Thermal-Mechanical Testing of Single Stage Full Tension "Swage" Type Connectors Installed on ACSR Conductor

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***Abstract* - This paper presents the results of thermal-mechanical cycling test on Single Stage "Swage Technology" full tension connectors installed on 795 kcmil ACSR (Aluminum Conductor, Steel Reinforced) "Drake" conductor. A total of eight (8) connector samples were thermally aged, in a laboratory environment, at a temperature of 150 °C while under a mechanical tension equal to 25% of the conductor's Rated Tensile Strength (RTS). A total of four (4) connector samples were installed following standard "Swage Technology" type connector installation procedure (i.e. without the application of inhibitor compound), while another four (4) samples received the application of inhibitor compound prior to installation. The collected test results show the "Swage Technology" samples installed without compound exhibited greater temperature stability and significantly higher post aging mechanical tension performance than samples installed with compound. Analysis of the chemical composition of both the aged and unaged inhibitor is presented in addition to x-ray images of sample "Swage" type connectors.**

Index of terms - swage connectors, single stage connector, thermal aging, thermal-mechanical testing, tensile load test, inhibiting compound, contact resistance, high temperature.

I. Introduction

Conventional crimp type connectors utilize two stage connector (TSC) systems with a separate strength holding member, such as a steel eye loop, for dead end applications and a steel sleeve for splices (i.e. full-tension mid-span joints). The steel components are subjected to an initial compression cycle with a hydraulic tool and corresponding fixed die and a secondary compression cycle is performed over the outer aluminum tube. In the late 1970s, single stage connectors (SSC), or one die systems, were introduced to the power delivery industry as a means of facilitating faster installation times. These connector designs utilized a collet which encapsulated the steel core of bimetallic type ACSR conductor. The collet/conductor assembly was inserted into the aluminum connector tube and one (1) compression cycle with a fixed die is applied to the outer aluminum tube. Images of SSC and conventional TSC dead-end connectors are shown in Fig. 1.

Two Stage Connector   Single Stage Connector

Fig. 1. Typical TSC and SSC Systems

Eliminating the compression cycle of the connector steel sleeve directly on the ACSR steel strands was successful in reducing installation times.

As transmission lines increased in length and economics drove conductor designs, the number of ACSR conductor sizes increased significantly. Multiple conductor sizes of this quantity proved very challenging for designers of "fixed" tube or extruded tube fittings. Due to long production time from extruding mills, raw material inventory cost of processed tubes and the upfront cost of extrusion dies, a concerted effort was made to maximize the number of conductor sizes assigned to a given tube size. The effects of this "range taking" approach yielded considerable differences in the area of reduction of a particular fitting size. This meant the smallest conductor size yielded the lowest compression ratio or area of reduction.

Percent compression, as seen in Fig. 2, is a means for determining the compression ratio of a particular connector/conductor assembly. Achieving higher percent compression is critical in creating residual radial forces necessary for establishing and maintaining low contact resistance between the connector tube and conductor surface.

Percent compression between connector and conductor

% COMPRESSION = [(D2 – (D1 – (O.D. – I.D.))) / D2] * 100

Where:

I.D. = The closed position inner diameter of swage die
O.D. = The outer diameter of connector tube
D1 = The inside diameter connector tube
D2 = The outer diameter of the conductor

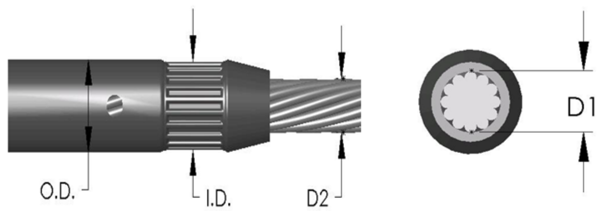

FIG. 2. PERCENT COMPRESSION CALCULATION

Typical SSC crimp connectors used for ACSR conductor are manufactured from tubes produced through extrusion or drawing process. These tubes have well established geometric tolerances for the outside diameter, inside diameter, and wall thickness. Small variances in each of these three (3) parameters can lead to significant compression ratio variances along the axis of the connector tube.

The need for repeatable and reproducible low contact resistance connection systems has never been more critical then today. Increasing demands on power grids has led to increased line temperatures and consequently, a higher number of both SSC and TSC connector failures. These facts were recently amplified in the United States Department of Energy's (U.S. DOE) 2015 quadrennial assessment report. The report characterized compression connectors for overhead lines as the weak links in the electricity delivery network, where power transmission can be limited by the connector resistance and disruptions can occur owing to mechanical failures [1]. Additionally, in a recent publication by Avista Utilities, they acknowledged that 4% of all splices were in "very poor" condition heading towards failure with an additional 25% of all installed splice classified as questionable [2]. This reinforces the need for reliable testing of SSC and TSC connectors which more closely reflects stresses encountered during modern-day service.

