Executive Summary

AEP has successfully installed nearly 50 circuit miles of ACCC (“Aluminum Conductor Composite Core”) conductor on four 138 kV reconductoring projects to increase power transfer capabilities and improve transmission line efficiency. During AEP’s first installation of the ACCC conductor, three mechanical failures occurred. All three failures were ultimately determined to be the result of exceeding the manufacturer’s recommended bending limits during installation. These failures brought to light the need for AEP to better understand the sensitivity of ACCC to a wide range of operating conditions to assure that the proper installation, maintenance and operating procedures are followed when ACCC is installed on the AEP Transmission System.

AEP developed a Sequential Mechanical Test Procedure which simulates the normal installation and in-service mechanical loads that any conductor could be exposed to over its service life. Following this procedure, a single sample of ACCC “Drake” size conductor was subjected to a series of tests at Kinectrics Lab in Toronto, Ontario, Canada. The conductor sample was subjected to combined bending loads (as would be encountered during stringing) followed by vibration and galloping tests. A section of the sample was then placed in a tensile test frame and cyclically loaded. During the 3rd of five planned holds under tension, the conductor failed. This tensile failure, in and of itself, is not a deterrent to the application of ACCC but underscored the need to more clearly define the conductor’s strength rating and the tensile load sharing between the aluminum strands and composite core. Following the Kinectrics Lab testing, core samples were shipped to AEP’s Dolan Lab for further testing and analysis.

The results of the Dolan analysis are summarized as follows:

1. The premature tensile failure of the ACCC conductor was the result of the aluminum strands no longer contributing to the conductor’s overall tensile strength. The aluminum strands became loose in a localized area (birdcaged) as a result of the specific test conditions during the cyclic tensile tests and were not able to add to the total conductor strength.

2. The composite core carried the full applied tensile load and failed just above its rated tensile strength of 34,500 pounds.
3. The composite core of the ACCC conductor does not appear to mechanically age when sequentially exposed to stringing (bending), vibration, galloping, and extreme cyclic tensile loads. However, the composite core of the ACCC conductor is sensitive to excessive localized bending which can result in significant core damage and loss of tensile strength. The stringing (bending) loads cannot exceed the manufacturer’s recommendations.

Recommendations based on the Dolan analysis are summarized as follows:

1. All construction, maintenance and operations procedures, tools, and devices, which could be brought into play with the ACCC conductor, must be reviewed to assure that they will not expose the conductor to localized bending loads that could damage or break the core. The specific ACCC handling and installation specifications will need to be reviewed to address any procedures which are determined to be detrimental to the conductor. The ACCC installation specifications must be well communicated to construction and inspection personnel. Additional testing may be required to determine the effects of specific construction/maintenance procedures.

2. Based on these test results, ACCC can be installed on the AEP Transmission System without undue concerns of mechanical aging of the composite core wire as long as the core wire is not subjected to bending loads exceeding the manufacturer’s recommendations.

3. The design tensions for ACCC should consider the ultimate anticipated ice and wind load conditions that the conductor may be exposed to and limit the conductor’s tension to reasonable limits to avoid over stretching or loosening the aluminum strands.

4. The AEP Sequential Mechanical Test procedure for the ACCC conductor should be repeated to establish the upper tension limits of the ACCC conductor to account for possible plastic deformation of the aluminum strands.

Introduction

This report summarizes the results of a series of cyclic load tests and post-testing evaluations that were performed on ACCC (Aluminum Conductor Composite Core) with specific attention focused on the carbon and glass fiber composite core. The purpose of this testing was to observe how the ACCC conductor core might mechanically age over time, what specific mechanisms could potentially cause aging, and what impacts these mechanisms might have on conductor performance and service life. The knowledge gained has increased AEP’s insight into the ACCC conductor’s attributes, installation considerations, anticipated service life, and its application on the AEP Transmission System.

Background

American Electric Power is viewed as an industry leader and strives to maintain this position by applying new technology which has the promise of improving the performance and reliability of the grid. AEP’s early application of the new ACCC conductor came after a diligent review of the existing test data and the ACCC core manufacturing processes. Much of the existing test data had been performed at various independent labs and was based
upon the current industry accepted standards for conductors and/or optical ground wire (OPGW) that AEP and other utilities would normally consider prior to installing a new conductor system on their transmission system.

Various sizes and strandings of ACCC conductors had been subjected to tensile, bending, vibration, and other testing protocols which had successfully demonstrated ACCC’s properties based upon the individual test results. AEP subsequently installed its first ACCC as a reconductoring project to increase the power capacity of a 15 mile 138 kV wood H-frame line near San Antonio, Texas, in late 2005 - early 2006. During this first AEP installation the conductor experienced two mechanical failures during stringing and one incident where the conductor was severely damaged at the conductor tensioner. All three of these incidents were eventually attributed to improper stringing techniques. Although improved installation techniques learned from this first ACCC installation helped AEP successfully complete other installations in Rogers, AR, Abelinene, TX, Tulsa, OK, and other locations without incident, the initial experience highlighted the need for further understanding of the fundamental mechanisms that impact both the short and long term mechanical soundness of ACCC’s composite core.

