Condition of Steel Cable after Period of Service

By S. Leigh Phoenix,[1] Herbert H. Johnson,[2] and William McGuire,[3] F. ASCE

Abstract: The condition of the interior of a 3-1/4-in. steel cable after approximately 20 yrs in service is described. The cable studied was one of 21 bridge strands that support a very large radio telescope. It had suffered minor surface wire breakage and was replaced for testing and dissection to provide information needed for judging the condition of the entire cable system, and ensuring long-term satisfactory operation of the telescope. Very little information has been published on the condition of cables after a period of service. The paper is presented in the interest of partially filling this gap in the information needed for estimating the service life of steel structures.

Introduction

The National Astronomy and Ionosphere Center is operated by Cornell University under contract with the National Science Foundation. Its principal instrument is a very large radar-radio telescope located at the Arecibo Observatory in Puerto Rico. This telescope, completed in 1963, has been the source of outstanding discoveries in radio astronomy and the atmospheric sciences.

As shown by the aerial view of the structure in Fig. 1, the feed systems for the telescope are supported by a large steel suspended structure. Wire breakage in the cables of this structure has been experienced since its construction. In 1981, the cable having the largest number of broken wires was replaced for the purposes of studying the internal condition of that cable and developing information needed for safeguarding the telescope. This is a report of the condition of the removed cable. Before presenting this evaluation, the structure will be described briefly, the history of the wire breaks related, and the past maintenance and remedial measures summarized.

The Structure.—The essential components of the structure are outlined in Fig. 2, and described in detail in Kavanagh and Tung (7). The elements of interest here are the twelve 3-in. (76-mm) diam main cables, the fifteen 3-1/4-in. (83-mm) diam anchorage (backstay) cables, and the connections between these cables and the anchorages, towers, and feed platform. For reference, the key points are designated by their clock position when viewed in plan. Thus, the northerly tower and anchorage are T12 and A12, respectively, the southeast tower is T4, and so forth.

The cables are conventional bridge strand with Class A galvanized coating. Socketing followed standard industry practice which, at the time

[1]Assoc. Prof., Sibley School of Mech. and Aerospace Engrg., Cornell Univ., Ithaca, NY 14853.

[2]Prof., Dept. of Materials Sci. and Engrg., Cornell Univ., Ithaca, NY 14853.

[3]Prof. of Struct. Engrg., Cornell Univ., Ithaca, NY 14853.

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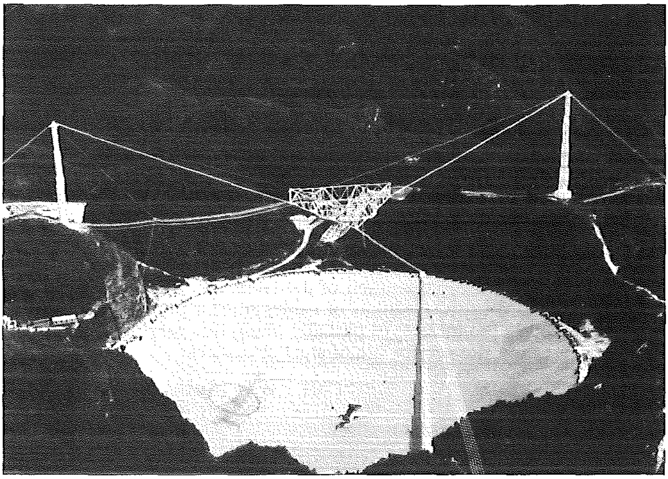

FIG. 1.—Aerial View of Arecibo Radar-Radio Telescope

of manufacture, involved brooming out the ends of the strand, removing the original galvanizing with mild acid and then neutralizing, inserting the ends into the basket of the socket, and filling the basket with molten zinc. The cables were subsequently pretensioned in the shop to the lower of 600 kips (2,669 kN) or 56% of the specified breaking load.

Figs. 3 and 4 show some of the cable terminations and connections to the rest of the structure. At the top of each concrete tower is a steel saddle with troughs for receiving the upper ends of the main and backstay cables. The face of each socket butts up against the saddle, and the rear is open as shown. A similar method of force transmittal to the socket exists at the feed platform. At the lower end of each backstay, however, a large rod is threaded into the open (rear) end of the cable socket. The force in the backstay is transmitted through an adjustable nut and beveled washer on this rod to a yoke which, in turn, is connected to two 2-1/2-in. (64 mm) diam prestressed cables embedded in the concrete anchor (Fig. 4). The design forces and breaking strengths for the main, backstay, and prestressed anchor cables are tabulated in Table 1.

Wire Breaks.—Fig. 5 is a chart of the wire breaks and their dates of discovery from the period of construction to the time of replacement (1981) of the cable of interest here (A12-3). All of the breaks occurred near the point where the wires enter a socket.

Briefly, there were nine breaks at the lower ends of the backstays, seven breaks at the lower (platform) ends of the main cables, one break at the upper (tower) ends of the backstays, and three breaks at the upper ends of the mains. (There are over 5,000 wires in the 27 cables.)