II. SWAGE TECHNOLOGY SYSTEM

Unlike conventional fixed die crimp systems, "Swage Technology" incorporates a 360^0 flexible die technology as seen in Fig. 3. This flexible die applies the forces generated from the hydraulic tool radially and symmetrically around the connector tube as seen in Fig. 4. This forces the material under the die to move inwards radially to the axis of the connector tube. A symmetrical swaging motion can produce as much as twice the area of reduction, or percent compression, as other fixed die compression systems. The swaging motion also eliminates the losses created by moving material tangentially to the connector tube as seen in the fixed die crimp in Fig. 4. The 360° flexible die provides symmetrical motion regardless of the initial positioning of the tube in the swaging tool. A comparison of resulting connector cross sections from flex die and fixed die crimps are seen in Fig. 5.

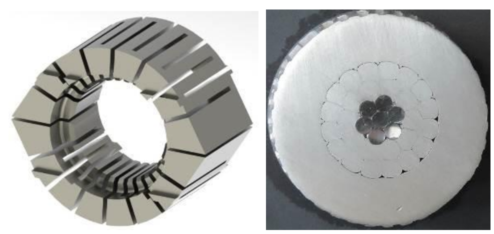

FIG. 3. 360° DEGREE SWAGE TECHNOLOGY FLEX DIE

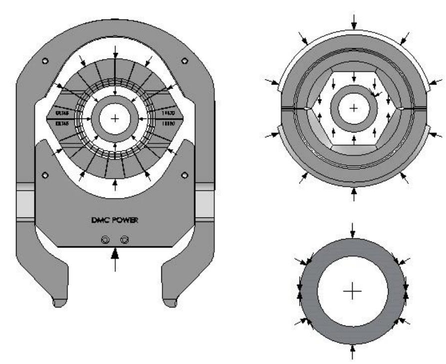

FIG. 4. 360° RADIAL FORCES APPLIED BY SWAGED DIE VS. VERTICAL FORCES APPLIED BY FIXED DIE

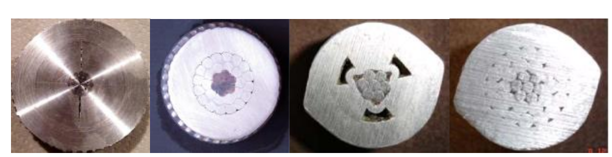

FIG. 5. COMPARISON OF CROSS SECTIONS OF FLEX DIE AND FIXED DIE COMPRESSION

III. USE OF OXIDE INHIBITING COMPOUND

Compounds have been typically used for three (3) primary purposes: increasing mechanical holding strength, protection from corrosion and lowering contact resistance [3]. The performance of these three (3) parameters when installing Swage Technology connectors without inhibitor compound were evaluated in previous testing as briefly described below.

A. *Mechanical Holding Strength*

Swage Technology connectors incorporate a flaring and locking design behind the swage area as seen in Fig. 6. This key design feature increases system sheer forces which lead to increased mechanical holding strength and eliminates the need to rely on the grit found in typical inhibitors for increased mechanical strength. Maximum load tests were successfully performed on different sizes of ACSR connectors as per ANSI C119.4 without the use of the inhibitor compound to verify their mechanical strength [4, 5, 6].

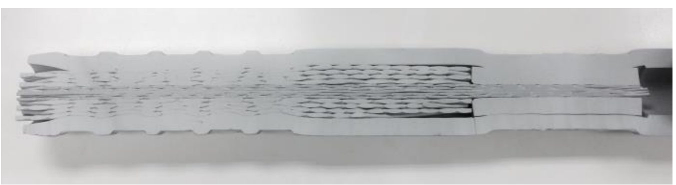

FIG. 6 FLARE OUT OF CONDUCTOR BEHIND SWAGED AREA LONGITUDINAL SECTION IN SWAGED CONNECTOR

B. *Corrosion Protection*

Corrosion Tests were performed in parallel on two (2) sets of Drake swaged connectors as per ASTM B117-2007 for 1000 hours [7]. One (1) set was swaged with inhibitor compound present at the electrical interface and one (1) without inhibitor compound. The Corrosion Tests simulated an accelerated aging process by exposing both sets of connectors to salt spray conditions. The final difference in measured contact resistance between samples from the two (2) sets was negligible [8].

C. *Contact Resistance Performance*

A Current Cycling Test as per ANSI C119.4 Class "AA" was performed on Swage Technology SSC connectors installed on 2156 ACSR Bluebird. Five hundred (500) cycles were completed as per the standard and an additional aging up to one thousand (1000) total cycles was completed. Temperature and contact resistance measurements, as seen in Fig. 7 and Fig. 8, met ANSI C119.4 requirements [9].

