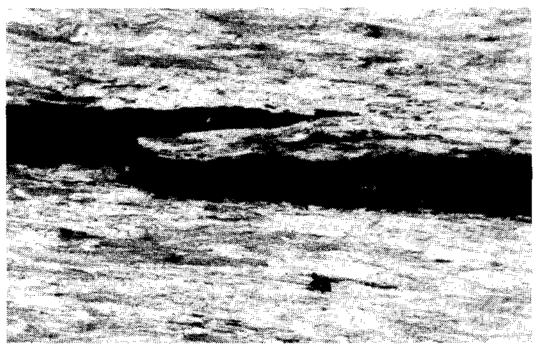


Figure 25. - Photomicrograph of longitudinal section. Notice the filament of steel between the cracks, about 200X.

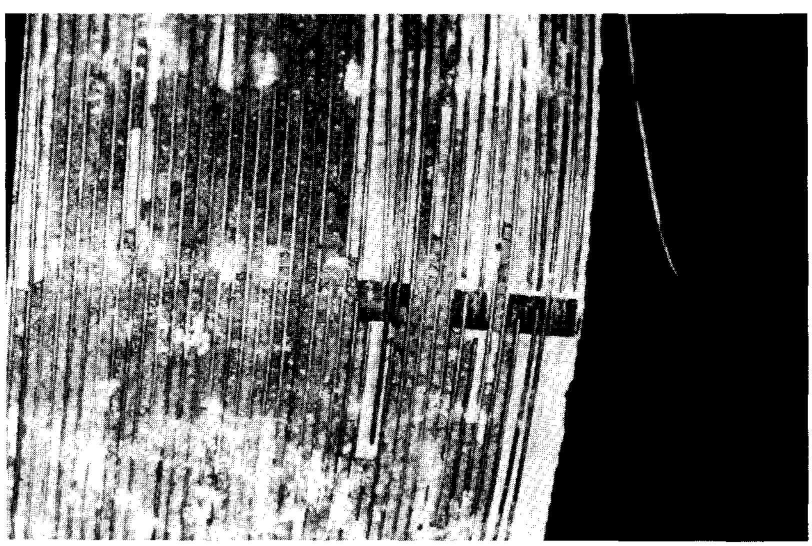


Figure 26. - Numerous wire fractures were observed opposite the bonding strap on unit 797. The unit was oriented in service such that the bonding straps were at spring line.

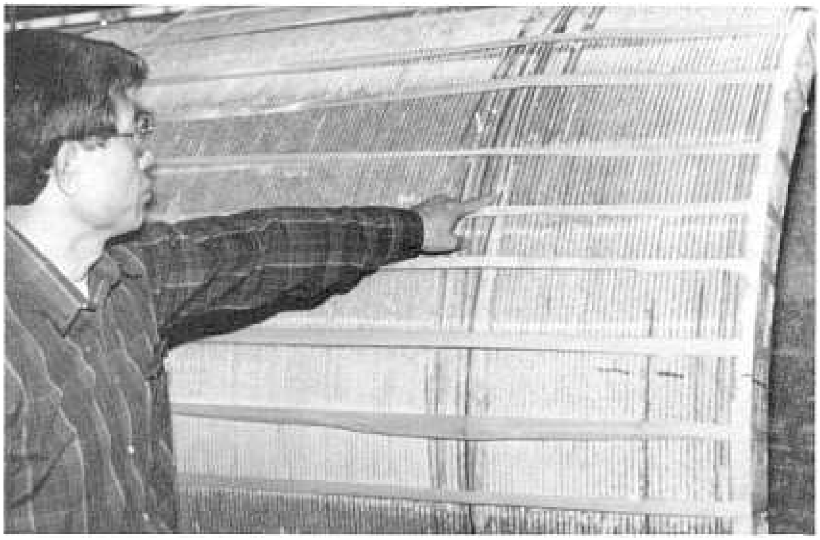


Figure 27. - Fewer and randomly located fractures were found on unit 798. The bonding straps were at the 5 and 11 o'clock positions on this unit in service.

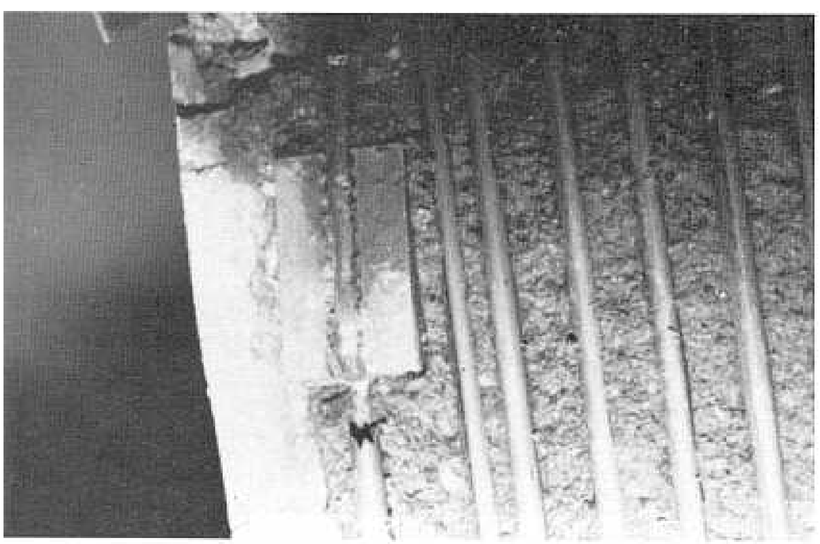


Figure 28. - Wire fracture adjacent to bell anchor of unit 798.