The cable with the largest number of breaks (six) was the center backstay (A12-3), as shown in Fig. 5. Breakage occurred at roughly a constant rate from 1972 to 1978. Broken ends of several of the wires were studied. Analysts mentioned some possible evidence of both stress corrosion and corrosion fatigue, but the conditions of the fracture surfaces at the times

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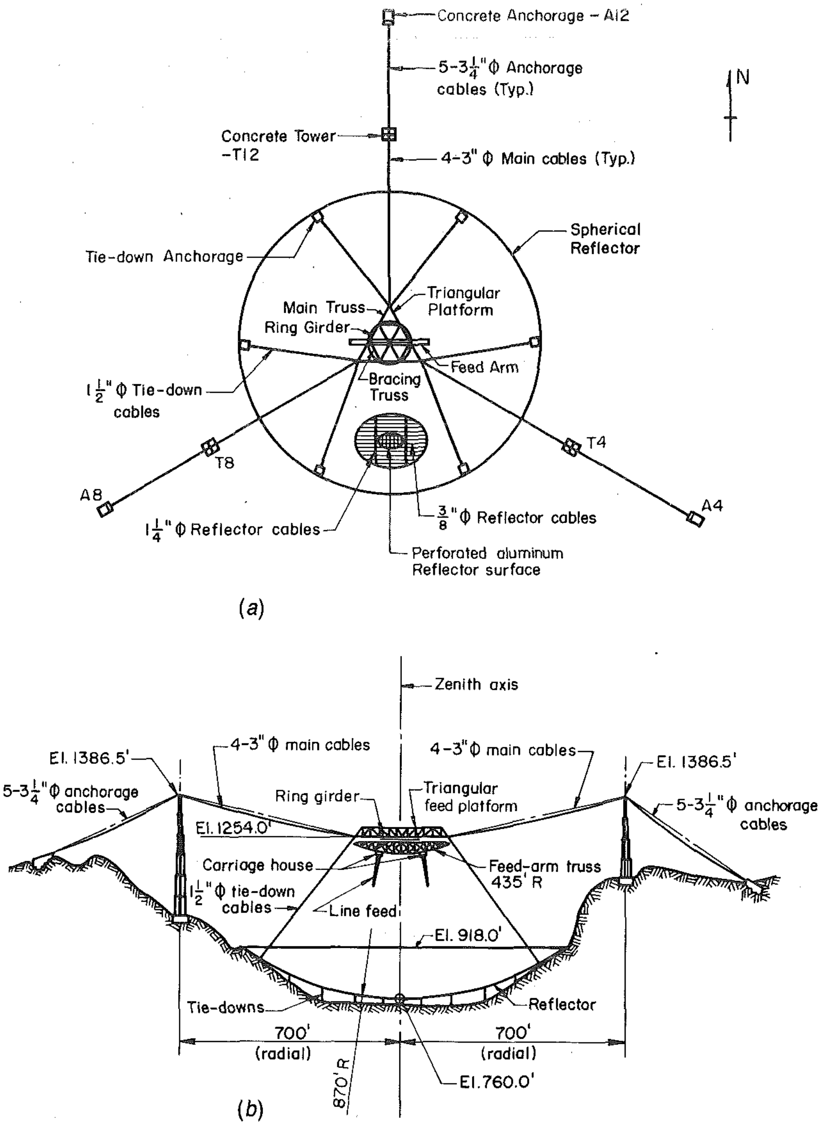

FIG. 2.—Line Diagrams of the Arecibo Structure: (*a*) Plan of Observatory; (*b*) Elevation of Observatory

of discovery were such that no definitive conclusions could be drawn.

Three additional wire failures were reported in January 1983, after the replacement of A12-3. These were at the platform and tower ends of M4-4, and at the platform end of M8-4. From an examination of fracture surfaces, at least two of these failures occurred long (perhaps years) before the reporting date.

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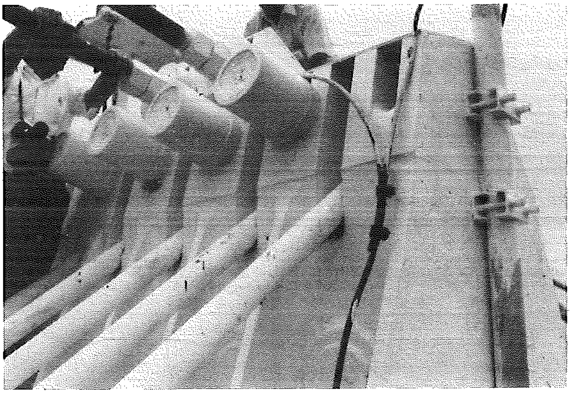

FIG. 3.—Saddle and Cables at Top of Tower

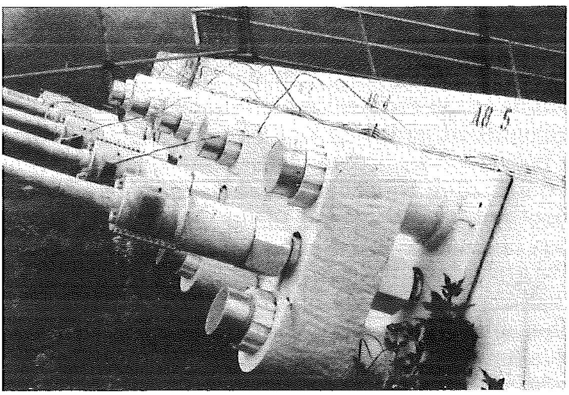

FIG. 4.—Anchorage and Backstay Cables

Maintenance and Remedial Measures.—Several remedial measures were initiated. In the mid 1960s, Stockbridge dampers were installed to minimize aeolian vibration (which had existed, though on a minor scale). A jacket was placed around the lower end of each backstay cable to permit the pumping of dry air into the cable for the purpose of keeping the interior dry (Fig. 4). These systems were in operation by the early 1970s.