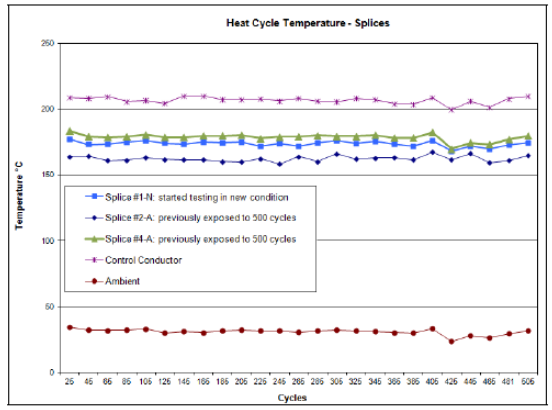

Figure C-4: Steady State Temperatures of Class "AA" Splice Connectors and 2156 kcmil ACSR Control Conductor

FIG. 7. ANSI C119.4 CLASS "AA" TEMPERATURE GRAPH AT 175°C RISE - CYCLES 500 TO 1000

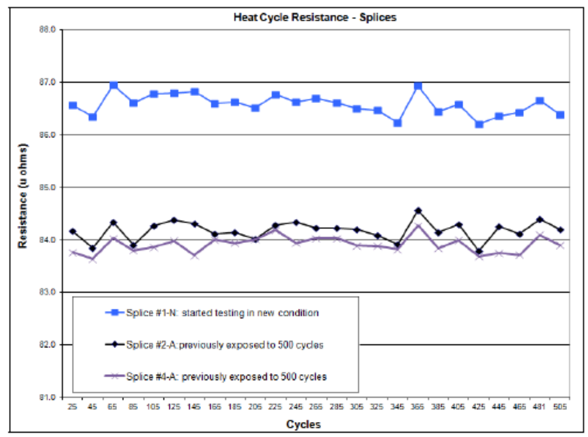

Figure C-1: DC Resistance across Swaged Class "AA" Splice Connectors connected to 2156 kcmil, ACSR Conductor

FIG. 8. ANSI C119.4 CLASS "AA" RESISTANCE GRAPH AT 175°C RISE - CYCLES 500 TO 1000

In order to investigate the effects of applying compound in full tension applications, two test (2) assemblies were established: one (1) assembly with inhibitor compound and a second assembly without inhibitor compound. A discussion of the contrast in performances between the two (2) assemblies is presented later in this paper. Notable changes in performance of Swage Technology connectors under Thermal-Mechanical Testing will also be discussed.

IV. THERMAL-MECHANICAL CYCLING TEST

Traditional thermal cycle aging is performed under static conditions as per ANSI C119.4. Recently, some tests began incorporating tension in thermal cycling to more closely emulate real line conditions.

In September 2015, DMC initiated a research project to evaluate the performance of single stage swaged connectors installed on ACSR conductor under tension and high temperature operation at Kinectrics Inc. The primary purpose of this test was to study the mechanical and electrical effects of repeated high temperature cycling on connectors while under tension. A secondary objective was to compare the performance of the swage connectors installed with and without oxide inhibitor compound. A target temperature of 150°C measured on the 795 kcmil ACSR conductor surface was chosen for the study. Since no published industry standard currently exists for thermal cycling of overhead transmission connectors while under mechanical tension, general procedural guidelines were incorporated from CIGRE Guide B426 to conduct this thermal-mechanical testing [10].

A. TEST SETUP

The test setup consisted of two (2) assemblies each with two (2) single stage swaged full-tension joints (i.e. splices) and two (2) single stage swaged dead-ends installed on 795 kcmil Drake ACSR conductor. This is shown schematically in Fig. 9. One (1) assembly was installed without the application of oxide inhibitor compound between the electrical interface of connector and conductor surface. The second assembly received the application of inhibitor compound prior to connector installation. The conductor on both assemblies was wire brushed loosely in the contact area with the aluminum connector sleeve. This was performed in order to remove surface oxidation or other surface contaminants prior to connector installation. No other preparation of the conductor or connector was performed.

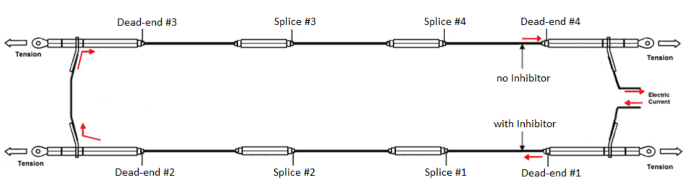

FIG. 9. SCHEMATIC OF TEST SPAN ASSEMBLIES

The assemblies were installed to form a span approximately 130 ft long. The two (2) assemblies were electrically connected in series and physically were located parallel to each other as shown in Fig. 6. Both test assemblies were instrumented with numerous thermocouples and a load cell to monitor sample temperatures and tensions during the thermal-cycling test program. Thermocouples were drilled and peened into each connector at a distance of 2 in from their ends.

