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8 CORROSION TESTS

Overview

Carbon conductor cores are not subjected to the same corrosion degradation mechanisms as are steel conductor cores, such as (Aluminum Conductor Steel Reinforced) ACSR and (Aluminum Conductor Steel Supported) ACSS. In an ACSR or ACSS conductor the core coating (galvanizing or mischmetal) is consumed due to exposure to the steel core while in Composite Core Conductors such as the ACCR or ACCC conductors the aluminum strands are subject to degradation when exposed to the composite core.

Aluminum strands can be subjected to two types of corrosion. These are:

- Atmospheric corrosion due to moisture and pollutants (chlorides in marine environments and sulfates in industrial environments), and
- galvanic corrosion due to the contact with a bare carbon core.

This chapter details the evaluation of the galvanic corrosion of two advanced conductors (ACCC and C7) after an intensive thermomechanical cycle aging procedure corresponding to 40 years of operation.

This chapter will also detail the corrosion evaluation of 3 ACSS conductors from three different conductor manufacturers.

Carbon Core Conductor Evaluation

The C7 (Celanese core) ACCR conductor from Southwire and the ACCC conductor from CTC Global were part of this evaluation. The ACCR C7 Overhead Conductor from Southwire is composed of seven carbon-fiber composite strands coated in high-performance Polyethylene PEEK coating and twenty fully annealed, trapezoidal aluminum outer strands in two layers. The ACCC from CTC Global utilizes a hybrid carbon and glass fiber core, and is composed of 22 fully annealed, trapezoidal aluminum outer strands in two layers.

Both manufacturers have overcome the galvanic corrosion problem by coating the carbon fiber in a protective layer, PEEK for the C7 conductor from Southwire, and fiber glass for the ACCC conductor from CTC global. Thermally aged samples of the two conductors are shown in Figure 8-1.

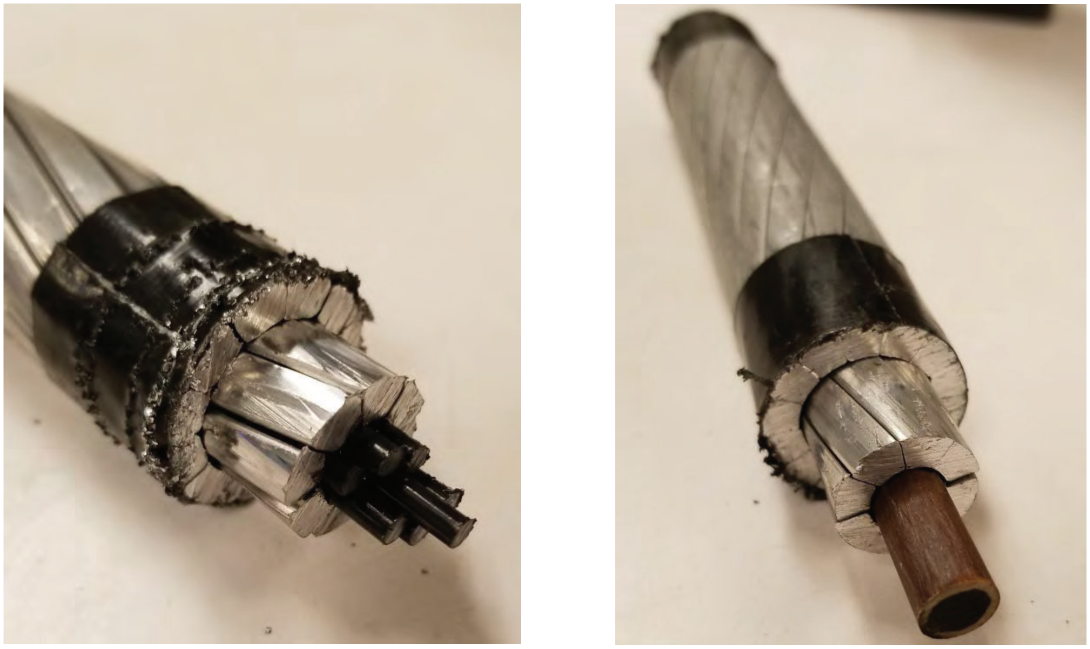

Figure 8-1. Southwire C7 ACCR conductor (left) and CTC Global ACCC conductor (right)

Galvanic corrosion in composite core advanced conductors

Galvanic corrosion occurs when two dissimilar metals or materials are in contact. When in contact, electrons flow from the most active material to the most noble material. The metal losing electrons is corroding while the other metal is “protected”. It is the fundamental principle of sacrificial anode cathodic protection.

In the case of the carbon core conductor, the two dissimilar materials interacting are the aluminum strands and the carbon core. In this situation, aluminum is the most active metal while the carbon core is the most noble material, resulting in the corrosion of aluminum strands. This phenomenon will only occur if the carbon core is directly exposed to aluminum. Because both manufacturers coat the carbon core in a protective layer, the carbon core could only be exposed if the protective layer is damaged possibly due to improper installation, improper fabrication, fretting/vibration during the service life of the conductor or thermal aging.

A corrosion cell is created when an aluminum strand and the bare carbon core are in contact. The four essential components of a corrosion cell are then present:

1. An electrical path for electrons movement (aluminum strand touching bare carbon fiber)
2. An electrolyte (present in the form of rain or moisture), allowing for metal to dissolve and chemical reactions to occurs
3. An oxidation site, where the aluminum (anode) losses electrons

4. A reduction site, where electrons are consumed at the surface of the carbon fiber (cathode).

Evaluation Overview

Galvanic corrosion of aluminum strands exposed to an advanced conductor carbon core (coated or uncoated) was evaluated by creating a corrosion cell and measuring the amount of current flowing from the anode (aluminum) to the cathode (carbon fiber) using a highly sensitive, low resistance ammeter. This experiment was performed with different solutions (tap water, high chloride solution, and high sulfate solution), at two different temperatures (20 and 60˚C), and with different anode to cathode ratios.