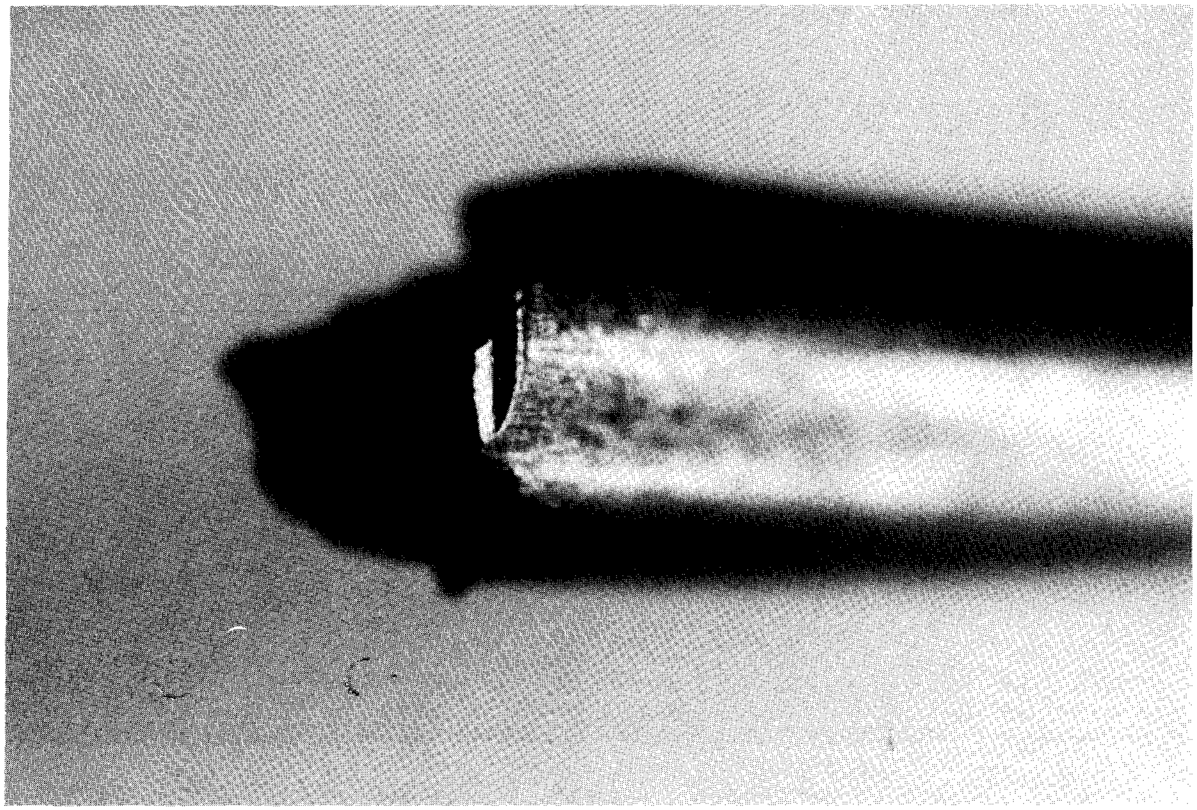


Figure 29. - Close-up of fractured wire at bell anchor of unit 798. Note notch at tip, about 14X.