Overview of Combined Cyclic Load Testing

AEP developed a series of cyclic mechanical tests to simulate the proper installation of the ACCC conductor and replicate in-service conductor vibration and galloping. Conductors are routinely subjected to bending, vibration, galloping and tensile tests but these tests are normally conducted on new, unstressed conductor samples. The industry has extensive experience with standard ACSR and ACSS conductors but has limited correlation between specific tests and conductor longevity. There is no long term data available with the ACCC conductor, thus AEP developed a series of combined accelerated aging tests that could provide further insight into the long term field performance of the ACCC conductor.

AEP proposed a series of cyclic and sequential mechanical tests designed to simulate the mechanical loads that any conductor could experience during its in-service lifetime. The fundamental concept of AEP’s sequential mechanical tests was to first expose a single conductor sample to the installation loads the conductor would see when pulled through a series of string blocks followed by subjecting the same conductor sample to Aeolian vibration and galloping loads. The conductor sample was then run through a cyclic tensile test and was ultimately intended to be pulled to mechanical tensile failure. There were no pass/fail criteria for these tests. The tests were performed to observe and record physical changes to the composite core wire and the conductor after simulated field aging. After this initial series of tests were completed, several core samples were taken from various sections of the overall test specimen to allow additional testing, evaluation, and comparison to un-aged core samples.

The sequential mechanical testing of a 120 foot length of 1020 kcmil ACCC conductor was initially performed at Kinectrics Lab in Toronto, Ontario, Canada. The sequence included simulated sheave wheel (stringing wheel) loading, Aeolian vibration testing, and a galloping test.
The simulated sheave wheel loading was accomplished by gripping a 45 foot length of the center section of the 120 foot sample of the ACCC conductor and pulling a 15 foot long section of the conductor back and forth over a 28” sheave wheel with the conductor at various angles to simulate the mechanical loading a lead portion of conductor could experience during the stringing of a typical reel length (Figure 1). A total of 30 passes were made over the sheave wheel at 20 and 30 degrees, at a tension of 10% conductor RTS. No damage to the conductor core or strands was observed.

Following industry standard protocols, the full 120 foot conductor specimen was then placed in an Aeolian vibration test fixture (Figure 2), tensioned to 25% conductor RTS (“Rated Tensile Strength”), and subjected to 100 million cycles of vibration at an amplitude of 1/3 the conductor’s diameter at a frequency of 29.5 hz. After 60 million cycles the frequency was increased to 43.5 hz to accelerate the test. The 15 foot section of the conductor that was subjected to the sheave wheel testing was centered under the suspension clamp (Figure 3).

A preformed armor rod was also installed on the conductor at the suspension clamp (Figure 3) to simulate the standard AEP construction practice. No degradation to the conductor’s
strands was observed along the entire 120 foot span or under the suspension clamp, except where the shaker arm (Figure 4) was mounted to the conductor on the active side of the span, where a few broken strands were observed.

![Figure 5 – Galloping Test Setup (Kinectrics)](image)

After the vibration test was completed, the conductor, suspension clamp and armor rod were left intact and moved to the galloping test fixture. The conductor assembly was then subjected to an additional 10 thousand cycles of galloping (Figure 5). No degradation was noted to the aluminum strands after the suspension clamp and armor rod was removed following the completion of the test.

A 45 foot section of the conductor was then removed from the center of the test span - which included the conductor section that had been located under the suspension clamp and armor rod - and placed into a horizontal tensile load frame (Figure 6), after conventional dead-ends (Figure 7) were installed at each end of the 45 foot long conductor sample.

![Figure 6 – Horizontal Load Frame](image)  ![Figure 7 – ACCC Dead-End](image)

The first dead-end was placed approximately 6 feet away from one side of where the suspension clamp and armor rod was mounted (Figure 8). A piece of duct tape marked the location (Figure 9). The armor rod location extended about six feet (to the left) from where its end was marked. The suspension clamp was mounted in the center of the armor rod (which can be seen in Figure 3)
After the dead-ends had been added to the 45 foot long conductor sample and placed into the test frame, the conductor sample was re-tensioned to 6,150 pounds (15% RTS) and held for 5 minutes. (The sample had previously been tensioned to 25% RTS during the vibration test and 2% RTS during the galloping test, and 10% during the sheave test) The tension was then increased to 20% RTS (8,200 pounds), held for 5 minutes, and then increased in 10% increments to 70% RTS (28,700 pounds) with 5 minute holds at each increment. After the 70% hold the conductor was pulled to 85% RTS (34,850 pounds) and held for 30 minutes.