The cable system is carefully maintained, with frequent inspections. Evidence of vibration is reported. The white exterior paint is kept in excellent condition. Loads on the feed platform are monitored, and operation of the movable feed arm truss is carefully supervised. Also, plans exist for both cable replacement and cable additions, should either be judged desirable.

Cable Replacement.—In 1978, it was decided that the best way to prepare for making a rational judgment regarding the need for major structural work to safeguard the facility was to replace and study the cable

TABLE 1.—Cable Strengths and Service Loads

Cable Characteristics					
Cable (1)	Number (2)	Diameter (in.) (3)	Minimum breaking strength (kips) (4)	Tension per cable (kips)—dead load at 90° F (5)	Tension per cable (kips)—dead load at 70° F + 100 mph wind (6)
All main cables	12	3	1,076	527	600
Backstay					
T4-A4	5	3-1/4	1,250	593	685
T8-A8	5	3-1/4	1,250	541	630
T12-A12	5	3-1/4	1,250	566	655
Embedded in anchors					
A4	10	2-1/2	752	296	342
A8	10	2-1/2	752	270	315
A12	10	2-1/2	752	283	327

Note: 1 in. = 2.54 cm; 1 kip = 4.45 kN; 90° F = 32.2° C; 70° F = 21.1° C; 100 miles per hour = 161 km/h.

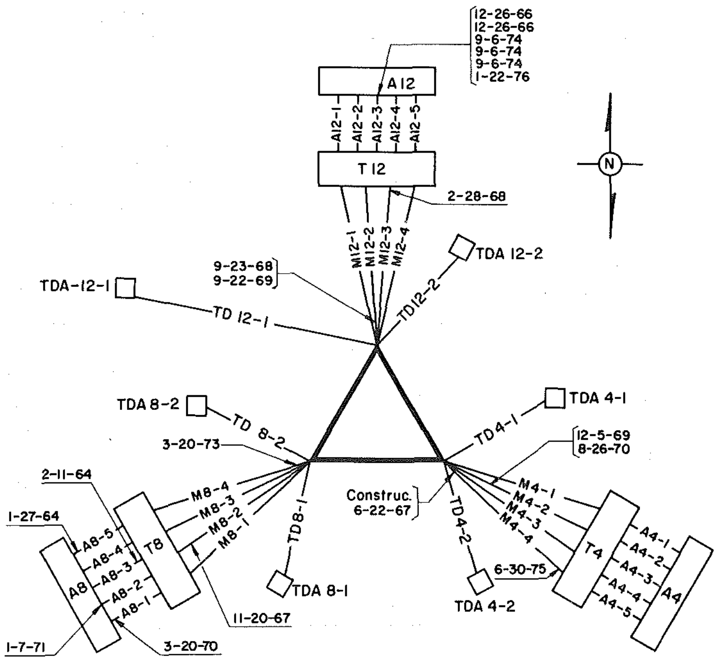

FIG. 5.—Summary Chart of Wire Breaks in Cables

with the most broken wires—the center backstay (A12-3) between A12 and T12. A major factor influencing the decision was the absence of information on the condition of the interior wires. Manufacturers and other users of cables had no useful information on the interior condition of a bridge strand in service. Although the outward appearance of the other cables was good, in this state of ignorance (and in view of the literature summarized shortly) it was prudent to admit the possibility of deteriorated galvanizing, deteriorated socketing, and cracked or broken interior wires in this or other cables supporting the feed platform. Further, the six visible broken wires in A12-3 raised serious doubts regarding the ability of this particular cable to serve for the life of the structure. For these reasons the decision for replacement was made. The replacement was accomplished in September 1981, and the upper and lower ends of that cable were then sent to Cornell University for analysis.

Relevant Literature.—The wires used to make up bridge strands are a carbon steel that has been highly cold-worked by drawing, sometimes with intermediate annealing steps. Cold-working produces a very fine microstructure and a correspondingly high ultimate strength. Typically the wires are galvanized by hot-dipping or electroplating.

Under cold-working the wire strength steadily increases with drawing strain (4), typically achieving 230 ksi (1.59 GPa) in mean ultimate strength with a coefficient of variation of about 2%. On the other hand, the fatigue strength (stress range producing a mean number of cycles to failure of at least 2×10^6 cycles) is approximately 60 ksi (410 MPa) but with greater variability (6). The galvanizing process, which typically lowers the ultimate strength by only 5%, may lower the fatigue strength by 20% (10). During drawing, the fatigue strength does not increase as fast as the ultimate strength, and eventually drops, even though the ultimate strength may continue to increase (4). This is a consequence of an increased notch and flaw sensitivity at high strength levels. Moreover, wire fatigue strength appears to be highly dependent on surface roughness, whereas ultimate strength is dictated primarily by internal plastic yielding (1,3).