New conductor cores were evaluated with and without their protective coatings (PEEK for the C7 ACCR Southwire conductor and glass fiber for the CTC Global ACCC conductor), and aged conductor cores were evaluated with their protective coatings. The measured galvanic current was then used to calculate the corrosion rate of aluminum (thickness of aluminum loss per year).

Carbon strands preparation for Southwire C7 conductor and CTC conductor

Carbon fiber strands from the C7 ACCR conductor were prepared in two different ways as shown in Figure 8-2. . Test strands were cut into a 6-inch-long segment, one end was stripped of the protective layer (PEEK) to provide an electrical connection point for the instrument (ammeter), and the other end tip was covered with silicon (to cover the exposed carbon due to the cut). This preparation was used to assess coated carbon fiber strands from a new conductor and a carbon fiber strand from an aged conductor. The second preparation involved stripping one end of the 6-Inch-long strands to provide an electrical connection point, while the other end was stripped of the PEEK layer to expose exactly 1 in. of the strands. Each preparation also involved the use of electrical tape to control the amount of area exposed to the electrolyte, like the preparation of aluminum strands as seen in Figure 8-2.

It was noted that the PEEK layer of the C7 ACCR conductor carbon fiber strands was hard and difficult to remove. This finding shows that the PEEK layer is highly resistant to abrasion which is an indication that the carbon core is unlikely to be exposed directly to aluminum.

Figure 8-2. Coated Southwire C7 carbon strands (left) and uncoated Southwire C7 carbon strands (right).

The carbon core preparation for the CTC ACCC conductor was done in a similar manner to the C7 ACCR strands as shown in Figure 8-3. Like the PEEK layer, the glass fiber protection layer in the CTC ACCC connector was difficult to remove. A grinder with an abrasive tip was used to remove the protective layer and exposed the carbon fiber. This also suggest that it is unlikely that the carbon core will be directly exposed to the aluminum strands during regular operation.

Figure 8-3. CTC cores prepared for testing: exposed core from new conductor (2 left samples), coated core from aged conductor (2 middle samples), and coated core from new conductor (2 right samples).

Evaluation procedure

The chloride solution and the sulfate solution were 3.5% sodium chloride and 3.5 % sodium sulfate respectively, using reagent grade chemicals and deionized water while the other solution used tap water.

Once the test solutions were prepared and poured into a 1-liter beaker, the solution temperature was adjusted with a heating plate located under the beaker. Once the target temperature was achieved, the aluminum strand(s) and carbon fiber(s) were placed into the beaker and connected to the Galvanostat (smart ammeter). The strands were placed in such a way that their tips were submerged up to the electrical tape (to control the exact amount of surface area exposed to the solution). A calomel reference electrode was placed in the beaker and connected to the instrument to measure metal potential.

The test sequence started, and the amount of current flowing from the aluminum strand to the carbon fiber was measured. The instrument measured the current for 10 minutes and the galvanic current was recorded. The test typically required ten minutes to achieve a stable current flow and that was used to calculate the aluminum corrosion rate.

The experiment was repeated with the different solutions at different temperatures. The surface area of the anode (aluminum) and the cathode (carbon fiber) were changed by adding more or fewer aluminum strands or carbon fiber cores to the beaker. Cathode to anode ratios were then varied by changing combinations of aluminum strands to carbon core stands as shown in Table 8-1 and Table 8-2. for Southwire C7 ACCR conductor and CTC Global ACCC conductor, respectively. For example, eight C7 aluminum strands were connected to one C7 carbon fiber strands for a cathode to anode area ratio of 0.07.

Table 8-1. Cathode to anode ratio calculation for C7 ACCR conductor experiment

	Carbon/aluminum Experimental ratio	**Cathode area (cm^2) *carbon strand***	**Anode area (cm^2) *aluminum strand***	**Cathode/anode Area Ratio**
Coated Strands	8/1	2.85	5.46	0.07
	1/1	2.85	5.46	0.52
	1/7	2.85	5.46	3.65
Uncoated Strands	8/1	2.46	5.46	0.06
	1/1	2.46	5.46	0.45
	1/7	2.46	5.46	3.15

Table 8-2. Cathode to anode ratio calculation for CTC ACCC conductor experiment

	Carbon/aluminum Experimental ratio	**Cathode area (cm^2) *carbon strand***	**Anode area (cm^2) *aluminum strand***	**Cathode/anode Area Ratio**
Coated Core	1/8	8.3	5.38	0.19
	1/1	8.3	5.38	1.54
	2/1	8.3	5.38	3.09
	1/8	6.29	5.38	0.15

Uncoated Core	1/1	6.29	5.38	1.17
	2/1	6.29	5.38	2.34

Results and Discussion

CTC Global ACCC conductor galvanic corrosion results

Coated carbon fiber from new and aged conductor against aluminum strands

Corrosion rates of aluminum strands in contact with coated carbon core (glass fiber) from new and aged conductors are shown in appendix A. The data shows that extremely low current was exchanged between the aluminum and the coated carbon cores. The current measured (not shown) was in the order of nano-amperes. This resulted in no measurable corrosion damage to the aluminum strands. The glass fiber surrounding the carbon fiber core in the CTC Global ACCC conductor has excellent dielectric properties which insulated the carbon from the aluminum, blocking any potential galvanic corrosion, even after the conductor has been thermo-mechanically aged.

Uncoated carbon fiber core against aluminum strands

Corrosion rates of aluminum strands exposed to an uncoated (glass fiber removed) carbon core from a new CTC ACCC conductor are shown in Figure 8-4. Its anode shows the effect of the different solutions, temperatures, and cathode to anode ratios on the corrosion rate of aluminum in contact with bare carbon fiber.

Several observations can be drawn from Figure 8-4:

- As the cathode to anode ratio increased, so did the aluminum corrosion rate
- As the temperature of the solution increased, so did the aluminum corrosion rate
- Chloride solution results in the highest corrosion rate followed by sulfate solution and tap water
- The highest corrosion rate was observed with hot chloride solution with a cathode to anode ratio of 2.34. This corrosion rate was extremely high with a value of 54 mils per year.