As the tension was subsequently reduced back to 15% of the conductor’s RTS (so the cyclic load series could be repeated), a substantial birdcage appeared next to the duct tape marker on the side closest to the dead-end (Figure 9). While it is very unusual for a birdcage to occur after a conductor has been subjected to extreme tensile load conditions and subsequently released back to a lower normal tension, any device that prevents the aluminum strands from relaxing and traveling over a wider area can cause this to happen. An example of this can occur during the installation of a dead-end when recommended back pressing techniques are not used and a grounding clamp is placed too close to the dead-end, which can allow birdcaging to occur as the aluminum strands begin to extrude from the dead-end during the compression process. Such birdcaging will, however, dissipate after the grounding wire is subsequently removed and the aluminum strands are allowed to travel over a wider area. However, after a conductor is subjected to extreme load conditions where the tension is subsequently relaxed back to a normal tension, it is not uncommon for some strand loosening to occur.
After the first tensile load sequence was completed, the tensile loading series was then repeated and the birdcage was observed to diminish as the load was reapplied. As the second cyclic load test was completed and the tension was reduced back to 15% RTS, the birdcage reappeared at the same location (as the duct tape had not yet been removed). The duct tape marker was then removed and the series was repeated a third time. (Please note that the photo shown in Figure 8 was taken during the 3rd cycle after the duct tape was removed and load was being reapplied). Note: A discussion of conductor “knee points” can be found in the appendix of this report under the heading “Additional Information.”

Unfortunately after two complete cycles the aluminum strands in the birdcaged area became so deformed, that at seven minutes into the third 85% RTS hold (34,850 pounds) the conductor core broke under the birdcaged area where the aluminum strands had been deformed and yielded, and were no longer able to contribute to load sharing in that area. The core failed at just over its rated strength of 34,510 pounds. Figure 10 shows how the stress strain graph was affected by the birdcaged area. The normally “sharp” knee point - seen during stress-strain testing when the core and aluminum strands begin to share load - became very “soft” or “gradual” as the birdcaged area tightened up and the aluminum strands began to re-engage.

While the original goal of the AEP combined cyclic load testing was to complete five full cycles prior to performing further evaluations of the core, the tensile failure of the conductor sample caused AEP and CTC to develop a revised post-testing protocol. With the exception of a few small samples, the entire conductor sample from the Kinectrics sequential and cyclic tensile tests was cut into 50 inch long, well labeled samples, and shipped to AEP’s Dolan Lab near Columbus, Ohio. The following section in this report describes the evaluations performed at AEP’s Dolan lab.

Post Testing Evaluation

The post-test specimens were separated into three primary sections. The first section included pieces A, B, C, D, E, F, G, H, and I, that were taken from the Center Section that was subjected to the cyclic tensile testing (where the break had occurred) that were also included in the sheave, vibration & galloping tests. Figure 11 shows the center section with pieces A through I.
The second section (that was also cut into 50 inch lengths), was taken from the “Active” side of the vibration and galloping test, where the shaker arm was mounted. This section provided samples numbered A-1 through A-7. Samples A-1 and A-2 were shipped to the Dolan Lab with the aluminum strands left on the core, while sections A-3 through A-7 were sent as core-only samples with the aluminum strands removed. Figure 12 shows the three overall sections. While some of the core samples taken from the failure zone in the Center Section were obviously damaged (as shown in some of the photos in Figure 11), the balance of those samples, as well as all of the samples taken from the Active and Passive sides of the test appeared undamaged.

Samples from the third section, known as the “Passive” side of the vibration & galloping test (where no shaker arm was mounted), were returned to the Dolan Lab in pieces labeled P-1 through P-10, with pieces P-3 through P-10 being core only (Figure 13). The dark areas that appear on the core specimens were residual oil used during the stranding process. No anomalies or degradation to these core samples was visually observed.
In addition to these specimens, two other “un-aged” 50 inch long “control” samples of the core wire were shipped to AEP’s Dolan lab along with several other shorter pieces that arrived at a later date. The un-aged “control samples” were taken directly off the new reel and were used to establish comparative base-line values. While the initial phase of the AEP testing conducted at Kinectrics Lab considered the overall ACCC conductor, the second phase of testing conducted at AEP’s Dolan Lab focused on the composite carbon and glass fiber core and did not consider the complete conductor. It was felt that the birdcaging of the aluminum strands that was observed during the Kinectrics testing - and the resulting loss of contribution to the overall ACCC tensile strength from the aluminum strands - was well understood. The intent of the Dolan tests was to observe and record any physical changes to the composite core that may have occurred during the Kinectrics testing or through any subsequent testing conducted at Dolan.