Studies suggest that exposing wires to elevated temperatures can reduce their strength, especially their fatigue strength. Andrä et al. (2) report that a 10-min exposure to 752° F (400° C) reduced the ultimate strength by 5%. A more severe 12% reduction was observed at 842° F (450° C), whereas a negligible reduction occurred with exposure to 662° F (350° C). On the other hand, Kondo et al. (8) report a fatigue strength of about 50 ksi (350 MPa) after exposure to 842° F (450° C), but only 21 ksi (150 MPa) after exposure to 896° F (480° C) during casting. While their original fatigue strength was not reported, the suggested reductions are alarming in view of the fact that conventional zinc-poured sockets for cables are cast at 860° F (460° C) or higher. In fact, lower-temperature casting alloys and other socketing procedures have been developed in Germany to avoid the problem (1,5,6,8,12).

The effects of surface fretting and corrosive environments on wire fatigue strength and time-dependent failure under constant loads have been studied by Nürnberger and Wiume (9) and by Rehm et al. (11,12). It has been found that surface fretting in a corrosive environment due to the transverse contact of hard objects can reduce the wire fatigue strength from a nominal 50 ksi (350 MPa) to 21 ksi (150 MPa). Furthermore, uncoated and zinc-galvanized wires are reported to suffer from stress-corrosion cracking and hydrogen embrittlement (9,11), though the exact mechanisms are poorly understood. Indeed, at a recent international symposium (13), only two papers dealt even remotely with such effects in these highly cold-worked steels.

In summary, ultimate wire strength is a carefully controlled variable that translates well (through mechanical analyses) to cable strength. Wire fatigue strength, on the other hand, is highly variable and sensitive to environmental and processing factors.

Note that the stress ranges and numbers of cycles for any past cyclic loading (diurnal, aeolian or feed platform induced movement) are not really known. However, the ranges are believed to be less than the 21-ksi (150-MPa) value cited in the literature above.

Cable (A12-3) Analysis

A comprehensive testing program was developed to evaluate the condition of the removed (A12-3) cable. The program included strength tests of wires removed from representative locations in the cable, mechanical tests of socket integrity, careful dissection of the upper and lower sockets, and detailed tests for cracks and the remaining strength of nearly all the wires removed from the socket regions. Special attention was directed to the lower socket region, where the six adjacent wire breaks were located.

Wire Strength Tests from Strand Midsection

Two 6-ft (1.8-m) sections of the strand were selected for detailed testing. The first section (upper section) was a segment beginning 5 ft (1.5 m) below the upper socket (as placed in the structure) and ending 11 ft (3.4 m) below. The second section (lower section) began 5 ft (1.5 m) above the lower socket and ended 11 ft (3.4 m) above. These sections were unraveled for inspection and tension testing of the individual wires. Generally it was established that there was no significant deterioration of wire quality or strength during service. Further observations follow.

Upper Section.—The outer surface of the strand was covered with several coats of paint which partially engulfed the outer wires (row 1); these wires were essentially free of corrosion, as in fact were all the wires. The wires in the third layer (row 3) began to show signs of indentation (Brinell marks) at wire crossover points, and this increased for the remaining layers. Wires from rows 5 inward were covered with grease which appeared to be uncontaminated. At the Brinell marks, the galvanized coating was worn away and the surface was typically shiny. The indentations, though slight, did appear to involve plastic deformation of the steel. No broken wires were discovered. All wires were permanently deformed into a mild helical shape.

Tension tests were performed on several 6-ft (1.8-m) lengths of wire from each layer. A Baldwin tension test machine and standard wire clamps were used. Yielding typically commenced at about 85% of the ultimate failure load. At failure, the plastic strain was typically about three times the elastic strain at the onset of yielding. Fracture surfaces were typically

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of the cup and cone type with about a 35% reduction in area. Failure often occurred at a Brinell point. Very few clamp failures occurred, and the failure positions were random along the length. The mean tensile strength was found to be 229 ksi (1.58 GPa) with a coefficient of variation of 2.0%. There were no significant differences among the row mean strengths.

Lower Section.—The tests performed on the upper section were repeated for the lower section with similar results, except as follows. Upon unraveling the wires in rows 1–4, a white powdery debris was found deposited among the wires. It is believed that this debris was a mixture of paint dust, zinc oxide and zinc chloride washed down the cable by water penetrating the cable along its length. The amount of grease on the wires in rows 5 and 6 was less than that observed in the upper section, perhaps due to water washout. Some small rust spots were noticed on the wires from rows 1 and 2, and to a lesser extent on those from row 3. Also, the Brinell points tended to be black rather than shiny. Wires from row 4 inward were clean with almost no rust or corrosion. Again, no broken wires were found.

In this case, tension tests produced a mean tensile strength of 230 ksi (1.59 GPa) with a coefficient of variation of 2.2%. The mild rust spots and corrosion on the wires from rows 1 and 2 did not significantly reduce their strength (the sample mean is actually higher than for the upper section) though there was a predisposition for these wires to fail at a rust spot. Again wires from rows 3 inward failed primarily at Brinell marks which tended to distort the failure surfaces but otherwise did not reduce the strength.

The mean tensile strengths and coefficients of variation determined above for wires from the strand midsection are believed to be typical of the virgin wire. There was no evidence that the mechanical properties of these wires had been degraded significantly by the approximately 20 yrs of service.