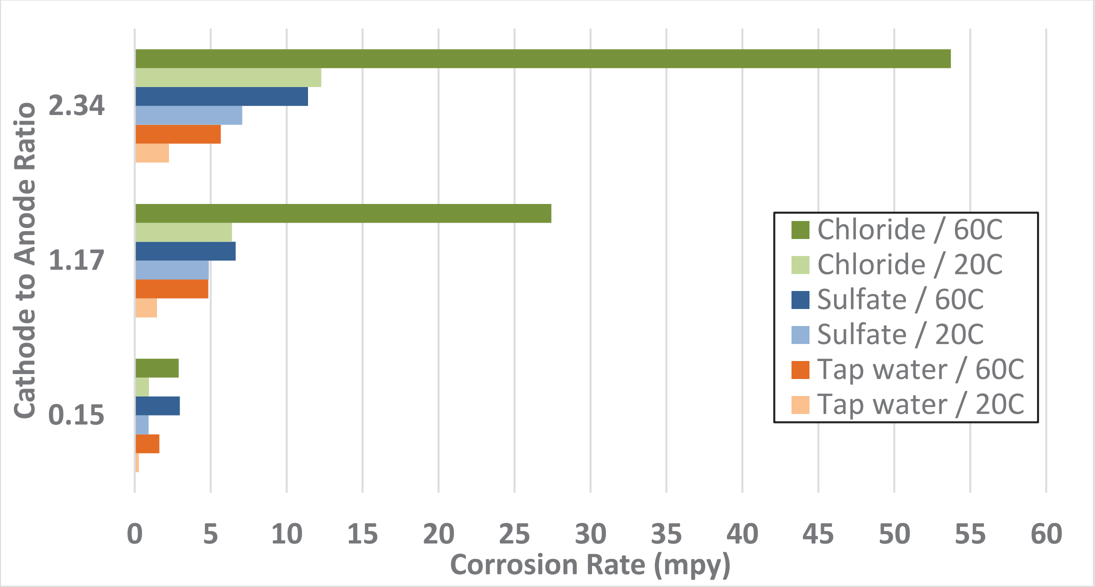

Figure 8-4. Aluminum Corrosion rate when exposed to CTC Global ACCC uncoated carbon core

Cathode to anode ratios impact the corrosion rate in a predictable way. As more cathode surface area is exposed (high ratio), the demand for electrons is higher, hence the amount of electrons leaving the anode is higher, which leads to an increase corrosion rate. As the solution temperature increases, the corrosion rate increases. This is due to the thermodynamic nature of the corrosion process. Chloride solutions increase the corrosion rate due to two factors. First, chlorides increase the electrical conductivity of the solution which allows more ionic current to flow. Secondly, chloride ions are known to be strong depolarizers, which means that chloride ions can easily break down the microscopic protective layer formed on the aluminum surface. When exposed to the atmosphere, aluminum is highly corrosion resistant due to the formation of a thin layer of aluminum oxide at its surface (passivation layer), protecting the metal from corrosion. Chlorides, and to a lesser extent sulfates, easily break down the passivation layer increasing the corrosion of aluminum.

Southwire C7 ACCR conductor galvanic corrosion results

Coated carbon fiber strands from new conductor against aluminum strands

No corrosion was observed on aluminum strands exposed to coated carbon fiber strands from new Southwire C7 ACCR conductor regardless of the solution, solution temperature, or cathode to anode ratio. The PEEK layer surrounding the carbon fiber was very efficient at insulating the carbon fiber strands from the aluminum preventing charge transfer.

Uncoated carbon fiber strands from new conductor against aluminum strands

Corrosion rates of aluminum strands exposed to uncoated carbon fiber strands from new Southwire C7 ACCR conductor are shown in Figure 8-5. The observations made for the uncoated CTC ACCC carbon core in the previous section can also be made for the C7 ACCR carbon strands, except that the sulfate solution seems to be as corrosive as the chloride solution. Temperature and cathode to anode ratios both had an impact on the aluminum corrosion rates. The highest corrosion rate measured was also observed for the highest ratio with a 60˚C chloride solution with a value of about 57 mils per year, which is extremely high.

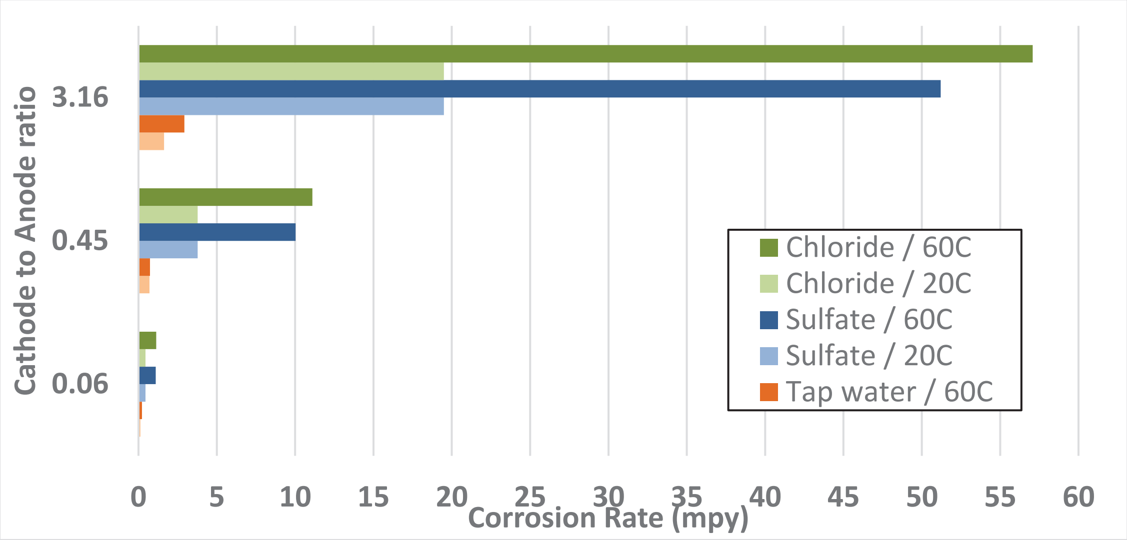

Figure 8-5. Aluminum corrosion rate when exposed to C7 uncoated carbon core

Coated carbon fiber strands from aged conductor against aluminum strands

Corrosion rates of aluminum strands exposed to coated carbon core from aged C7 ACCR conductor are shown in Figure 8-6. Unlike the carbon core of the aged CTC ACCC Global conductor, which did not impact aluminum corrosion, the carbon strands of aged C7 ACCR conductor seemed to create a corrosion cell with the aluminum strands resulting in light corrosion of aluminum. However, the highest corrosion rate observed (60˚C solution of chloride at the highest ratio) was 1 mil per year, which is a low value. Like the observations made earlier, solution temperature and cathode to anode ratio had a predictable impact of the corrosion rate of aluminum.