**Test 1 – Tensile Test of Un-Aged Core Sample**

Core from an un-aged 50" long conductor specimen (labeled C-1) was removed from the aluminum strands and bonded into tensile test fixtures. This core sample was taken directly off of the new reel of conductor and was completely un-aged. The core was pulled at approximately 6,000 pounds per minute until failure. The core broke at 35,750 pounds or 104% RTS. This test was conducted to establish a base line tensile strength from the production reel of conductor used for this test series (Figure 14).

**Test 2 – Cyclic Load Test of Un-Aged Core Sample**

A cyclic load test was conducted on an un-aged core sample (labeled C-2 – also taken directly off of the new reel) to establish a baseline for further cyclic load core tests. The 50”
core sample was placed in tensile test fixtures and pulled to 20% of the core’s RTS (6,900 pounds). The load was increased in 10% increments with 5 minute holds at each increment to 70% RTS. The load was then increased to 85% RTS with one 30 minute hold. The load was reduced to 20% RTS and pulled back and forth to 85% RTS five times with 5 minute holds at 20% and 85% only. The core specimen was subsequently pulled to failure at 36,000 pounds or 104% RTS.

Test 3 – Dye Penetrant Testing of Un-Aged Core Sample

An un-aged core sample taken from the new reel of conductor was cut into a 10 millimeter length (following industry standard protocols) and placed into a dye penetrant solution (Figure 15). Zyglo dye penetrant was used for this test as it is commonly used to identify anomalies, defects, or degradation in metal or composite materials. Zyglo is a fluorescent material that has the ability to identify microscopic flaws which become visible to the naked eye when observed under a UV light (black light). No wicking of dye penetrant was observed in the glass or carbon fiber region of the core, or along the outside edge during approximately six hours of observation. AEP has used Zyglo penetrant to test for internal voids in the composite fiberglass rods from non-ceramic insulators (NCI) and generally observed that minimal dye penetration occurs in a sound test sample after 10 minutes of immersion. Much additional work is necessary to fully define definitive pass/fail criteria for Zyglo penetration of NCI fiberglass rod and AEP’s findings to-date should be considered as early observations.

Post Testing Evaluation – Center Section

Preface: The “Center Section” consisted of Samples labeled “A” through “I” which were subjected to all of aging tests performed at Kinectrics lab described above. The tests described below were performed on various specimens (or in pieces from various specimens) in various chronological orders, and not necessarily in the order presented.

Description of Samples:

A. Sample A (Figure 16) was retrieved from the north end of Kinectrics test fixture (as viewed from the right side of all associated photographs. Sample A exhibited substantial degradation, but remained partially intact after the conductor sample failed during the 3rd 85% RTS (overall conductor RTS) hold. The right side of Sample A exhibited a compressive failure about one inch from the entrance to the dead-end as the result of the instantaneous release of energy at the nearby core failure.
B. Sample B (Figure 17) was adjacent to Sample C where the primary core failure occurred. Sample B was very fragmented due to tensile failure. Only a very small section of Sample B remained partially intact although cracks were visually apparent.

C. Sample C (Figure 18) appeared to be the primary tensile failure area due to the “feathering” of the fibers and proximity to the birdcaged area of the conductor during the cyclic load test.

D. Sample D (Figure 19) was also completely destroyed when the core failed during the cyclic load test at the area where birdcaging occurred.

E. Sample E (not shown) that was located directly adjacent to Sample D, showed some minor cracking, but essentially remained intact and pulled to failure at 95% RTS.

F. Samples F (Figures 20 and 21) and G were shipped to AEP’s Dolan Lab in one piece. No damage to Section F or G was visually apparent. Tensile testing of these parts showed strengths over 100% RTS and no degradation was noted after 48 hours of dye penetrant testing.

G. There was no visual damage to the F/G Sample, but its relatively short length required that a tensile test specimen be removed from the center of the F/G section. Pieces from each end were labeled F & G.

H. Sample H showed no visual degradation and achieved over 100% of RTS when tensile tested.

I. Sample I showed no visual degradation
and also achieved over 100% RTS when tensile tested

**Test 4 – Tensile Test of Aged Core Sample “I”**

Sample I was placed in tensile test fixtures and pulled to failure. It achieved 36,100 pounds or 105% RTS.

**Test 5 – Tensile Test of Aged Core Sample “H”**

Sample H (Figure 22) was tensile tested to failure. It achieved 35,200 pounds or 102% RTS.

**Test 6 – Tensile Test of Aged Core Sample “F”**

Sample F/G (“F”) was tensile tested to failure. It achieved 35,800 pounds or 104% RTS

**Test 7 – Dye Penetrant Testing of Aged Core Samples “F”**

Two pieces of Sample F (that were taken from very close to where the core failed under the area of the birdcaged aluminum strands observed during the cyclic load testing performed at Kinectrics Lab) were cut into 10 millimeter lengths and placed into dye penetrant. Neither piece showed any dye penetrant propagation in the glass, carbon, or outer perimeter of the samples after over 48 hours of immersion (Figure 23). A third sample, whose ends were not sanded or polished (normal protocol), also did not show any dye penetrant propagation after a similar period of exposure. These samples were of great interest due to their close proximity to the armor rod and suspension clamp and the fact that they were essentially taken from the opposite side of the armor rod and suspension clamp where the birdcaging and subsequent core failure occurred. These specimens were also exposed to the extreme release of kinetic energy when the adjacent core section broke when it exceeded its rated tensile strength at the birdcaged area when the aluminum strands at that point no longer contributed to load sharing.