Tests for Effectiveness of Sockets

As mentioned, the lower socket showed evidence of degradation in the form of broken wires. To further evaluate the integrity of both cable sockets, a special fixture was built to allow clamping of a socket in the lower end of the Baldwin tension test machine (Fig. 6) so that "in-situ" tension tests on the wires could be performed. This fixture was adjustable with respect to both the angular orientation and horizontal positioning of the socket axis with respect to the vertical line of pull of the tension test machine.

Upper Socket.—The upper socket and 5 ft (1.5 m) of strand were placed in this special clamp fixture. By loosening, sliding and tightening several hose clamps, a single wire was unraveled from row 1 of the strand and its free end placed in the upper (wire) clamp of the Baldwin machine. The axial alignment of the lower socket was set so that the wire exited the lower socket exactly tangent to its original helical path (14° helix angle), thus avoiding bending or kinking. The unraveled wire was then proof-loaded to 212 ksi (1.46 GPa), a value which was 92.5% of the mean wire strength obtained from earlier tests. (The terms "proof-loaded" and "proof-testing" used here refer merely to the loads applied in this in-

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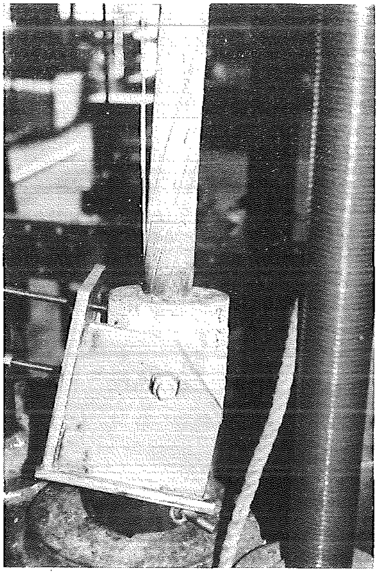

FIG. 6.—Cable Socket in Tension Test Machine

vestigation. They are not material property definitions such as those used to define the effective yield load of steel bolts.) In like manner, each wire from rows 1 and 2 was unraveled, aligned and proof-tested to the same stress.

It was found that this proof-testing caused yielding which had a permanent straightening effect on the wires. However, no wires failed and there was no evidence of any slippage or other abnormalities in the socket. As a more severe test, six of the wires from row 1 and seven of the wires from row 2 were pulled to failure. In addition, three more of the wires from row 2 were pulled to just short of failure [all three survived 233 ksi (1.61 GPa)] for later microscopic inspection. None of the wires failed in the clamp region, and the failures were randomly distributed along the gage length.

We found no evidence of any weakening in the upper socket region using this in-situ tension test procedure. Furthermore, the means and coefficients of variation of the strengths for these two rows agreed very closely with the corresponding values obtained for rows 1 and 2 of the upper section.

Lower Socket.—The above experiments were repeated for the lower socket. However, in this case the steel basket on the lower socket was cut off to relieve the internal transverse compressive stresses in the zinc (Fig. 7) caused by socket seating (wedging action in the tapered basket) during cable pretensioning. The basket was then securely bolted back on. The proof-test procedure described earlier was applied to the wires in row 1, which we recall already had six adjacent broken wires (Fig. 7). The five wires opposite the break region of the strand (180° around the

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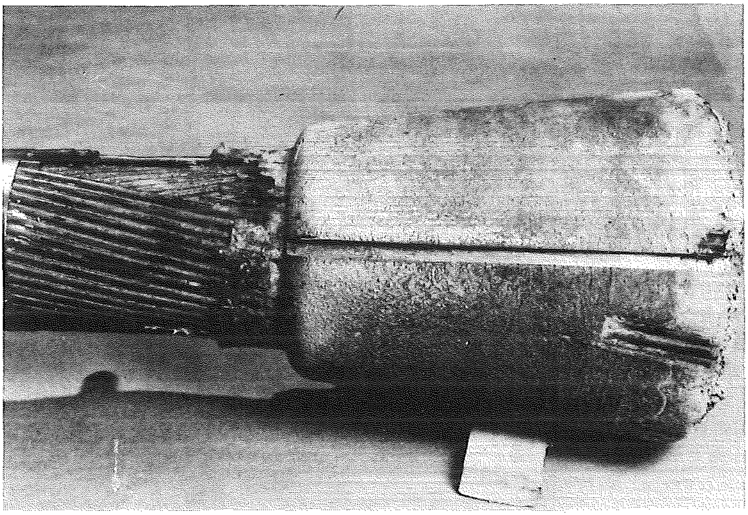

FIG. 7.—Lower Socket without Jacket Showing Degraded Zinc Collar and Wire Break Region (Note Saw Cut from Jacket Removal Process)

strand surface) were proof-loaded to 212 ksi (1.46 GPa). The proof-load for most of the remaining wires was 137 ksi (945 MPa), or about 30% above the service load.

Most of the wires survived this initial proof-test; however, a few wires near the region of the breaks slipped at loads substantially below the 137 ksi proof-load. This slippage was viewed as evidence of poor bonding between these wires and the zinc. It is likely that these wires would not have slipped in service under the transverse compressive stresses described above. Two wires were not proof-tested. As will be evident later, one of these would probably have failed the 137 ksi proof-load test.