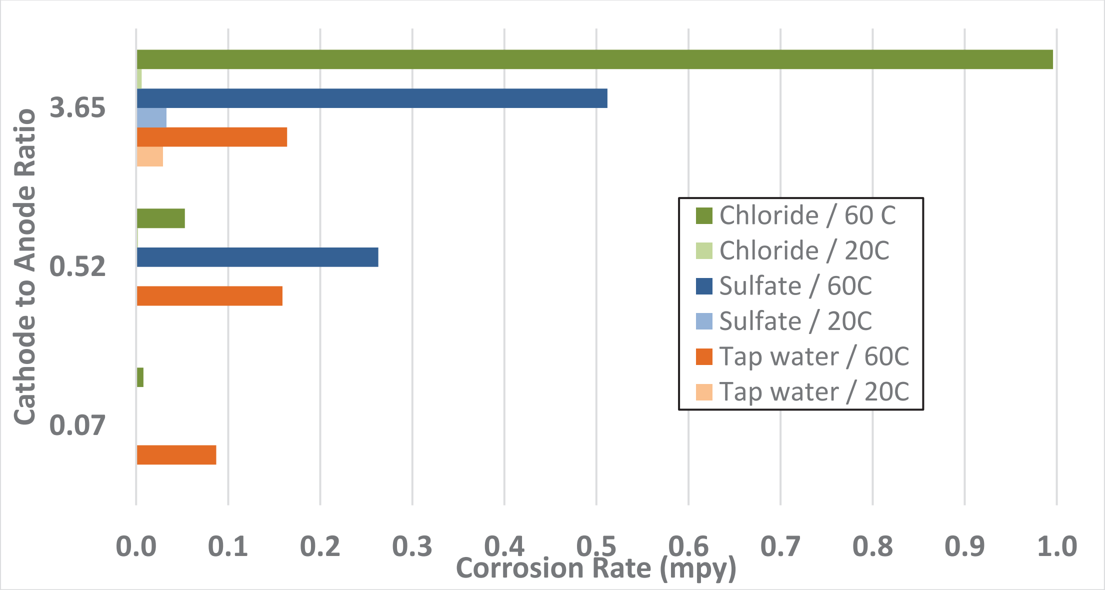

Figure 8-6. Aluminum corrosion rate when exposed to aged C7 ACCR carbon core

The difference between the corrosion rates at low cathode to anode ratios and the rates at high cathode to anode ratios is not as pronounced as the previous experiment. Moreover, at the lowest and medium ratios, tap water solutions resulted in a higher corrosion rate than chloride and sulfate (only at low ratio), a phenomenon that was not observed previously. This suggests that the results shown in Figure 8-6 should be taken with prudence due to the inconsistency of some data. It is probable that the tip of the carbon fiber strands were not perfectly coated with silicon during sample preparation, exposing the bare carbon fiber, even if visual inspection did not identify any problems.

Steel Core Conductor Evaluation

Four ACSS conductors were evaluated as part of this study. The accelerated corrosion test of ACSS conductors consisted in aging small conductor segments in a cyclical corrosion chamber (Q-fog from Q-lab) and measuring the coating loss of the inner steel core with time. Conductor samples were removed from the aging chamber at regular intervals and the steel core coating degradation was measured using a galvanizing loss method (ASTM A90) or using a coating thickness gauge.

The four conductors evaluated include:

1. ZTT (Chinese) ACSS Mallard Conductor
2. Southwire (U.S.) ACSS/TW Suwannee Conductor
3. General Cable (U.S.) ACSS Squab Conductor
4. LS Cable (Korean) ACSS/TW 425 Conductor

The effect of bird caging of the outer strands were evaluated in this study. Each conductor had 3 different types of samples.

5. Conductor sample with no birdcage
6. Conductor sample with a birdcage = 1.2 times the original diameter
7. Conductor sample with a birdcage = 1.4 times the original diameter

The samples are shown in Figure 8-7.

Figure 8-7. ACSS Conductor Samples

Aging Procedure

The ACCS conductor samples from each manufacturer were placed inside the Cyclical Corrosion Chamber “Q-Fog” in a random pattern. The remaining segment was set aside as control (not exposed to corrosion). Similarly, the six bird cages were also placed randomly inside the aging chamber. Every week during the aging process, the conductor samples were turned 180 degrees and randomly moved within the chamber to avoid preferential corrosion.

The ACSS conductor segments placed in the Q-Fog were aged according to the standard CCT-IV, an automotive paint corrosion standard known to best replicate atmospheric corrosion. The Q-FOG aging chamber has programmable settings that enable the temperature, salt spray, and humid/dry cycles to be adjusted. The aging sequence comprised a salt spray quench cycle of 5% sodium chloride and alternating wet/dry cycles.

Corrosion measurements

The main method used to evaluate the steel core coating thinning was the galvanizing loss method based on ASTM A90 "Standard Test Methods of Weight of Coating on Iron and Steel Articles with Zinc or Zinc-alloy Coatings." This method consists in weighing the coated steel strands before and after spending five minutes into an acid bath. The coating coverage is then calculated in oz/ft2, and coating loss trended over time.

If the ACSS conductor core showed any sign of zinc corrosion (insoluble white compound), this compound was removed prior to zinc coating thickness measurement using the NACE (National Association of Corrosion Engineers) recommended cleaning solution.