**Test 8 – Tensile Test of Aged Core Sample “E”**

Sample E (Figure 24), which was directly next to the completely failed Section D, showed some visual degradation, but it still achieved 95% RTS when tensile tested.
Test 9 – Dye Penetrant Test of Broken Section B

A dye penetrant test was performed on samples from broken Section B (Figure 25) to assess how quickly the dye penetrant could identify a visually apparent crack. The dye penetrant reached the top of the 10 millimeter sample in about 2 seconds. Pieces taken from inside the tensile test fixtures after the tensile test was performed on Sample E were also inspected with dye penetrant. One of the two pieces inspected was not complete as it was taken from an area inside the test fixture where the core was intentionally split for epoxy gripping. The other piece also showed rapid penetration of the dye as the sample was destroyed during the tensile test to failure procedure.

Post Testing Evaluation – Sections A and P

Preface: Samples taken from Sections A and P were all exposed to 100 million cycles of vibration and 10 thousand cycles of galloping at Kinectrics Lab, but were not initially exposed to sheave wheel or cyclic tensile loading. The testing conducted and presented in this section (below) was performed on these partially aged samples to assess how additional cyclic tensile and bending loads might impact core integrity.

Test 10 – Cyclic Load Test of Partially Aged Core Sample “P-6” (50 to 85% RTS 25 Times)

Core Sample P-6 was placed into tensile test fixtures (Figure 26) and pulled to 50% RTS. It was held for 5 minutes at 50% RTS and then cycled 25 times back and forth between 50% and 85% RTS. After the cyclic test, the core was pulled to failure at 35,500 pounds (103% RTS).

Test 11 – Cyclic Load Test of Partially Aged Core Sample “A-4” (50 to 85% RTS 25 Times)
Core Sample A-4 was placed into tensile test fixtures and pulled to 50% RTS (Figure 27). It was held for 5 minutes at 50% RTS and then cycled twenty-five times back and forth between 50% and 85% RTS. After the cyclic test, the core was pulled to failure at 35,250 pounds (102% RTS). *Photo taken before load applied.

**Test 12 – Cyclic Load Test of Partially Aged Core Sample “P-10” (50 to 95% RTS 25 Times)**

Core Sample P-10 was placed into tensile test fixtures, pulled to 20% RTS, and held for 5 minutes. The sample was then pulled to 95% RTS, held for an additional 5 minutes, and relaxed back to 50% RTS. The core sample was then cycled from 50% to 95% twenty-five times. The core sample was then pulled to failure where it achieved 35,850 pounds (104% RTS).

**Test 13 – Cyclic Load Test of Partially Aged Core Sample “P-7” (50 to 85% RTS 25 Times) Followed by Dye Penetrant**

Core Sample P-7 was pulled to 50% RTS, held for 5 minutes and then pulled to 85% RTS with a second 5 minute hold. The cycle was repeated (without 5 minute holds) twenty-five times. The core sample was then removed from the tensile test fixtures. A few 10 millimeter pieces were removed from about one inch from one end of the sample and placed in dye penetrant. A very small spot of dye penetrant (about the size of a fiber optic fiber) appeared in the glass fiber area of the core about 45 minutes after the sample (P-7, S-1) was placed into the dye penetrant (Figure 28 above).

**Test 14 – Cyclic Load Test of Partially Aged Core Sample “P-7” Followed by Bending & Dye Penetrant**

After being cyclically tested (as described in Test #11) from 50% RTS to 85% RTS 25 times, an 18” piece of Sample P-7 was placed on 1-1/2” blocks that were placed 14-1/2” apart. A 300 pound load was applied to the core sample 100 times to induce bending. Four 10 millimeter samples were then cut and placed in dye penetrant (numbers P-7 - 1L, 2L, 1R, and 2R). A dot was observed in the glass region of specimen #1L after 6-1/2 minutes. A dot also appeared in specimen #1R at some time between 30 and 50 minutes (Figure 29). Specimens 2L and 2R
showed dye penetrant around the outer glass fibers when observed the following day (after approximately 20 hours).