Dissection of Upper Socket

The outer basket was cut off the upper socket, and the socket region was dissected by chipping away the potted zinc with a saw and chisel. It was first observed that no zinc existed on the wire surfaces from a point about 1 in. (25 mm) above the socket face to points well into the socket itself. (The manufacturer indicated that this zinc had been removed by acid etching as the first phase of the socketing procedure.) The dissection was carried out row by row on the splayed-out wires. In the outer row (row 1), some of the wires were not well bonded to the zinc. These wires had a black, "wet"-looking coating, or were dry and rust-colored. The coatings were thin with no evidence of pitting. Some of these wires could be tapped longitudinally out of the zinc mass with a punch (though they did not slip in the earlier proof testing). The situation was similar with the row 2 wires. From the third row inward, the wires were found to be well wetted and bonded to the zinc at points deep in the socket, and were much more difficult to remove. The bonding was typically poorest near the exit point from the socket, that is, just

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under the socket face, and some black surface coating was observed there. The innermost wires showed the best bonding to the zinc deep in the socket. The region of good bonding was quite symmetric with respect to the axis of the socket. It appeared that the zinc wetting and bonding were poorest in the vicinity of the surface of the steel basket. No doubt this basket acted as a heat sink, drawing heat from the molten zinc and reducing the effectiveness of the wetting. The temperature of the steel basket just before potting was well below the nominal 860° F (460° C) temperature of the poured zinc.

Tension Tests on Wires Removed from Upper Socket.—The dissection procedure unavoidably resulted in some surface damage to the wires in the form of a few chisel marks and an occasional saw mark. Nevertheless, tension tests were performed on 14-in. (36-cm) segments of these wires, of which about 7 in. (18 cm) was originally embedded in the socket. About half the wires from each row were tension tested.

Typically about half the failures were at points of surface damage caused by the chisel; otherwise cup and cone failures were typical with about a 35% reduction in area; we call these "clean failures" in that chisel damage was not a factor. The points of failure were typically points which were originally 3–4 in. into the socket region in areas where the poured zinc was found to be well bonded to the wires. Most of the wires showed little or no rust or corrosion in this test region.

We compared the strength results for these socket wires having "clean failures" with those for the corresponding rows in the upper section and found the socket wire results generally to be lower by 1–2%. These results, coupled with our aforementioned observations on the points of failure, suggest that the wire strength was degraded just slightly by the temperature increase resulting from exposure to the 860° F (460° C) molten zinc during socketing. To test this hypothesis, we tension tested several specimens which had been heated to 786° F (419° C) in an oven for about 1/2 hr, and oven cooled. This treatment resulted in about a 3% drop in mean strength. Repeating the experiment at 1,112° F (600° C) in Argon for 1 hr reduced the strength by about 45%.

Thus, temperature effects during socketing are the probable cause for the slightly reduced wire strength associated with the upper socket. However, the effectiveness of the socket did not seem to be reduced by this factor, as evidenced by the in-situ test results described earlier. (Note that the actual wire stress drops off with increasing depth into the socket.)

Dissection of Lower Socket

As with the upper socket, the lower socket was dissected by chipping the zinc from between the wires. It was first noticed that a "collar" of zinc existed around the cable at the socket face (Fig. 7), being thinnest in the area of the six wire breaks. It was again observed that no zinc existed on the wire surfaces from a point about 1 in. (25 mm) above the socket face to points well into the socket itself (Fig. 8). Considerable corrosion was found in this region at the collar. During dissection it was found that the zinc was easier to remove than in the upper socket, and that the wires of row 1 were splayed out closer to the surface (basket). The four wires adjacent to the break region in the counterclockwise direction (looking from the tower) were easily tapped out and had a com-

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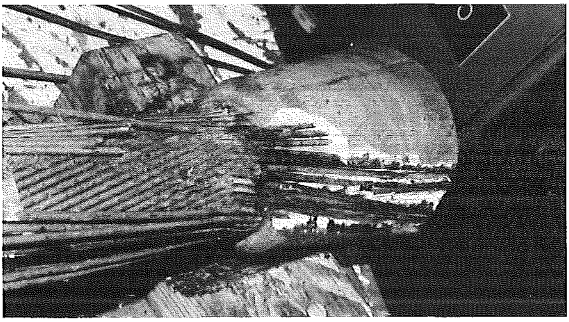

FIG. 8.—Wire Appearance in Lower Socket Break Region (Note Absence of Zinc)

pletely black surface with no zinc wetting. The ends of the wires at the deepest point in the socket were actually exposed to the outside of the zinc mass over about the last 1.5 in. (38 mm), and showed granular rust and dirt.

The six broken wires of the break region were easily tapped out longitudinally. They were not wetted by or bonded to the zinc, but were totally enclosed by zinc and 80% black. The next few wires in the clockwise direction were more difficult to remove, and showed some wetting to the zinc. In fact, the wetting seemed most complete in the few wires diametrically opposed to the six breaks. Proceeding in the clockwise direction, the wetting again diminished and the wires were again less well bonded to the zinc.