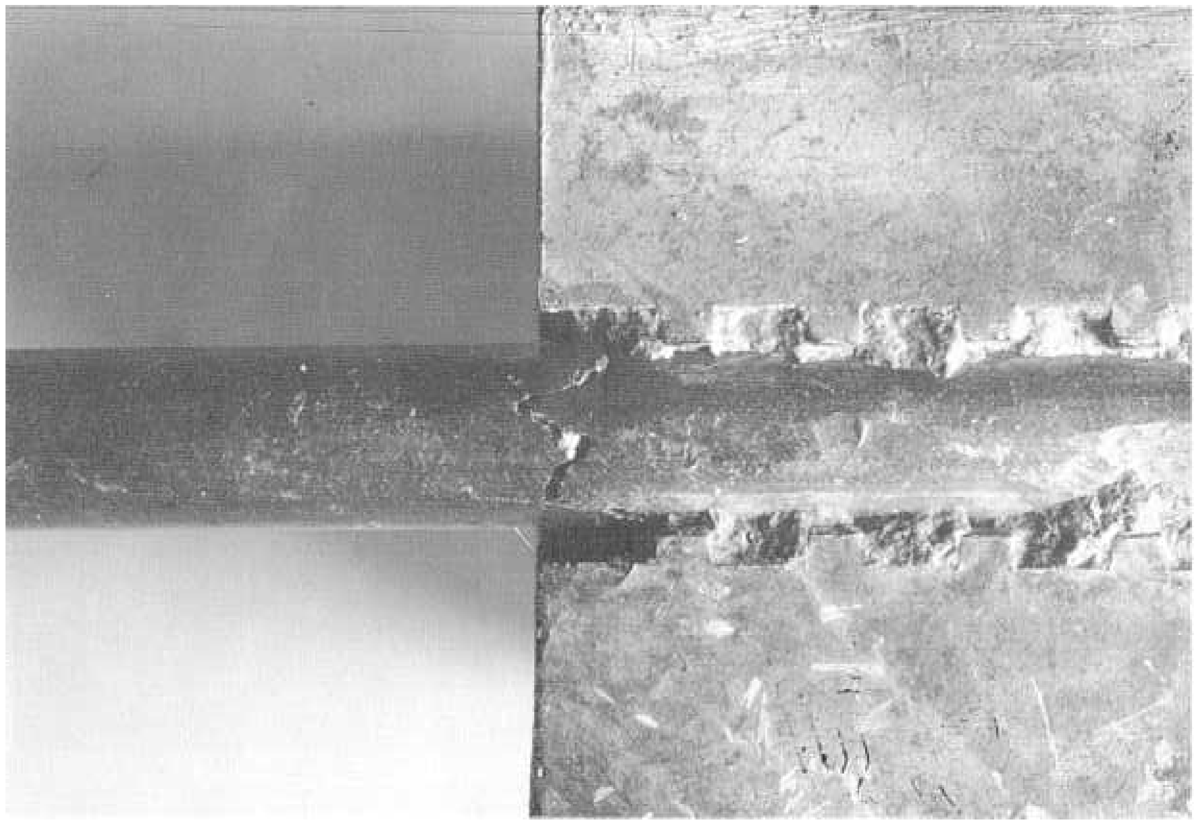


Figure 30. - Anchor and fractured wire, bell anchor, unit 798, about 5.5X.

Figure 31. - Mortar coating opposite bell anchor, unit 798. Mirror image of wire fracture is imprinted, about 5.5X.

Figure 32. - Matched field fractured wires showing fractures occurred at a cross section where two longitudinal cracks meet, about 12X.

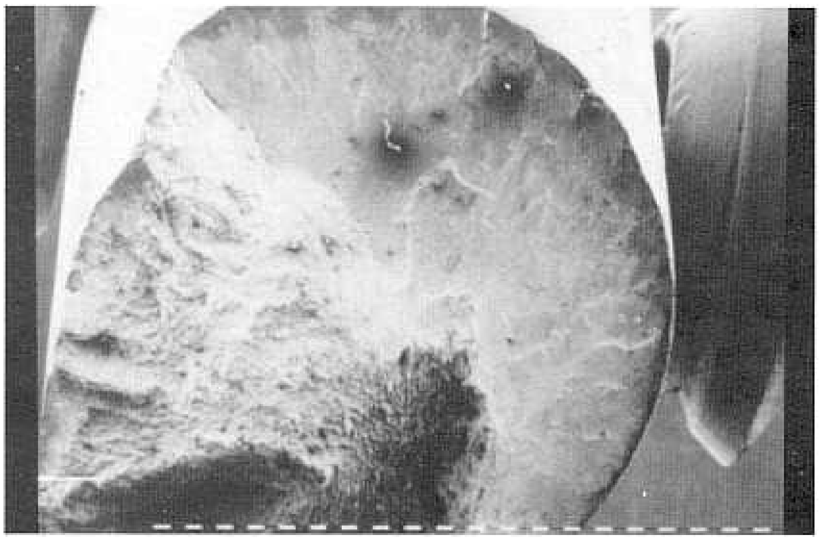


Figure 33. - Field fractured surface of wire, about 20X.