A secondary method was used in case the steel core coating could not be measured using the ASTM A90 method. The secondary method consisted in the direct measurement of the steel core coating using a thickness measurement gauge.

Results

GC Squab

GC ACSS Squab conductor has two layers of round aluminum strands, and a steel core composed of seven strands of 0.119 in. diameter. The full conductor has a diameter of about 0.96 in. The results of Mischmetal steel coating loss due to aging is shown in Figure 8-8. A linear trend line was fitted against the data point to measure the consumption rate of the Mischmetal coating. Initial Mischmetal coating coverage was measured at 1.18 oz/ft2 and the coating loss rate was measured at 1.24x10-4 oz/ft2/hr.

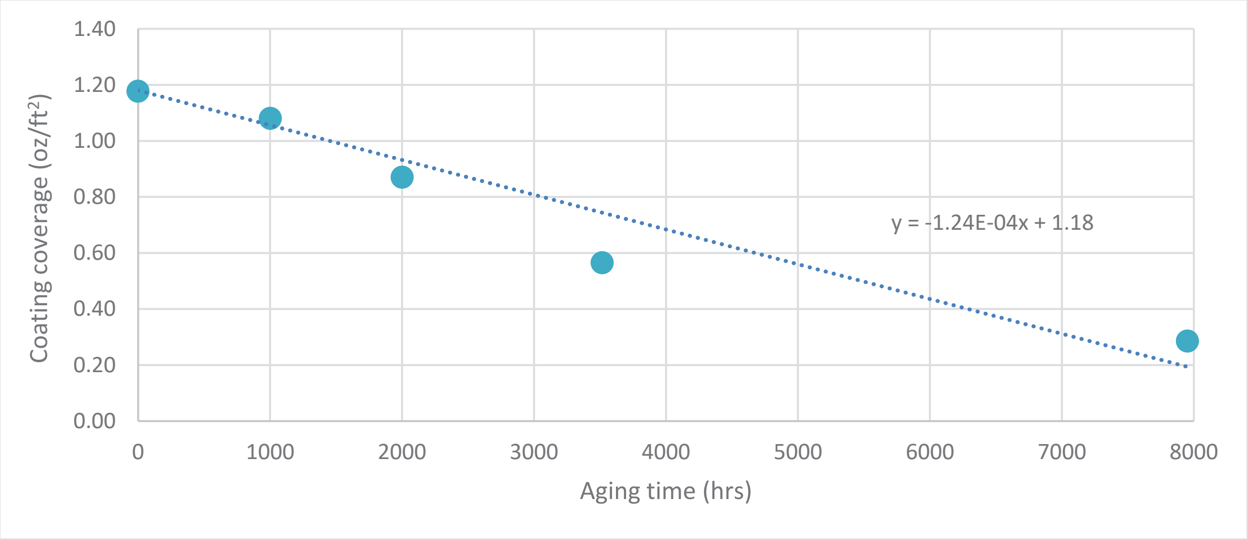

Figure 8-8. GC ACSS Squab steel core Mischmetal coating loss with aging

The impact of bird cages (1.2 and 1.4 times the original diameter of the GC ACSS Squab conductors) was also evaluated. The coating loss of the birdcage samples are shown in Figure 8-9. The Mischmetal coating loss rate of the birdcage with a 1.2- and 1.4-times diameter was measured at 1.44x10-4 oz/ft2/hr. and 1.60x10-4 oz/ft2/hr. respectively.

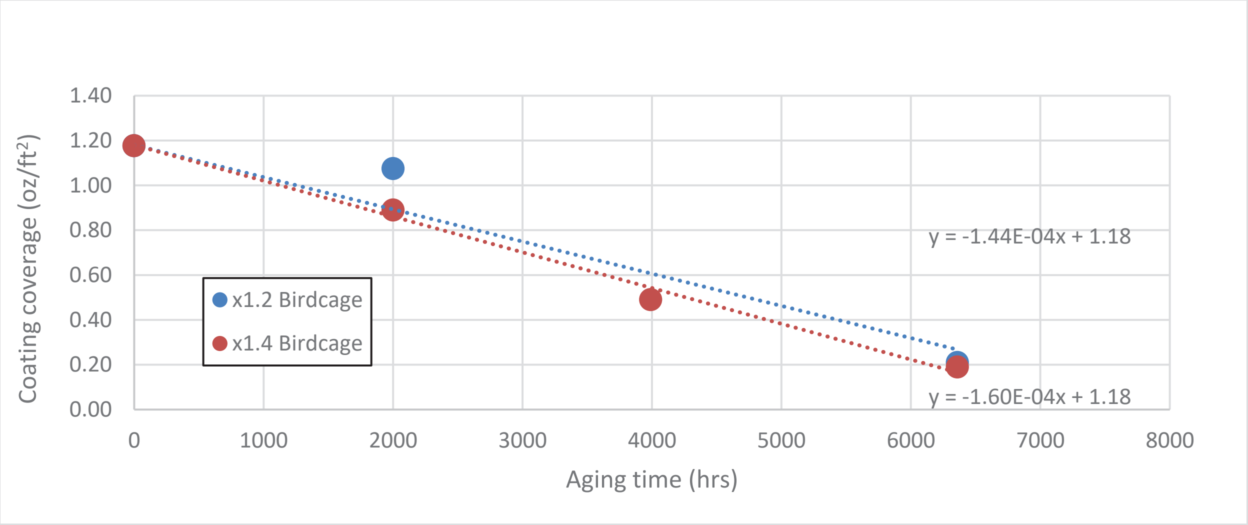

Figure 8-9. GC ACSS Squab birdcage effect on the steel core Mischmetal coating loss

Table 8-3 summarized the coating loss rate of the GC ACSS Squab conductor and the two birdcage levels. As expected, the coating loss rate for the birdcage samples was higher than the one of the GC ACSS Squab conductors without birdcage. The coating loss rate was higher by 16% and 32% for the samples with a birdcage 1.2 times and 1.4 times the original diameter.