**Test 15 – Cyclic Load Test of Partially Aged Core Sample “P-7” Followed by 3-Point Bending and Dye Penetrant**

After being cyclically loaded (as described in Test #11) from 50% RTS to 85% RTS 25 times, an 8” piece of Sample P-7 was placed in a three point bend test fixture with 3-1/2” spans, and cycled 100 times to a depth of approximately the diameter of the core (3/8”). It was noted that a transverse crack appeared at about 80 cycles (Figure 30). The crack defined a compressive failure as a result of the concentrated point load at the middle bar of the test fixture. Three 10 millimeter pieces of the core were cut off of this sample and placed in dye penetrant. The first piece “A” contained the compressive crack. The second and third pieces (B and C) were directly adjacent to each other and taken from one side of “A.” Dye penetrant confirmed the compressive failure of sample “A” in just over 3 minutes, when a transverse crack began to appear. Samples B and C also showed 2 or 3 small dots within 3 to 6 minutes. All three pieces showed dye penetrant across the top of the specimens the following morning (Figure 31). Note that the dye penetrant in Figure 31 had pooled on the surface of these samples which were all wiped off prior to this photo being taken to assess where the actual penetration had occurred. Scratch lines seen on the surface of these unpolished samples were cause by light sandpaper preparation that was performed to remove heavier diamond blade saw cutting marks.

**Test 16 – 3-Point Bend Test of Partially Aged Core Sample “A-3” Followed by Tensile Testing and Conventional Microscopic Evaluation**

Section A-3 was mounted into tensile test fixtures and then placed into the three point bend test machine (Figure 32) where the core was bent until it snapped around the small diameter center post. The failure (as with Test #15) was due to excessive bending around the highly concentrated point load - which caused compressive failure of the core. The broken core sample was then placed into the tensile test machine where it was pulled completely to failure at only 5,650 pounds (16% RTS). The broken core was examined under a conventional microscope (Figures 33 and 34).
Test 17 – Extreme Bending of Partially Aged Conductor Sample “P-2” Followed by Dye Penetrant and Scanning Electron Microscope Evaluation

Sample P-2 (complete conductor and core) was bent around a 6 inch radius (12 inch diameter) electrical conduit pipe bender 10 times to 90 degrees. (The recommend sheave wheel diameter for this size conductor is 28 inches.) The core was removed from the conductor sample and three 10 millimeter pieces were cut from the area that had been bent. Samples (from P-2) S-1, S-2, and S-3 were placed in dye penetrant. One spot appeared in the glass region of samples S-1 and S-2 after 2 minutes (Figure 35). The spots were located
at the same position in each sample and did not propagate further. A spot also appeared in sample S-3 after 4 minutes, followed by 2 more spots at 7 to 8 minutes. Sample S-3 was then removed from the dye penetrant and examined under a Scanning Electron Microscope (SEM). While some areas of the sample appeared to have some depth between fibers, no delaminations were observed and none of the three spots where dye penetrant had been seen could be identified conclusively (Figures 36 & 37).

**Figure 35 - Dye Penetrant Testing of Highly Bent Samples**

**Figure 36 - SEM of Carbon Fibers**

**Figure 37 - SEM of Carbon and Glass Fibers**

**Test 18 – 3 Point Cyclic Bend Test of Partially Aged Core Sample “P-8” Followed by Cyclic Tensile Test**

Section P-8 was placed in tensile test fixtures and subjected to 25 cycles of the three point bend test (similar to description in Test 16 though less severe) (Figure 32). After the 25 cycles, the test specimen was placed in the tensile test machine and cycled 10 times between 50 and 85% RTS. The sample was then pulled to failure at 34,300 pounds (99.4% RTS)
Summary of Post Testing Evaluation

After being subjected to 100 million cycles of vibration, 10 thousand cycles of galloping and various cyclic tensile, flexural, and bending load tests, the aged ACCC core specimens showed very little difference in retained strength compared to un-aged core specimens. Even after being cyclically loaded to as high as 95% RTS (after the combined vibration and galloping tests), the ACCC conductor core still maintained 104% of its rated tensile strength. After being bent 10 times around a diameter that was less than half of the recommended diameter for stringing blocks (after the same vibration and galloping tests), or being bent under a 300 pound load 100 times, the composite core showed very little internal damage. While dye penetrant did appear in some of these post flexural and tensile test specimens (after the earlier cyclic exposures), the amount of penetrant and rate of penetration was very minimal considering the extent of the exposure. After completing these tests, it would appear that the composite core is extremely robust, but care must still be exercised during installation to ensure that the core is not excessively bent around sharp objects.

Summary Chart of Tests Conducted on Control & Post-Aged Samples

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Test Performed</th>
<th>Result</th>
<th>Comment</th>
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<tbody>
<tr>
<td>1</td>
<td>50” Control Sample</td>
<td>Simple Tension</td>
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<td>13</td>
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<td>Cyclic / Dye</td>
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<td>Cyclic T / B / Dye</td>
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<td>Cyclic T / B / Dye</td>
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<td>Bent to failure / T</td>
<td>5,650</td>
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<td>Extreme B / Dye</td>
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<td>Cyclic B / Tension</td>
<td>34,300</td>
<td>99% RTS</td>
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Findings:

The AEP Combined Mechanical Loading Tests of 1020 kcmil ACCC conductor resulted in the following observations, conclusions, and recommendations:

Observations:

1. Exposing a single conductor sample to a series of mechanical tests provided a reasonable simulation of the accumulative in-service stress aging any conductor might
experience over its service life. It would be useful to apply the same sequential tests to traditional ACSR and ACSS conductors to establish relative test results.