In rows 2 and 3, poor wetting was observed directly under the break region; however, wetting was much better elsewhere around the circumference. Regions near the exit point or face of the socket were not well wetted. Specimens from rows 4 and 5 were generally well wetted deeper into the socket except under the break region. Grease was found on the wires outside of the socket region and some spots of red rust were noticed at the socket entry point. Rows 6, 7, and 8 were uniformly wetted around the circumference in the lower half of the socket. The upper half of the socket region near the exit point showed the wires again to be black on the surface. Fig. 9 illustrates some of the observations about the lower socket.

Tension Tests on Wires Removed from Lower Socket.—Tension tests identical to those performed for the upper socket were performed on wire segments from the lower socket, with similar results except for the following. A few of the wires showed corrosion and pitting at the socket exit point under the socket face, especially in row 1. A few of these wires failed at low loads with fractures that originated from surface flaws or cracks in the aforementioned region of corrosion. The wires with these surface cracks originated from the same region as the six wires that broke in service, with the same longitudinal position for their fracture surfaces (Fig. 9).

In searching further for cracked wires, we retested several surviving wire pieces from rows 1 and 2 which had spanned the socket face region where cracks and corrosion had been found. No new cracks were found,

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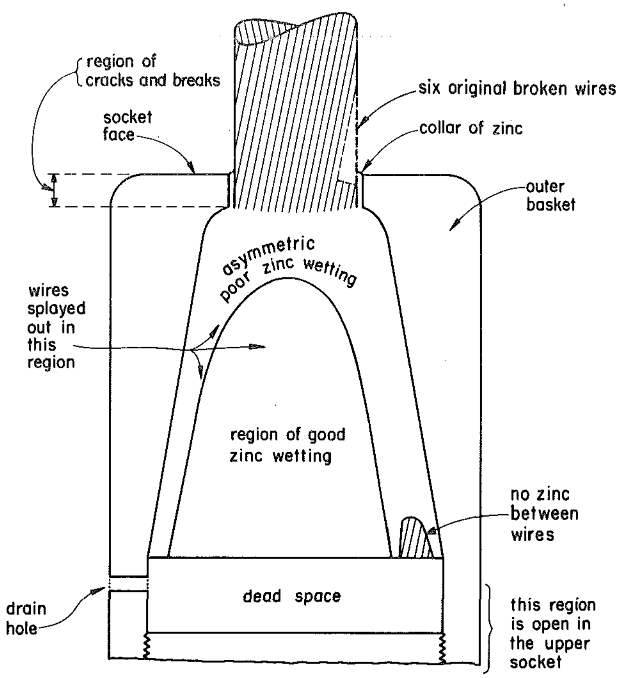

FIG. 9.—Schematic Diagram of Lower Socket Region

and the wires again failed at points originally deep in the socket, being "clean failures" with slightly higher strengths than before.

As with the upper socket, the wire strengths in the socket region appeared to be 1–4% below those for the lower section, with the largest decreases occurring in the inner rows. One interesting observation was that the wires in rows 2, 3, and 4, which were in the region directly underneath the break region, had about 1% higher average strengths than their respective row averages; this effect was very slight but noticeable nonetheless. During the dissection it was noted that these wires were poorly wetted relative to the others, and were easier to pry loose. Their higher strength was possibly the result of their being exposed to less heat during socketing (as evidenced by their being poorly wetted), though we cannot confirm this.

Cracked Wires from Lower Socket.—In all, 11 wires from row 1 and one of the wires from row 2 failed at preexistent surface cracks. All of these failures were at surface cracks which protruded into the steel less than 0.025 in. (0.1 mm). These cracks were easily seen on the fracture surface with an optical stereo microscope. The cracks tended to be perpendicular to the surface and to the wire axis, but sometimes formed an angle with the surface. All cracks appeared to have existed for some time, and showed surface corrosion. A microprobe analysis of one of the cracks revealed the element zinc. This zinc was not thought to be galvanizing but rather some zinc compound washed into the crack. The

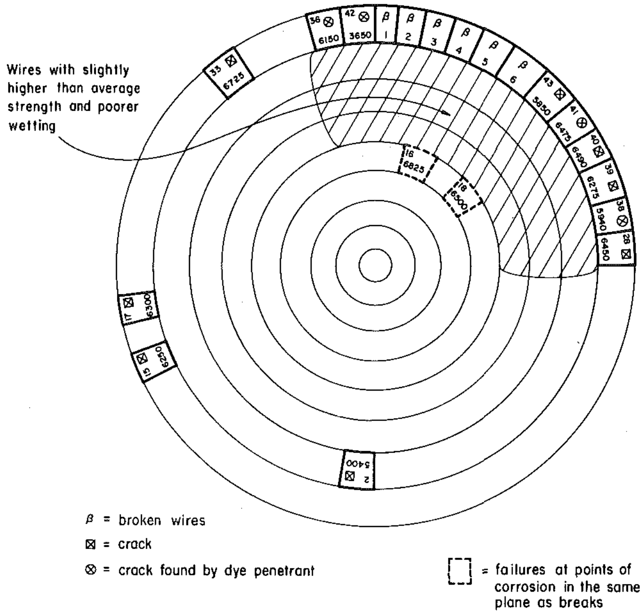

FIG. 10.—Map of Broken and Cracked Wires in Lower Socket; Failure Loads of Cracked Wires are Shown in Pounds (230 ksi = 6,730 lb) (Note: Wires in Each Layer Are Numbered in Order Tested)

fresh failure surface revealed no zinc.