Table 8-3. GC ACSS squab coating consumption rates comparison

	Coating loss rate (oz/ft²/hr.)	**Change in coating loss rate due to birdcage**
GC Squad conductor	1.24E-04	1
GC Squad birdcage (x1.2diameter)	1.44E-04	1.16
GC Squad birdcage (x1.4 diameter)	1.64E-04	1.32

Southwire Suwannee

Southwire (SW) ACSS Suwannee conductor has two layers of trapezoidal aluminum strands surrounding seven steel strands of 0.149 in. Diameter. The full SW ACSS Suwannee conductor has a diameter of 1.11 in. The results of the Mischmetal steel coating loss due to aging is shown in Figure 8-10. The initial Mischmetal coating coverage was measured at 1.2 oz/ft2. A linear fit was used to evaluate the coating loss rate. It was measured at 8.59x10-5 oz/ft2/hr.

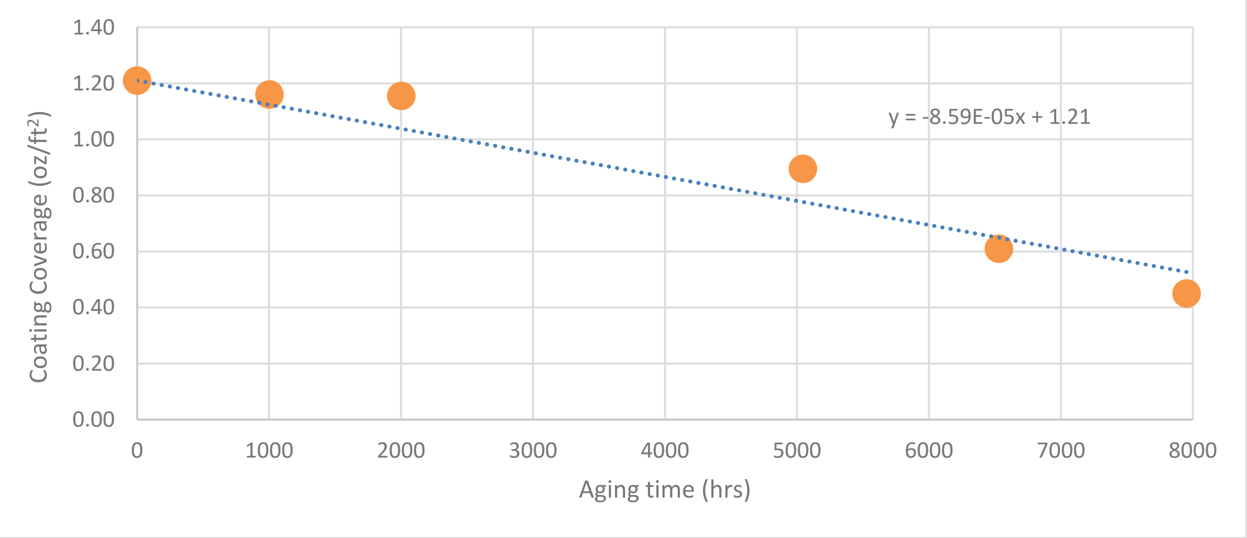

Figure 8-10. SW ACSS Suwannee steel core Mischmetal coating loss due to aging

A similar coating loss rate was measured for SW ACSS Suwannee conductor with bird caging. The coating loss rates were evaluated at 9.91x10-5 and 1.02x10-4 oz/ft2/hr. for the conductor with a birdcage diameter of 1.2 and 1.4 times the original diameter respectively, shown in Figure 8-11.

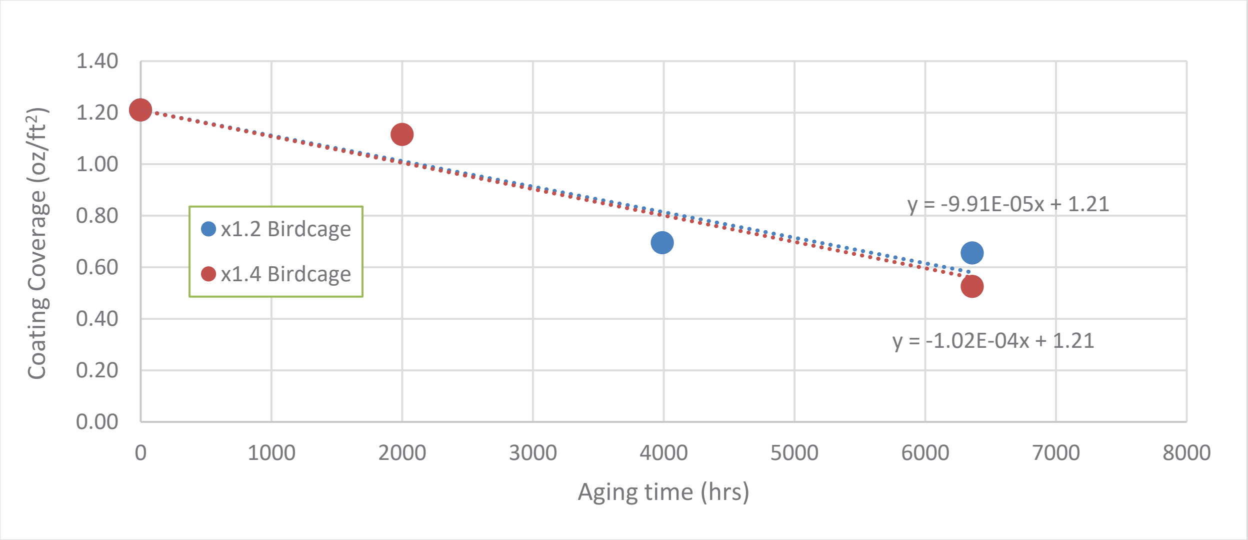

Figure 8-11. SW ACSS Suwannee birdcage effect on the steel core Mischmetal coating loss

The coating loss rate for the SW ACSS Suwannee conductor, and its birdcage samples are summarized in Table 8-4. As expected, the coating loss rate for the birdcage samples were higher than for the conductor without any birdcage. A birdcage of 1.2 times the original diameter resulted in a coating loss rate increase of 1.15, while a birdcage of 1.4 times the original diameter resulted in the coating rate increase of 1.18.