2. Subjecting a single ACCC conductor sample to the combined cyclic sheave wheel, vibration, and galloping loading prior to final cyclic tensile loading provided additional insights and understanding of ACCC’s mechanical properties.

3. The single strand ACCC composite core when bent within the manufacturer’s recommendations neither exhibits surface cracking, nor internal separation between the epoxy resin and carbon or glass fibers contained in the composite core.

4. A composite core subjected to numerous and combined stressors, replicating in-service conditions, exhibit little (if any) degradation, loss of integrity, or reduction in ultimate strength, even when loads of up to 95% of the core’s ultimate tensile were repeatedly applied.

5. The testing confirmed the composite core’s sensitivity to sharp localized bending and shear loads which result in significant core damage and loss of tensile strength. This further emphasized the need to follow correct installation, maintenance and operation procedures and not exceed the conductor’s recommended bending limits at any time.

6. Severe cyclic tensile loading of the conductor can cause plastic elongation of the annealed aluminum strands which may ultimately reduce the conductor’s overall strength. While no damage or significant loosening of the aluminum strands was observed after the vibration and galloping tests, severe cyclic tensile testing of the conductor indicated that the aluminum strands may elongate to the point that the entire tensile load may be carried by the composite core alone. This became especially apparent during the cyclic tensile testing when a localized birdcage developed in the aluminum stands which were subsequently unable to contribute to the conductor’s ultimate strength. The result was that the conductor core carried the full applied tensile test load and failed at a load of 34,850 pounds - just above the core’s rated strength of 34,500 pounds. While it is believed that this particular birdcage may have been artificially created as a result of a duct tape marker placed near one of the dead-ends (Figure 9) that prevented the strands from moving freely as they normally would, it does suggest a concern that loosened aluminum strands may reduce the conductor’s ultimate strength.

7. Samples of the composite core taken at a distance of approximately two meters away from the tensile failure zone (from the opposite end of the suspension clamp and armor rod assembly where birdcaging did not occur) showed no sign of strength reduction or internal damage. Dye penetrant tests, tensile testing, and sample observation under magnification and electron scanning microscope identified no observable change between the recorded physical conditions of stressed core samples when compared against similar observations and tests of unstressed core samples.

8. Mechanical damage to the composite core wire from excessive or sharp localized bending is very possible without any readily observable damage to the outer aluminum stands.
Conclusions & Recommendations:

1. The design tension of the ACCC conductor should consider the worst reasonably anticipated ice/wind load event. The conductor’s tension under this ice/wind load condition should not exceed 80% of the conductor’s overall Rated Tensile Strength (RTS). This will ensure that even if the aluminum strands become loosened by prior loading events or other mechanical aging mechanisms, the ACCC core will still provide a reasonable safety factor.

2. The tensile loads that might cause a loss of aluminum strength and subsequent reduction in overall ACCC conductor strength should be determined. Additional cyclic and/or sustained load testing may be needed - or existing test data reviewed (see “Final Questions” below) on the ACCC conductor to determine exactly what extreme load exposure and duration of the exposure expends the aluminum strand strength contribution to the overall conductor’s strength.

3. When performing cyclic tensile tests, mechanical markers, such as duct tape or hose clamps, should be avoided as they may restrain the movement of the aluminum strands and induce birdcaging of the aluminum strands. In the initial series of tests presented in this report, the Aeolian vibration exposure test was performed at 25% RTS and the cyclic load test that followed, had an initial loading of only 15 to 20% RTS. These reduced loads, in combination with the mechanical markers, are thought to have artificially contributed to the birdcaging of the conductor’s aluminum strands which reduced the conductor’s ultimate strength at the birdcaged area.

4. While field experience, to date, has not shown birdcaging to be an issue (there is currently about 5,000 linear miles of ACCC conductor in service), the possibility of birdcaging in very short spans or sub-span may require additional investigation. As learned in #3 above, the difference in elasticity between the aluminum strands and core wire may result in birdcaging on very short spans or on sub-spans where the strands may be constrained between mechanical devices that are placed closely together which could prevent the strands from relaxing over a wider area. These devices could include spacers, spacer dampers, or other devices placed closely together or near a compression dead-end, tap, or conductor splice. The specified mechanical loading of the conductor and the everyday design tensions will also factor into the possibility of birdcaging.