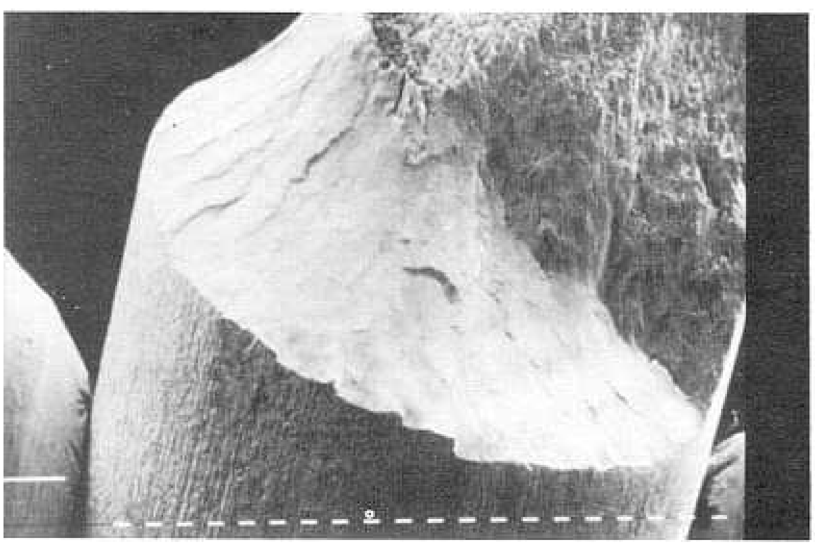


Figure 34 - Field fractured surface of wire, about 20X.

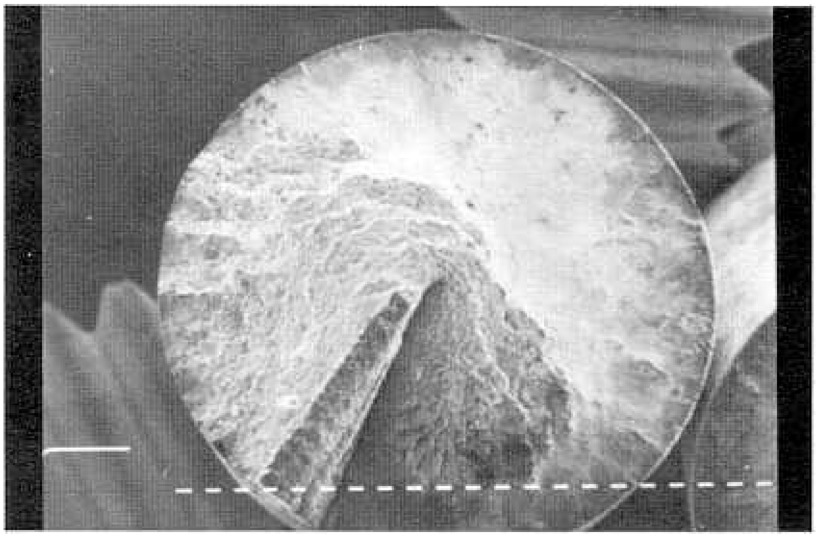


Figure 35. - Field fractured wire, about 20X.

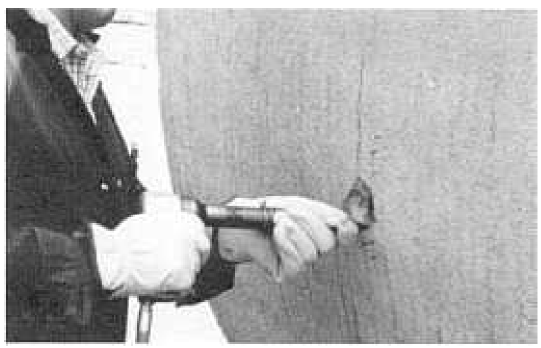


Figure 36. - Two holes were chipped in the mortar coating adjacent to each other in a line along the circumference of the pipe.

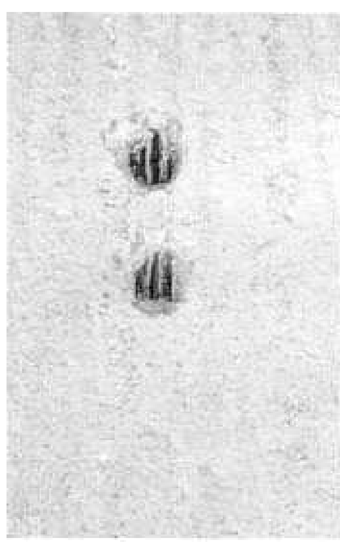


Figure 37. - The holes were separated by 1 inch of intact mortar coating and a minimum amount of prestressing wire was exposed for strain gage application.

Figure 38. - A strain gage was spot welded to the prestressing wire in one hole while the wire remained stressed around the pipe under *in situ* tension.

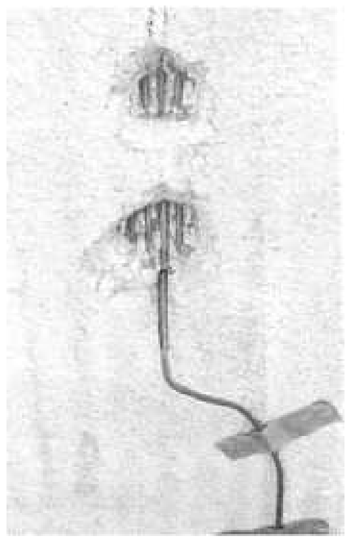


Figure 39. - A strain gage completely spot welded in place.

Figure 40. - A strain indicator was set and the initial strain reading was zeroed.