Table 8-4. SW ACSS Suwannee coating consumption rates comparison

	Coating loss rate ($oz/ft^2/hr.$)	Change in coating loss rate due to birdcage
SW Suwannee conductor	8.59E-05	1
SW Suwannee birdcage (x1.2 diameter)	9.91E-05	1.15
SW Suwannee birdcage (x1.4 diameter)	1.02E-04	1.18

ZTT Mallard

ZTT ACSS Mallard has two layers of round aluminum strands surrounding two layers of steel strands with a diameter of 0.0977 in. The coating loss rate for the two steel layers was measured separately. The full ZTT ACSS Mallard conductor has a diameter of 1.139 in. The Mischmetal steel coating loss due to aging is shown in Figure 8-12. The initial Mischmetal coating coverage was measured at about 0.80 oz/ft2. The coating loss rate of the outside steel layer was measured at 8.47x10-5 oz/ft2/hr., while the coating loss rate of the inside steel layer was measured at 7.42x10-5 oz/ft2/hr. As expected, the inside steel layer had the lowest coating loss rate (0.87 times lower) than the outside one.

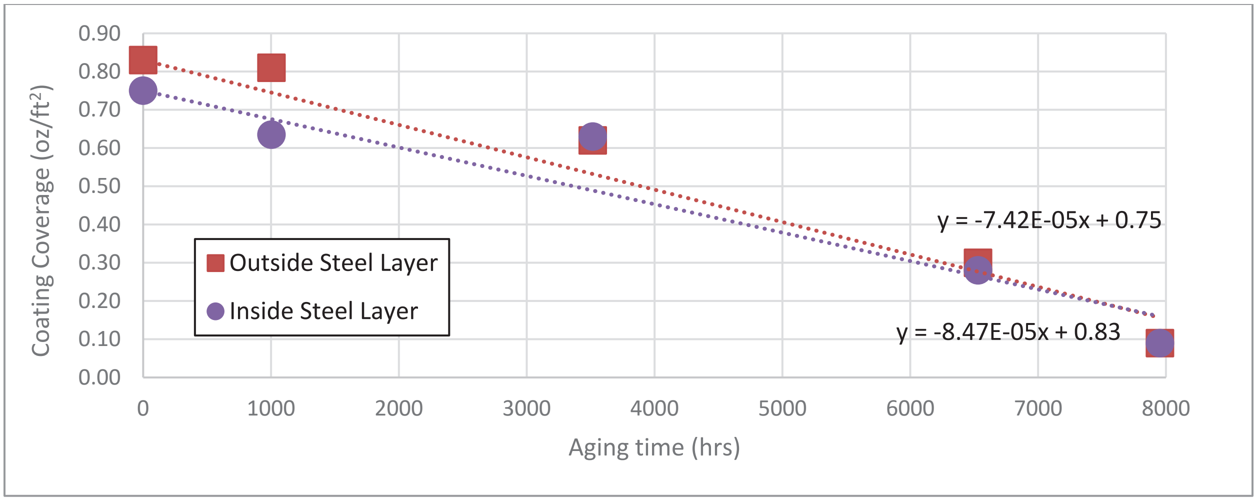

Figure 8-12. ZZT ACSS Mallard steel core Mischmetal coating loss due to aging

The Mischmetal coating loss rate was also measured for ZTT ACSS Mallard conductor with a birdcage. The coating loss rate of a conductor with a birdcage of 1.2 times the original diameter was measured at 1.07x10-4 oz/ft2/hr. for the outside layer and 5.44x10-5 oz/ft2/hr. for the inside layer. The coating loss rate of a conductor with a birdcage of 1.4 times the original diameter was measured at 1.12x10-4 oz/ft2/hr. for the outside layer and 8.04x10-5 oz/ft2/hr. for the inside layer, shown in Figure 8-13.

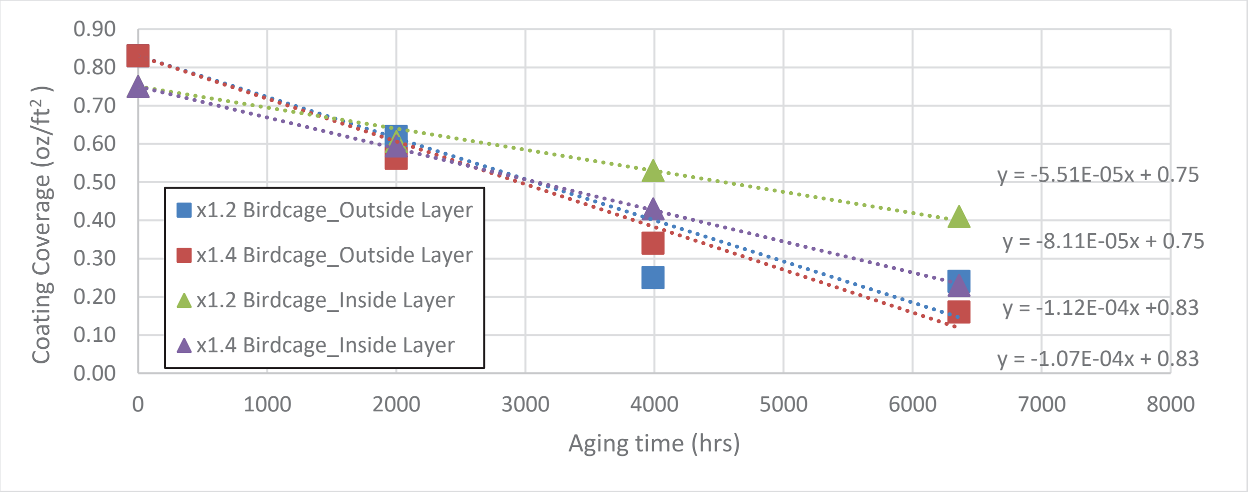

Figure 8-13. ZTT ACSS Mallard birdcage effect on the steel core Mischmetal coating loss

The coating loss rates of the ZTT ACSS Mallard conductor without and with bird cages are shown in Table 8-5. As expected, the birdcages increased the coating loss rate except for the inside steel layer of the birdcage with a diameter of 1.2 times the original diameter. The coating loss rate of the outside steel layer was increased by 1.26 and 1.32 for a birdcage of 1.2 times and 1.4 times the original conductor diameter respectively compared to the conductor without birdcage.