This meant each splice had two (2) thermocouples and each dead-end had one (1) thermocouple. The four (4) test connectors in each assembly were spaced such that the effective length of conductor between them was approximately the same. A dead-end connector installed for testing is shown in Fig. 10.

FIG. 10. TYPICAL DEAD-END CONNECTOR INSTALLED FOR THERMAL-MECHANICAL TESTING

The conductor used for this test was 795 kcmil, 26/7 ACSR (Drake), consisting of twenty-six (26) round aluminum strands and seven (7) regular strength, round galvanized strands. The conductor has a Rated Tensile Strength (RTS) of 31,500 lb. Tension and temperature data collection was done automatically throughout each cycle. DC resistance measurements for each connector were recorded every ten (10) cycles up to a total of one hundred (100) cycles and at twenty-five (25) cycle intervals until completion of the test. The contact resistance measurements were made across each connector entrance between equipotential points. The equipotential point on the stranded conductor was created by twisting a pair of copper wire around the circumference at a distance of 1 in from the connector entrance (i.e. mouth). A bronze bolt screwed into the body of each connector was used for the voltage drop measurements at the connector end.

B. TEST PROTOCOL

A thermal cycling test was designed and carried out under controlled ambient conditions in Kinectrics' Mechanical Test Laboratory. The complete test consisted of a total of 1,100 heating and cooling cycles. A single thermal cycle was completed by heating the conductor surface from ambient temperature to 150°C by applying 1,150 A of AC current. This temperature was maintained for a period of two (2) hours (i.e. soaking period) before allowing the assemblies to cool by natural convection. A temperature plot for a typical thermal-mechanical cycle is shown in Fig. 11. Both assemblies were allowed to cool until the maximum thermocouple reading did not vary by more than 2°C over a ten (10) minute period.

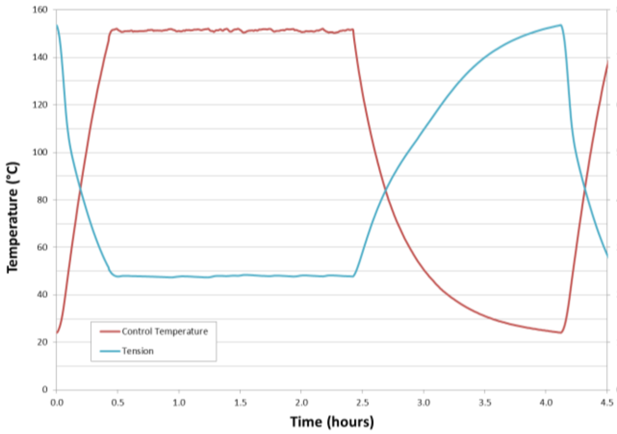

FIG. 11. TYPICAL TEMPERATURE AND TENSION DURING THERMAL CYCLE

The tension in each assembly was increased to 25% of the conductor's RTS while at ambient temperature. This load was allowed to decrease during the heating cycles as demonstrated in Fig. 11. Since some creep was taken out from the conductor during the test and due to slight variation of ambient temperature during the curse of the test program, the maximum tension measured at ambient temperature was monitored and adjusted within 2% RTS throughout the test.

C. TEST DATA

The temperature measured by the thermocouples at the end of the two (2) hour soaking period at 150°C was recorded as the steady state temperature for each respective electrical connection. The steady state temperatures measured on all connectors (with and without inhibitor compound) throughout the 1,100 cycles have been presented in Fig. 12, Fig. 13 and Fig. 14.