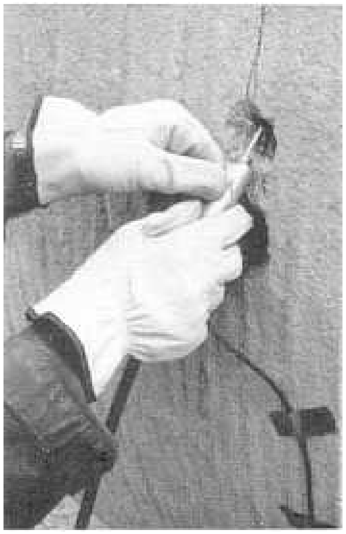


Figure 41. - The prestressing wire was cut to relieve the tension on the wire in the second hole opposite the strain gage and a strain reading was obtained.

Figure 42. - The mortar bridge separating the two holes was removed.

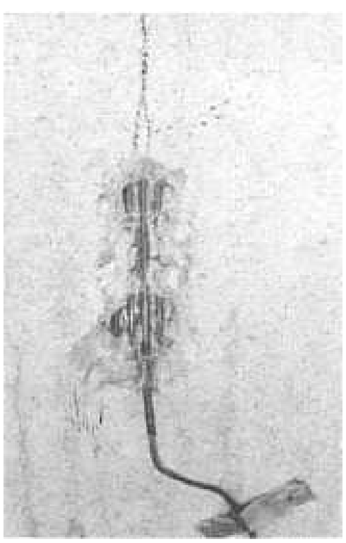


Figure 43. - A tested wire after the mortar bridge was removed. Notice that a large portion of the wire remained encased in the surrounding mortar.

Figure 44. - The wire was held down at the strain gage with a specially fabricated mandrel and a final strain reading was obtained. The mandrel was cut on the same wire radius as that of the pipe and was slotted to prevent damage to the strain gage.

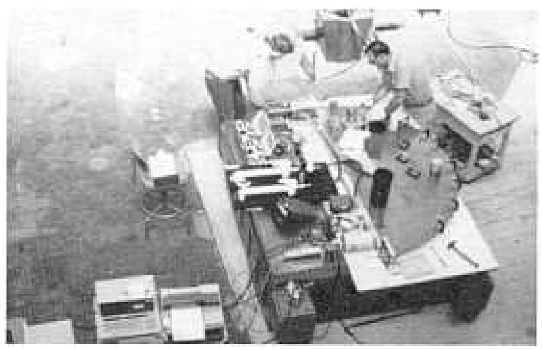


Figure 45. - An aluminum mandrel cut as a semicircle on the same wire radius as the prestressed concrete pipe was constructed to validate field data.

Figure 46. - The wire was cut and the strain relaxation was recorded.

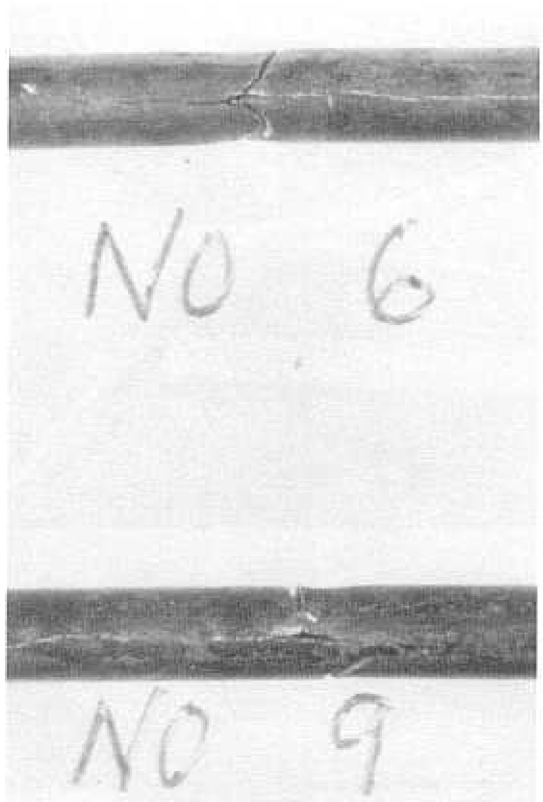


Figure 47. - Two wire samples fractured by laboratory tensile testing. Note similarity to field fracture, fig. 32, about 3X.