5. All construction, maintenance and operations procedures, tools, and devices, which could be brought into play with the ACCC conductor, must be reviewed to assure that they will not expose the ACCC conductor to excessive or sharp localized bending loads that can fatally damage the core wire. Reasonable field tolerances must be considered during this review and the Manufacturer’s Installation Guidelines must be correctly followed.

Additional Information and Considerations:

Following the testing presented in this report, CTC subsequently performed an additional cyclic load test using a protocol that was very similar to the one developed by AEP. This test
was performed at Tension Member Technology's Lab in Huntington Beach, California. [http://www.tmtlabs.com](http://www.tmtlabs.com). While the conductor tested at TMT was not previously exposed to sheave, galloping, or vibration testing - or held for extended periods of time under high load conditions - it is interesting to note that birdcaging of the conductor's aluminum strands did not occur when the conductor was cycled back and forth between 20% and 85% RTS (8,200 to 34,850 lbs) five times, although loosening of the strands was observed as the tension was relaxed back down from the higher loads.

However, prior to being pulled to ultimate failure at 41,900 lbs (102% RTS) the tension of the conductor was released down from 34,850 lbs to 1,000 lbs. Under this very low load condition - which would not actually occur in field conditions - the conductor strands did birdcage at an area near one of the two dead-ends. Figure 1A (below) shows the stress strain curve from the AEP Kinectrics testing. It can be seen that the initial knee point was very well defined upon the initial load release. However, as a result of the birdcage that developed from the tape marker (Figure 9 above), the subsequent knee points were less well defined (and became more curve-like) as the birdcaged strands gradually re-engaged. More discussion about the stress-strain relationship and knee-points can be found below.

![AEP Stress-strain Testing Results](image)

**Figure 1A – Stress Strain Graph of 15% to 85% AEP Cyclic Load Test**

Figure 2A (below), provided by the TMT cyclic load testing, shows the knee points remained very sharp as no birdcaging initially occurred, even though some strand loosening did occur.
Figure 3A shows how the birdcaged strands that occurred after the tension was released down to 1,000 lbs during the TMT testing also caused the knee point to soften or become more curve-like during the final loading event. Essentially, rather than becoming quickly re-engaged, a birdcage will cause the strands to re-engage more gradually as the birdcage dissipates (and tightens back up) as the load is reapplied. A single birdcage event that occurred during this particular test when the conductor was relaxed all the way down to about 2% of the conductor’s RTS (that would not happen under normal conditions), was not
particularly problematic as the aluminum strands did fully re-engage and the conductor achieved over 100% of its RTS at failure. However, during the Kinectrics cyclic load test, where the birdcaging happened during the first relaxation sequence (to 15% RTS) due to the mechanical marker, and the event was repeated, the aluminum strands became so deformed that they were no longer able to carry load at that point which is where the core subsequently failed.

**Final Comments:**

Other than a birdcage causing event *which is extremely rare under normal field conditions* (except possibly when a dead-end or splice is not properly installed on a very short span where the birdcage could not easily dissipate), what other conditions might “spend” all of the aluminum strands such that they are no longer able to contribute to load sharing? In Figure 4A (below), the “core only load” is projected out beyond the data gathered during the TMT cyclic load test. This line, shown in purple, is projected out until it intersects with the 85% RTS full conductor load - that is essentially equal to the core’s ultimate strength value. While this particular test did achieve over 100% RTS of the full conductor’s strength (shown in the red line), what conditions might cause the aluminum strands to “creep” over and intersect with the core only value that would essentially render the aluminum strands useless as it relates to load sharing? The area highlighted in orange represents the area where this creep would have to occur given some cyclic or sustained load event(s).

![TMT Results on Drake ACCC/TW](image)

*Figure 4A – Overlay of Stress Strain Data Showing Core & Aluminum Strands Exceed 80% RTS*

As long as a conductor can handle a reasonable number of sustained and/or repeated cyclic load events, for a reasonable number of occurrences and load periods over the conductor’s
anticipated service life, does de-rating the tensile strength of the conductor need to be considered, or should the design engineer simply exercise additional prudence given the specific requirements of a specific project and apply appropriate rules? Sustained load testing of the ACCC conductor at 77% RTS for one full week (168 hours) has shown that the conductor's aluminum strands will still re-engage when the entire conductor (held by regular dead-ends) is subsequently pulled to failure. This was also shown during the cyclic TMT test that went to 85% RTS. These design/application issues of ACCC conductor may require additional consideration. In the meantime, design prudence is advised.

Acknowledgements:

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<tr>
<th>American Electric Power</th>
<th>Kinectrics North America</th>
<th>CTC Cable Corporation</th>
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<tr>
<td>Eric Engdahl</td>
<td>Craig Pon</td>
<td>Dave Bryant</td>
</tr>
<tr>
<td>Bruce Freimark</td>
<td>Michael Kastelein</td>
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<td>Dave Klinect</td>
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<td>Darrin Witt</td>
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