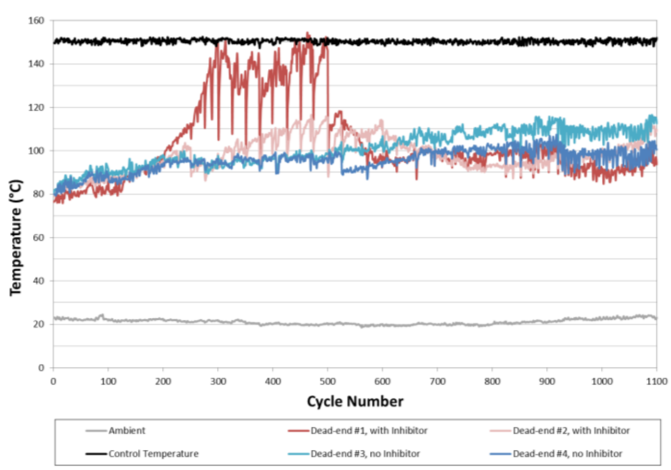

FIG. 12. TEMPERATURES OF DEAD-END CONNECTORS

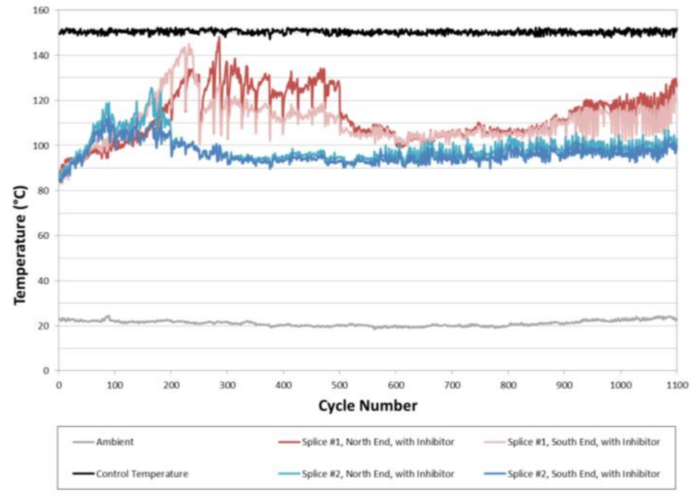

FIG. 13. TEMPERATURES OF SPLICES WITH INHIBITOR

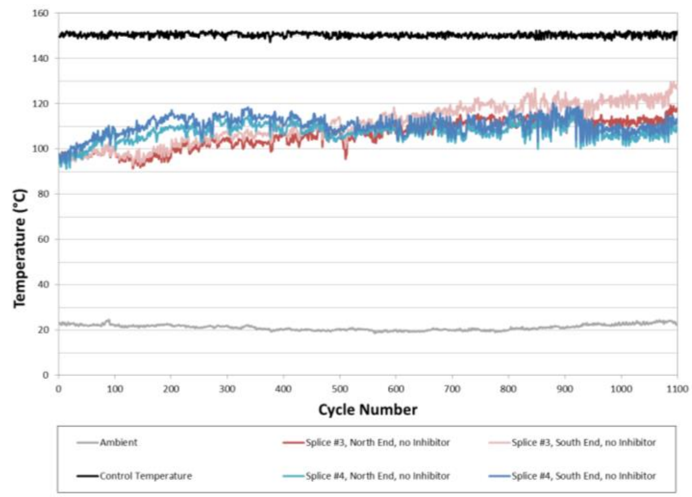

FIG. 14. TEMPERATURES OF SPLICES WITHOUT INHIBITOR

DC resistance measurements for each connector were recorded every ten (10) cycles up to a total of one hundred (100) cycles and at twenty-five (25) cycle intervals until the completion of the test. Two (2) measurements were taken on each splice to evaluate both electrical connections with the ACSR conductor. The contact resistance measurements, corrected to 20°C, are presented in Fig. 15 and Fig. 16.

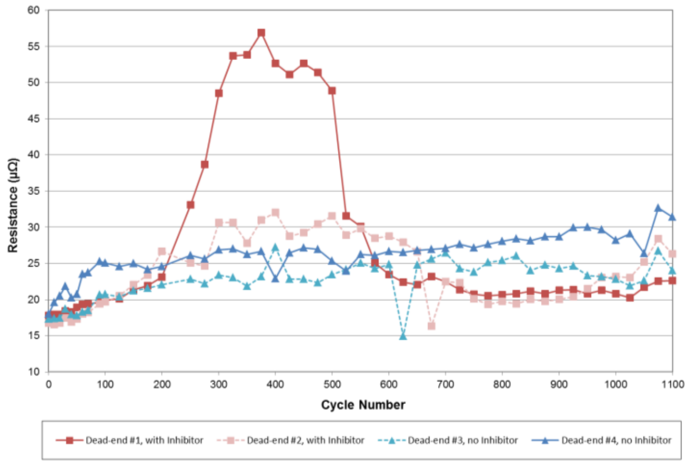

FIG. 15. DC RESISTANCE OF DEAD-END CONNECTORS

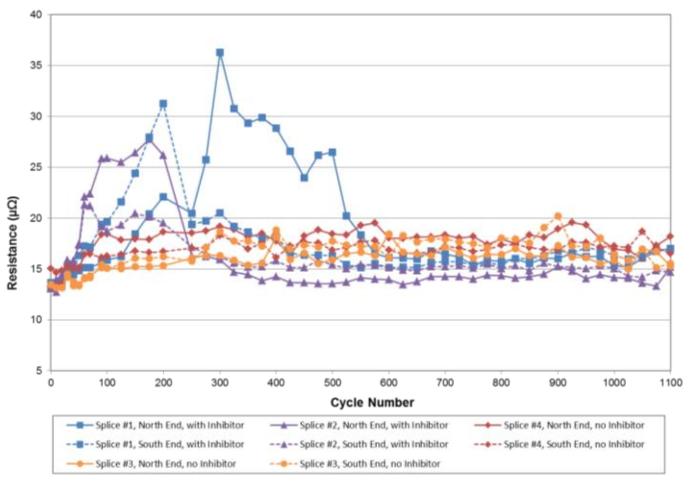

FIG. 16. DC RESISTANCE OF SPLICE CONNECTORS

Discussion of the temperature and contact resistance measurement results is presented in Section VI.