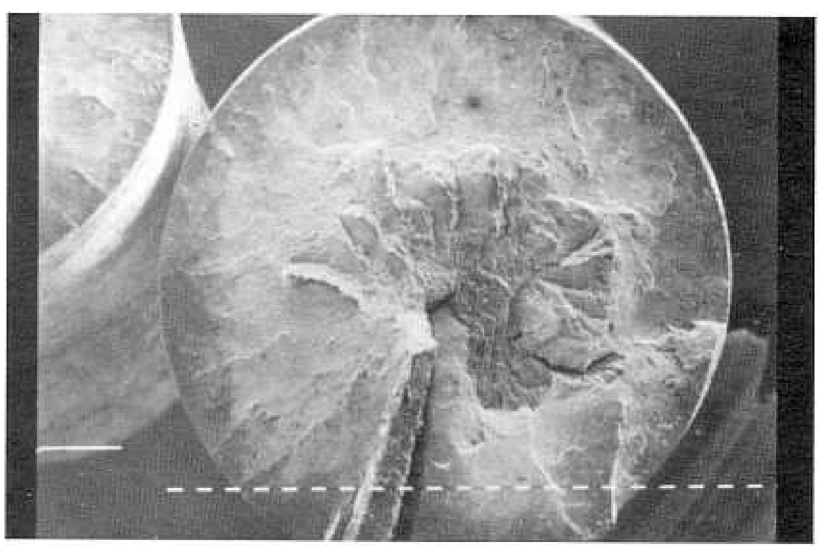


Figure 48. - Laboratory fractured wire. Note similarity to fig. 35, about 20X.

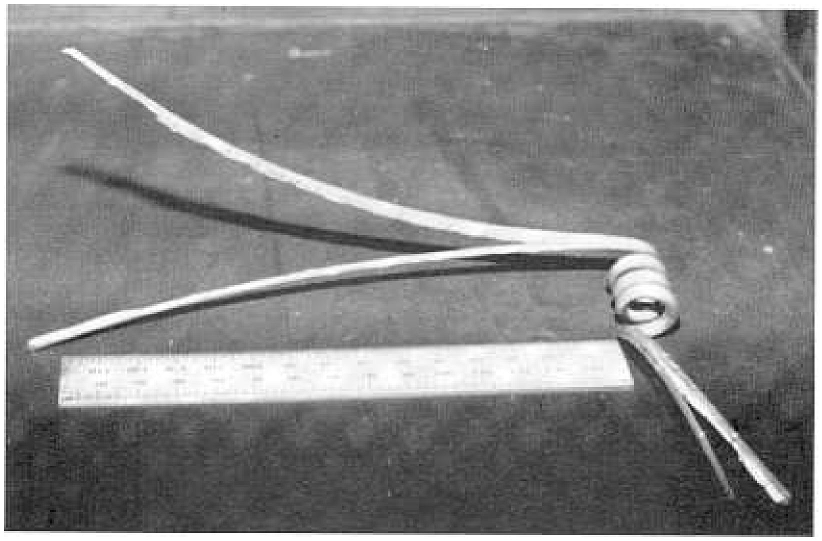


Figure 49. - In many cases, wrap test specimens showed no visible signs of cracking in the wrapping coils, but longitudinal cracks were easily split open on the ends with bolt cutters.

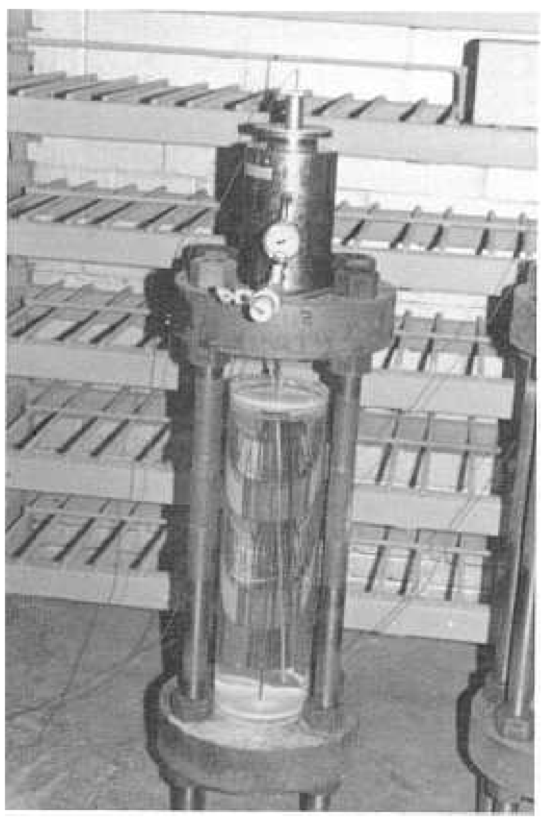


Figure 50. - Cell in which wire, both cracked and uncracked, was cathodically charged while under sustained stress.