Table 8-5. ZTT ACSS Mallard coating consumption rates comparison

	Coating loss rate (oz/ft^2/hr.)	Change in coating loss rate due to birdcage
ZTT Mallard outside steel	8.47E-05	1
ZTT Mallard outside steel (x1.2 birdcage)	1.07E-04	1.26
ZTT Mallard outside steel (x1.4 birdcage)	1.12E-04	1.32
ZTT Mallard inside steel	7.42E-05	1
ZTT Mallard inside steel (x1.2 birdcage)	5.44E-05	0.74
ZTT Mallard inside steel (x1.4 birdcage)	8.04E-05	1.08

LS Cable

LS ACSS conductor has two layers of aluminum trapezoidal strands surrounding seven steel core strands of 0.136 in. diameter. It was originally assumed that the steel core coating was Mischmetal like the other conductors. However, it was quickly discovered that the LS steel core coating did not react with the acid, and its coverage could not be measured using ASTM A90. The steel core coating was then measured using a coating thickness gauge. The initial coating thickness was measured at about 7.5 mils, and the change in coating thickness with aging is shown in Figure 8-14.

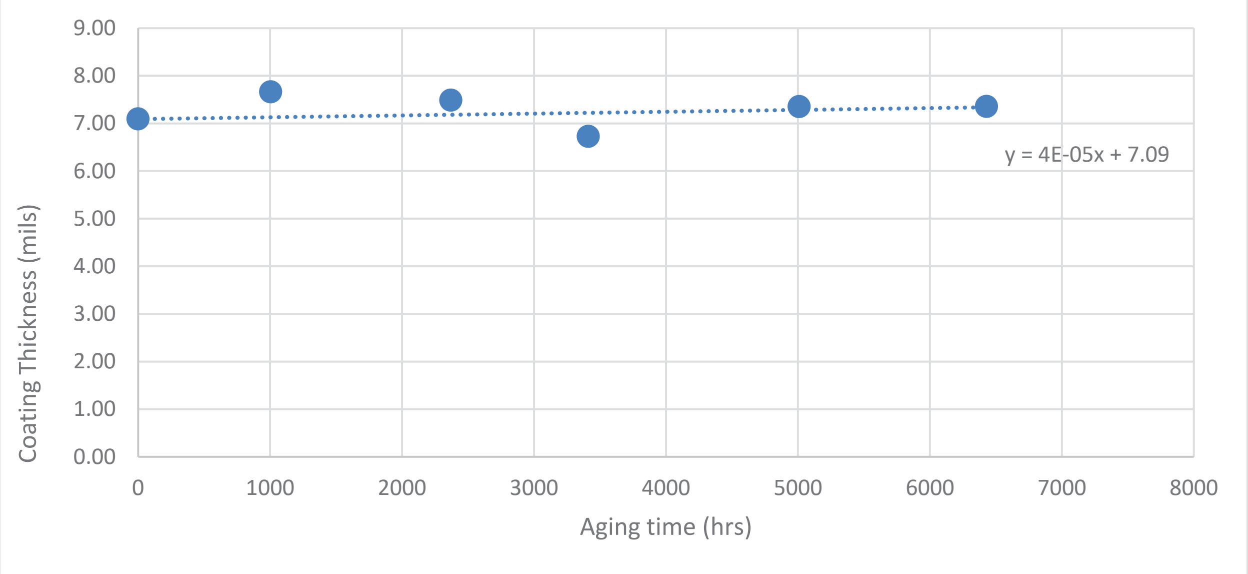

Figure 8-14. LS ACSS Steel Core aluminum Clad coating loss due to aging

The aging process did not impact the steel core coating as shown in Figure 8-14. . Considering that the steel core coating of the LS conductor did not react with acid nor corrode during the aging process, we can assume that the LS conductor core is composed of aluminum-clad steel. Additionally, no steel core coating corrosion was measured on the birdcage samples.

Conductor Comparison

The coating loss rates of each conductor, apart from LS conductor, are compared in

Table 8-6. . GC ACSS Squab had the highest coating loss rate at 1.24x10-4 oz/ft2/hr. SW ACSS Suwannee coating loss rate was lower by 30%. ZTT ACSS Mallard outside steel layer coating loss rate was 31% lower than GC ACSS Squab loss rate while the inside steel layer of the ZTT ACSS mallard had a coating loss rate 40% lower.

Table 8-6. Conductor steel core coating loss rates comparison (ACSS)

	Coating loss rate ($oz/ft^2/hr.$)	Coating loss rate compared to GC Squab
GC Squab	1.24E-04	1
SW Suwannee	8.59E-05	0.7
ZTT Mallard (outside layer)	8.47E-05	0.68
ZTT Mallard (inside layer)	7.42E-05	0.6

Regarding the birdcage impact of steel core corrosion, this study showed that birdcage increased the steel core corrosion rate (Table 8-7.). A birdcage with an opening diameter of 1.2 times the original conductor diameter increased the coating loss rate by 16 to 26 % depending on the conductor type. A birdcage with an opening diameter of 1.4 times the original conductor diameter increased the coating loss rate by 18 to 32% depending on the conductor type. While ZTT ACSS mallard birdcage had the strongest impact on the steel core corrosion rate, SW ACSS Suwannee performed better than other conductor potentially due to its trapezoidal shaped aluminum layers.

Table 8-7. Percent (%) increase of coating loss rate due to Birdcage (ACSS corrosion study)

Sample	**x1.2 Birdcage**	**x1.4 Birdcage**
GC Squab	16%	32%
SW Suwannee	15%	18%
ZTT Mallard (outside layer)	26%	32%