V. POST CYCLING TESTS

On completion of 1,100 thermal-mechanical cycles, both assemblies were removed from the test span for further evaluation. A series of maximum load tests (i.e. tensile load tests), digital radiography imaging and chemical analysis of the inhibitor compound in new and thermally aged condition were performed to gather additional information.

A. *Maximum Load Tests*

One (1) dead-end connector and one (1) splice connector were removed from each assembly for maximum load testing (i.e. 4 total connectors, 2 with inhibitor and 2 without inhibitor). The connector samples were separated in such a way that each connector had approximately equal length of conductor attached to it. The free conductor ends were terminated with laboratory type end-blocks. The end-blocks had all strands imbedded in epoxy resin to assure that all strands are equally loaded during the tensile test (i.e. representation of mid-span condition). The samples were then installed in a hydraulic, horizontal tensile machine. The minimum exposed length of conductor (12 ft) and maximum loading rate (1/4 in/min/ft of exposed conductor) met the procedural requirements of ANSI C119.4, Clause 7 "*Mechanical Test Procedures*" [11].

The results of the four (4) maximum load tests are seen in Fig. 17 and Tab. 1.

TAB. 1. RESULTS OF MAXIMUM LOAD TESTS

Sample ID	Failure Load	Comment
Dead-end #2, with Inhibitor	29,678 lb (94.2% RTS)	Aluminum broke at entrance of connector. Core remained intact, pulled out of connector.
Splice #2, with Inhibitor	17,525 lb (55.6% RTS)	Aluminum broke at entrance of connector. Core remained intact, south end pulled out of connector.
Dead-end #3, no Inhibitor	32,410 lb (102.9% RTS)	Aluminum broke at entrance of conductor. Steel core tensile failure.
Splice #3, no Inhibitor	31,930 lb (101.4% RTS)	Aluminum broke at entrance of conductor. Steel core tensile failure.

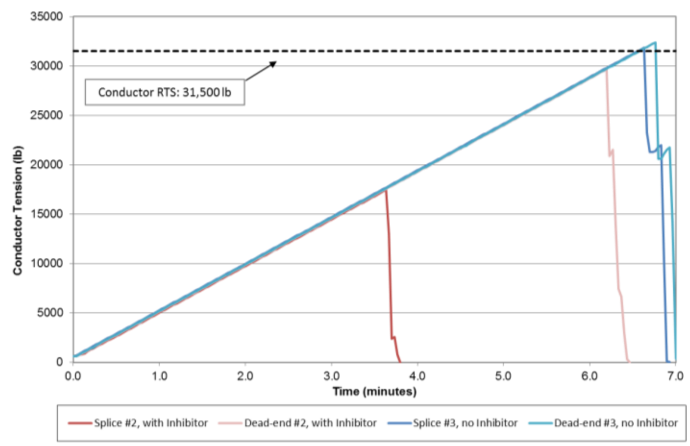

FIG. 17. RESULTS OF MAXIMUM LOAD TESTS

B. *Digital Radiography Imaging*

The purpose of the digital radiography imaging on connectors was to identify if the steel core slipped (moved) after the thermal-mechanical cycling. One (1) dead-end connector and one (1) splice connector were removed from each assembly for digital radiography imaging (i.e. x-ray imaging). The samples were positioned for the x-rays in order to observe the condition inside the connector after 1,100 cycles. Two (2) additional connectors in new condition were also supplied to create a reference image for comparison. X-ray images of the six (6) samples are presented in Fig. 18 to Fig. 23.

FIG. 18. DEAD-END CONNECTOR, AS-NEW

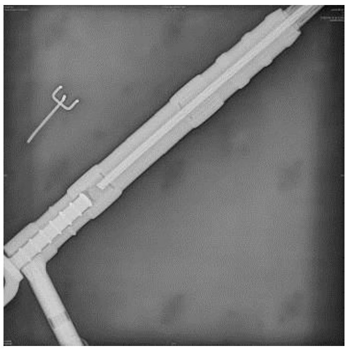

FIG. 19. DEAD-END #1 AFTER CYCLING, WITH INHIBITOR

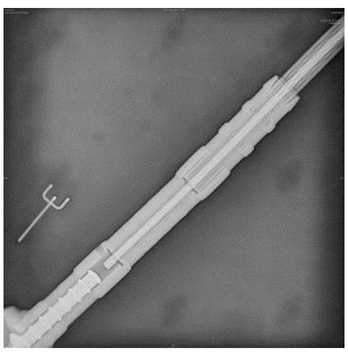

FIG. 20. DEAD-END #4 AFTER CYCLING, NO INHIBITOR

No slippage or other mechanical changes were observed between the dead-end connector in new condition and the dead-end connectors after 1,100 cycles. Small voids or separation of the inhibitor were visible near the steel core.