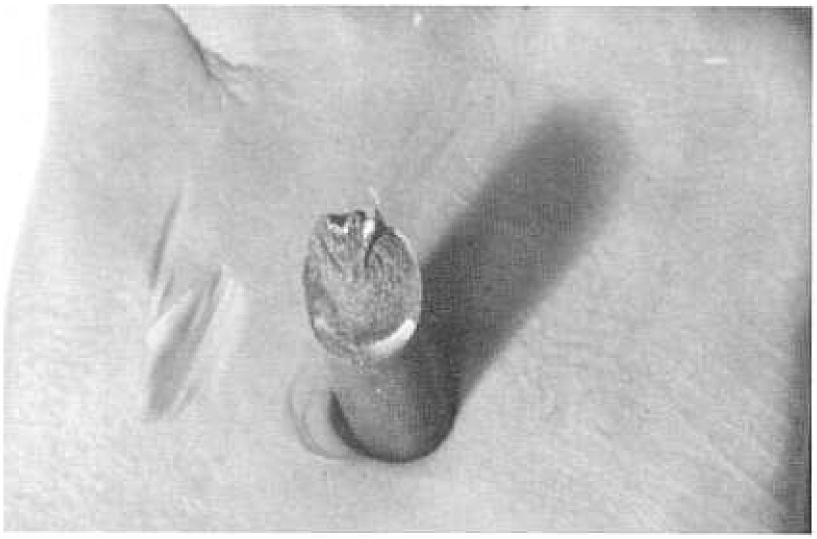


Figure 51. - Photomacrograph of wire embrittled in the laboratory, about 4X.

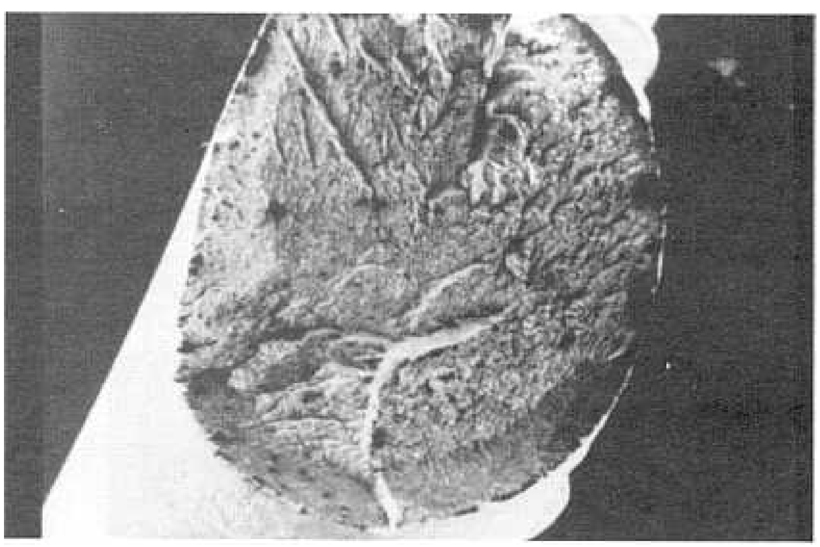


Figure 52. - Photomicrograph of surface in fig. 51. Notice the step transverse to the wire axis, about 14X.

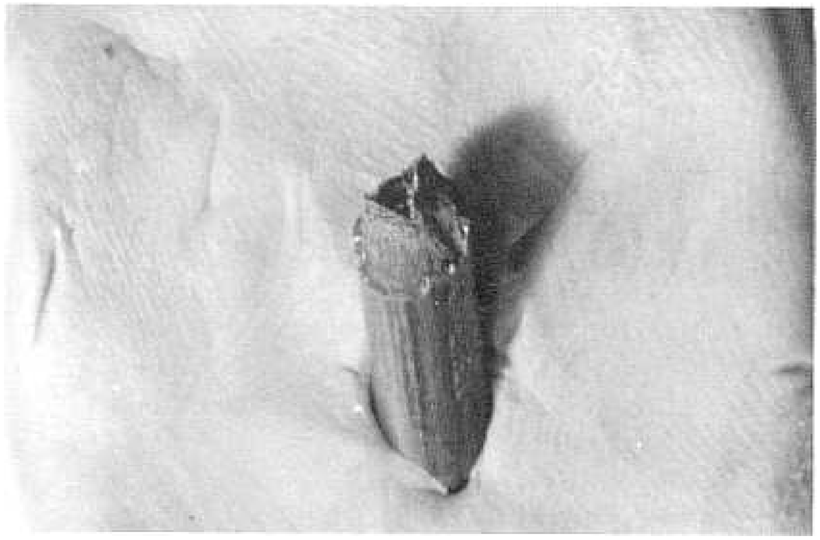


Figure 53. - Photomacrograph of wire embrittled in the laboratory, about 4X.

Figure 54. - Photomicrograph of surface in figure 53. Note the ledge or step transverse to the wire axis.