The cause of these cracks is not known, but they usually appeared in regions of substantial corrosion or pitting. Only four of the cracks were large enough to be detected by Zyglo and dye-penetrant techniques. The mildest crack was in a wire which failed at the normal value of 230 ksi (1.59 GPa). The most severe crack was in a wire which failed at 125 ksi (861 MPa), a strength slightly above the working stress. Stains on some of the crack surfaces indicated growth over time; however, it is not known whether this growth was influenced by the installation of air dryers. It is likely that these surface cracks were caused by the same factors which led to the six adjacent breaks of Fig. 7.

Corrosion was found on many other wires in the region just under the socket face. However, only two (row 5) failed in this region (as compared with the more typical point of failure originally deeper into the socket). Neither of these two wires were abnormally weak, nor showed cracks.

Fig. 10 shows a map of the cracked wires. Also shown are their failure loads in pounds. [The wire diameter for rows 1–7 was 0.193 in. (4.9 mm), and for row 8 and the center wire was 0.206 in. (5.2 mm).]

Strengths of Wires with Artificial Flaws.—To further consider the effect of flaws on wire strength, we introduced crack-like flaws of various depths into wire specimens removed from row 2 of the upper section using an electrical discharge cutter. The crack tip obtained by this method

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was not atomically sharp, but had a radius of about 0.006 in. (0.15 mm). Letting δ = ratio of crack depth to wire diameter, we found that δ values of 0.026, 0.052, 0.13 and 0.25 produced strength reductions of 0%, 7%, 15%, and 53%.

These results indicate that small flaws can lead to a large reduction in strength despite the plastic yielding of the wire material. Considering the percent area reduction of these cracks, we found that a 2% reduction in cross-sectional area caused a 7% reduction in strength, while a 20% reduction in area caused more than a 50% reduction in strength. These results were in agreement with the reduced strengths we observed with actual cracks, but also indicate that the very smallest cracks may not have been detectable by tension tests because of variations in strength along a wire.

Summary and Conclusions

The backstay cable removed in September 1981 from position A12-3 of the Arecibo Radio Telescope has been studied because it had six adjacent broken wires at the lower socket. The cable was a 3-1/4-in. (83-mm) diam bridge strand originally erected in 1962, and the sockets were molten zinc, poured sockets which were fabricated according to standard practice.

Tests were performed on four sections of the removed cable: the upper and lower socket with 5 ft (1.5 m) of adjacent wire, and two 6-ft (1.8-m) sections obtained from locations about 10 ft (3 m) from the upper and lower sockets, respectively. The two 6-ft sections, which were considered representative of conditions in the main part of the cable, were unraveled and inspected, after which tension tests were performed on the individual wires. The sockets and adjacent wires were subjected to various tests and analyses including in-situ tension and proof testing, dissection, residual strength determination, and searches for fatigue and stress corrosion cracks. Dye-penetrant techniques were also used in the search for cracks, with partial success.

Key observations follow:

1. No broken or cracked wires were found in the upper socket region, and little surface rust or corrosion was seen. The wire strength inside the socket was 1–3% below the values obtained outside the socket, probably because of heat effects from the molten zinc during socketing.
2. Examination of the 6-ft (1.8-m) lengths revealed no broken or cracked wires and no evidence of fatigue. Some rust spots were found on wires from the outer three rows of the lower 6-ft length, but they did not affect the wire strength. Similarly, Brinell indentation points found on inner wires did not reduce their strength significantly.
3. In the lower socket region, 12 cracked wires (of 217 originally) were found at the same location just inside the socket, 11 from the outer row and one from the second row. The strength reduction from these cracks varied from almost none to almost 50%. These cracks were usually associated with surface corrosion and pitting, and appeared to be old cracks.
4. Unlike the upper socket, the pattern of zinc wetting in the lower socket was asymmetric with respect to the cable axis. The few wires

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flanking the original six breaks in the outer row and the wires directly underneath the break region tended to be poorly wetted (Fig. 9). Water appears to have seeped between these wires to the base of the socket where corrosion and its products were found. The resulting chemical activity may have contributed to the wire cracking and breakage.

5. In effect, a region of "damage" was found in the lower socket surrounding the six adjacent breaks (Fig. 10). Here we found several cracked wires, a region of poor wetting and bonding of the zinc, corrosion on the wires just under the socket face, degradation of the zinc collar, and the presence of moisture, at least in the early years of operation.

The stress state in this region of damage was complex and time dependent as a result of socket constraint, thermal effects, motion of the suspended structure of the telescope, and perhaps wind loading. This damage region clearly existed in the early years of telescope operation, and the possibility that it was initiated during the socketing process cannot be overlooked.

It is highly probable that both the broken and the cracked wires sustained their initial damage as a result of the same factors. Although the wire fracture and crack surfaces were sufficiently degraded, presumably by reaction with water, and such that the crack failure mechanism could not be distinguished, it is quite probable that the initial damage grew at a rate controlled by the local stress and the availability of moisture. Although it cannot be conclusively proven from the record, it is believed that the rate of damage (crack) growth decreased after the installation of air dryers. Nevertheless, wire breaks in the cable were observed after dryer installation.

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