Slippage of the steel core strands was observed on the splice sample installed with inhibitor after 1,100 cycles. This slippage ranged from approximately 0.5 in to 1.0 in. No movement of the aluminum strands was detected on the connector. No slippage or other mechanical changes were observed between the splice connector in new condition and the splice installed without inhibitor after cycling.

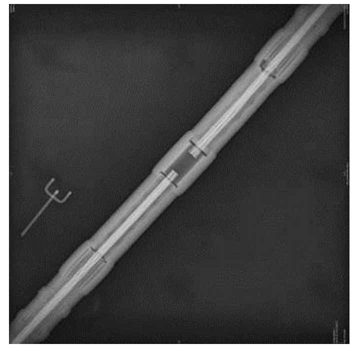

FIG. 21. SPLICE CONNECTOR, AS-NEW

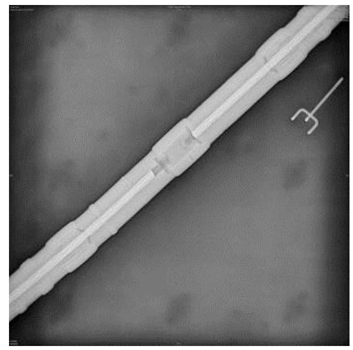

FIG. 22. SPLICE #1 AFTER CYCLING, WITH INHIBITOR

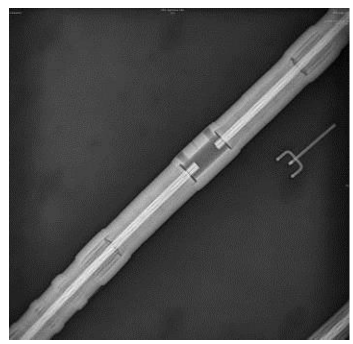

FIG. 23. SPLICE #4 AFTER CYCLING, NO INHIBITOR

C. Chemical Analysis of Inhibitor Compound

The following five (5) tests were performed on a sample of inhibitor in new condition and on a sample of aged inhibitor extracted from dead-end #2 and splice #2:

i) Fourier Transform Infrared Spectroscopy (FITR),
ii) Rheometry,
iii) Dropping Point,
iv) Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), and
v) Worked Penetration.

FITR analysis was used to measure the absorptivity of the organic content of the inhibitor compound across a range of wavelengths. Changes in the intensity and amplitude of the response to the infrared spectra are directly proportional to any change in the molecular structure of the organic content. If oxidation (i.e. the gain of electrons and a sign of degradation) of the inhibitor compound occurs, the infrared spectra response of the organic molecular structure would be altered. The results of the FITR analysis on the aged and as-new inhibitor samples are shown in Fig. 24. The FITR analysis showed minimal signs of oxidation of the aged inhibitor compared to the as-new sample.

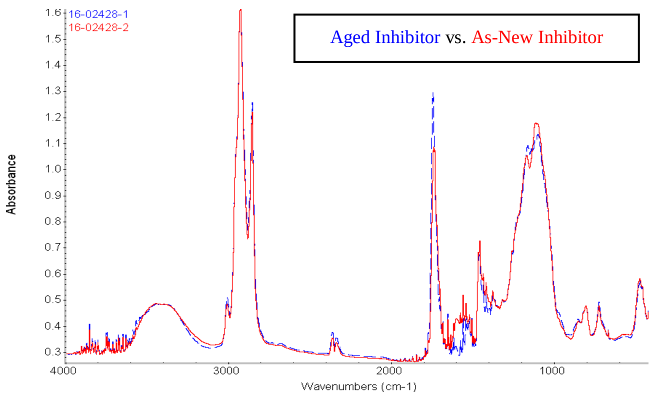

FIG. 24. RESULTS OF FITR ANALYSIS

The results of the remaining tests on the inhibitor are presented in Tab. 2. No measurable change in the dropping point of the inhibitor was noted and the results of the Worked Penetration showed a slight stiffening of the aged inhibitor compared to the as-new sample. This may indicate that no significant loss of water content of the inhibitor compound occurred. Rheometry was not possible on the aged inhibitor sample due to the presence of large particles.

Significant changes of certain key elements were noted in the chemical composition of the aged inhibitor. The increase in iron content can likely be attributed to transfer from the steel core of the conductor. Several hypotheses can account for the decrease in aluminum, nickel and silicon. These elements may be attached to more volatile species in the mixture and may be evaporated or burned off through cycling. Due to the presence of suspended particulates in the inhibitor, the thermal cycling may lead to slight separation of the components, thus resulting in a non-homogeneous (i.e. uneven) mixture. More investigation beyond the scope of this paper would be necessary to determine the root cause.