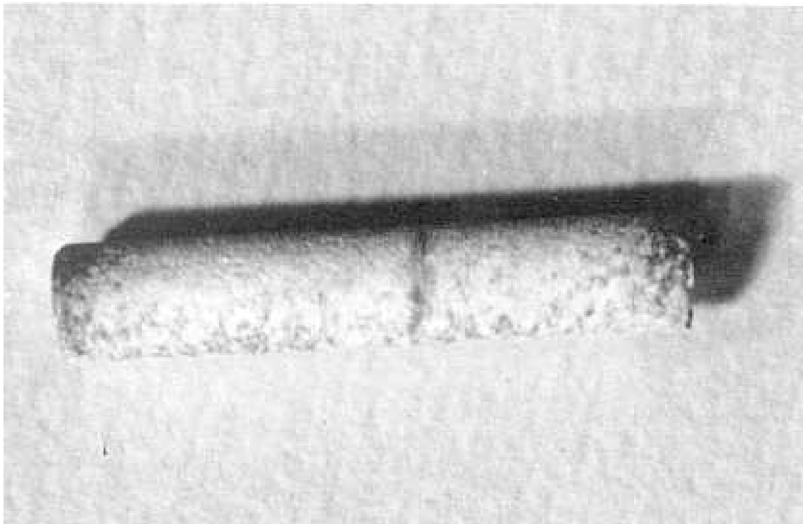


Figure 55. - Dye penetrant indication of transverse cracking after laboratory embrittlement, about 4X.

Figure 56 - Secondary transverse crack not associated with fracture of laboratory-embrittled wire, about 160X.

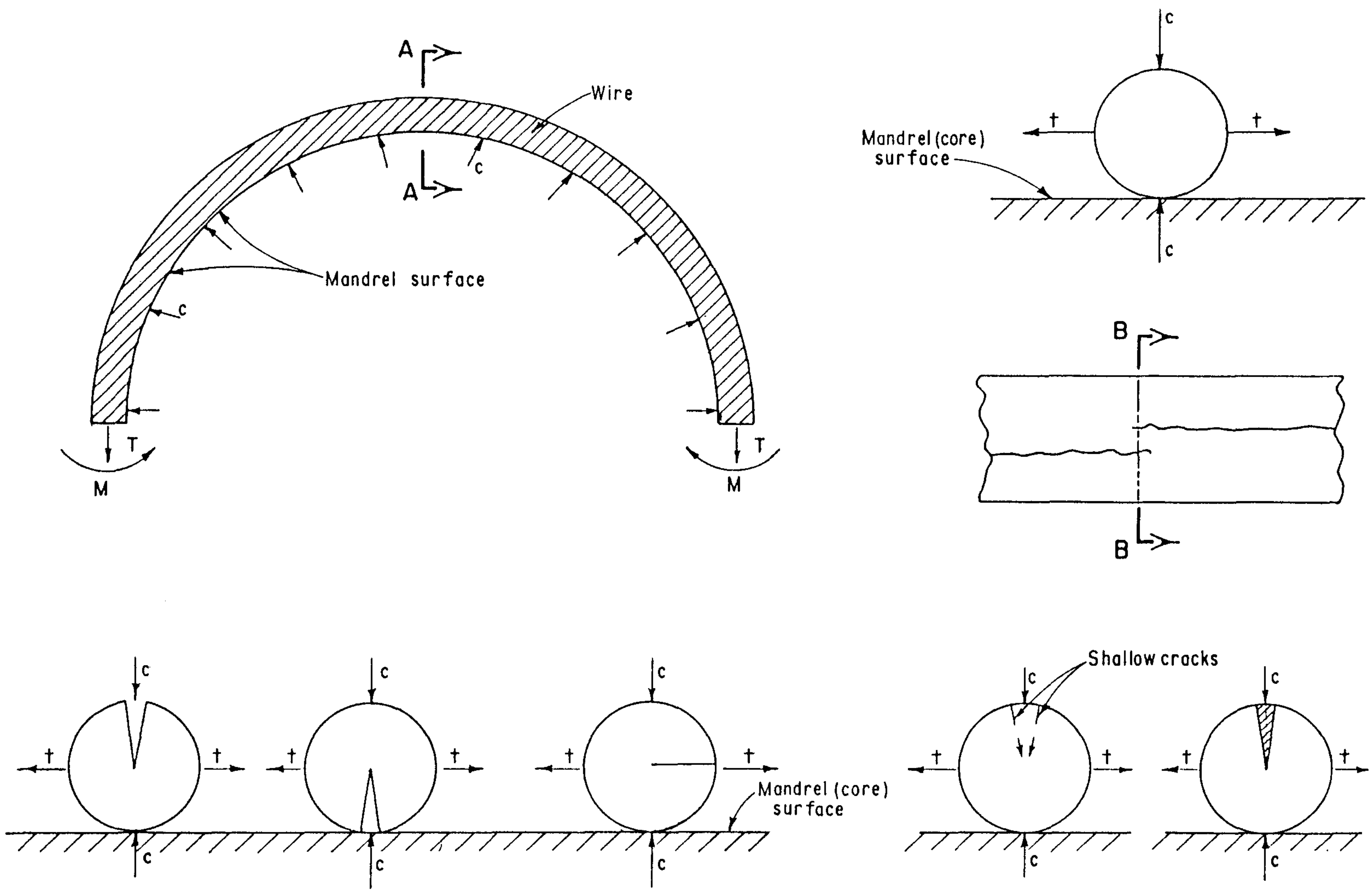


Figure 57. - Schematic showing growth of offsetting longitudinal cracks toward the center of a wire cross section caused by the Poisson's effect.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.