It must also be noted that the aged inhibitor sample was extracted mostly from the cavity in the connector surrounding the steel core. This was necessary to obtain a large enough volume of inhibitor to perform the testing. The inhibitor compound located at the contact interface would have been subjected to higher thermal and mechanical stresses. Thus, these tests provide some information as to the aging of the inhibitor compound but strict correlation of the results cannot be drawn to the condition of the contact interface. For this reason the chemical analysis tests shall not be discussed in subsequent sections.

TAB. 2. RESULTS OF INHIBITOR TESTING

Parameter	Inhibitor As-New [A]	Aged Inhibitor [B]	Percentage Difference [(B-A)/A]
¼ Worked Penetration [mm/10]	293	279	- 4.8 %
Dropping Point [°C]	>300	>300	N/A
Aluminum Content [ppm]	150,000	11,400	- 92.4 %
Nickel Content [ppm]	151,000	63.2	- 99.9 %
Silicon Content [ppm]	26,500	356	- 98.7 %
Iron Content [ppm]	169	1,280	657.4 %
Yield Point [Pa]	25.2	-	N/A
Plastic Viscosity [Pa.s]	0.75	-	N/A

VI. DISCUSSION OF RESULTS

Many previous studies present the benefits of using inhibitor compound during the installation of compression connectors. However, most comparative studies of contact resistance with and without inhibitor compound measure the benefits in low contact force mechanical connectors or compression connectors with lower percent compression ratios. area of reduction.

Generally, the connectors installed with the application of inhibiting compound at the interface of connector and conductor showed better thermal stability throughout the thermal-mechanical cycling test. It should be noted that towards the end of the 1,100 thermal cycles the measured temperatures for both types of installation were fairly similar. This is demonstrated for dead-end connectors in Fig. 12 and for splices in Fig. 13 and Fig. 14. Consequently, it is hypothesized that towards end of the test program, the inhibiting compound applied initially was no longer present at the contact interface (or at least not at the amount to significantly influence the measured temperatures and resistances). The measured contact resistances across connector entrances support this hypothesis, as presented in Fig. 15 and Fig. 16.

At the beginning of the thermal-mechanical cycling, the connectors (splices and dead-ends) installed with inhibitor exhibited slightly lower temperatures. However, the contact resistances were fairly similar for connectors installed with and without inhibiting compound. After the initial thermal cycles, the temperature of the connectors installed using inhibitor increased during the lab aging process. After approximately 200 thermal cycles, the dead-end connectors with inhibitor exceeded the temperature of the dead-end connectors installed without inhibitor. Splices installed with inhibitor exceeded the temperature of splices installed without inhibitor after approximately 150 thermal cycles. The reason for this difference could be that the splices have smaller thermal capacitance and initially run at higher temperatures than the dead-end connectors. Therefore, the thermal aging process would be accelerated for the splice connectors.

The thermal aging process for connectors installed with inhibitor was accelerated dramatically after exceeding the temperature of connectors without inhibitor. As presented in Fig. 12 and Fig. 13, the connectors with inhibitor reach significantly higher temperatures than the connectors without inhibitor. During certain thermal cycles, the temperature of connectors with inhibitor reached, and in some cases even exceeded, the temperature of the reference conductor. This increase in temperature is the consequence of the aging contact interface and correlates to the increase in the contact resistance presented in Fig. 15 and Fig. 16. The contact resistance and temperature of connectors installed with inhibitor stabilizes to similar values measured on connectors without inhibitor after approximately 500 cycles. It is thought this may have been a result of a loss of inhibitor, a shifting or movement in the contact interface or a combination of both. The degradation of the contact interface was not noticed for connectors installed without inhibitor.

As presented earlier, the remaining tensile strength of the connectors was measured in order to understand the mechanical effects of the accelerated laboratory aging process. A summary of results is presented in Tab. 1 and Fig. 17. The results demonstrated that the connectors without inhibiting compound retained the full tensile strength of the conductor. Contrary to this, the connectors with inhibitor had significantly less tensile strength after the aging process. The radiography imaging of connectors installed with and without inhibitor also provided additional information regarding remaining tensile strength. These are presented in Fig. 18 to Fig. 23. No internal differences were noted in connectors installed without inhibitor before and after thermal cycling. The movement observed on the steel core of the other splice connector installed with inhibitor supports the measured loss of mechanical strength for connectors with inhibitor. It is believed that the remaining connectors would exhibit similar results if subjected to tensile testing.

The loss of mechanical strength of connectors installed with inhibitor is attributed to the higher temperatures reached during thermal-mechanical cycling. The accelerated aging process was more severe on the connectors installed with inhibitor as measured by increased temperature, increased contact resistance and lower remaining tensile strength. Therefore, based on the results of the thermal-mechanical cycling test, the suggestion would be to not use inhibitor compound when installing single stage swaged connectors on ACSR conductor when operation at elevated temperature is expected. The results support that the use of inhibitor, under these conditions, can cause the assembly to reach "end-of-life" conditions earlier than without the use of inhibitor.

Acknowledgment

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