Background Information and Purpose

Underground cable electrical collection systems have become common in renewable generation system applications (wind farms and solar farms). However, the nature of these electrical generation systems (generation on/generation off) has led to larger load cycles on the underground electrical collection system than similar underground electrical systems found in utility distribution systems. The renewable generation load cycles can go from full load to no load while most utility systems will have a base load that adds 15-30% additional load to meet peak demands.

The performance of electrical connectors used in these underground electrical systems can be impacted by these larger load cycles. This study evaluated the temperature of typical compression and shearbolt connectors under medium voltage joints during long term load cycling in order to try and evaluate these impacts. The compression connectors used in this study have been used by utilities in their systems for more than forty years.

Experiment Set Up

Long term current cycle load tests were performed using two different types of connectors with two different installation techniques (wire brushed and not wire brushed). The connector temperatures and connector temperature stability was evaluated. These experiments were performed on min and max cable, 1/0 AWG and 1000 kcmil, 35 kV, JCN underground cable with 345 mils of TRXLPE insulation with strand filled aluminum conductors which were provided by the windfarm customer. The medium voltage splices used in these experiments were standard filled silicone 35 kV splices for 35 kV JCN cables. The sample identifications and comparison of connectors used in the experiments are shown in Table 1 below.

Table 1. Sample Identification and Comparison Connectors Used in Experiments

Sample	Conductor Size	Connector Type	Connector Length mm (inches)	Connector OD mm (inches)	Connector Wall Thickness mm (inches)	Conductor Wire Brushed	Connector Mass of Material grams
Sample A	1000 kcmil	Compression	133 (5.25)	47 (1.84)	16,6 (0.654)	Yes	362
Sample B	1000 kcmil	Compression	133 (5.25)	47 (1.84)	16,6 (0.654)	No	362
Sample C	1000 kcmil	Shearbolt	210 (8.25)	53 (2.1)	19,3 (0.76)	Yes	721
Sample D	1000 kcmil	Shearbolt	210 (8.25)	53 (2.1)	19,3 (0.76)	No	721
Sample E	1/0 AWG	Compression	76 (3.00)	23 (0.91)	13,13 (0.517)	Yes	70
Sample F	1/0 AWG	Shearbolt	123 (4.96)	33 (1.30)	12,95 (0.51)	Yes	178

For this evaluation, current transformers were installed around each cable loop and driven on the secondary side with a variac to induce the current into the cable loops. Thermocouples were placed in the cable conductor, on the connector under the joint, on the cable jacket surface, on the joint jacket surface, and on the conductor lugs. The thermocouples in the conductor and on the connector were two meters apart so there would be minimal thermal coupling between the temperatures. The conductor temperature was monitored and current was applied to the cable to obtain a 90°C conductor temperature with a 24 hour cycle of 9 hours current on and 15 hours current off. A current of approximately 264 amps for the min cable and 1,050 amps for the max cable was required to reach a 90°C conductor temperature. The temperature of each of the thermocouples was taken every hour leading to 24 temperature readings per cycle. Since 3-4 hours were required for the conductor to reach 90°C, the last four temperature readings during the current on period were averaged to determine the connector temperature for each cycle. The loops were continuously cycled until one of the monitored temperatures exceeded 225°C or it was agreed the loop had run for a sufficient length of time. For safety considerations, this was the maximum temperature allowed for any of the thermocouples. The experimental loop set-up is shown in Figure 1 below.

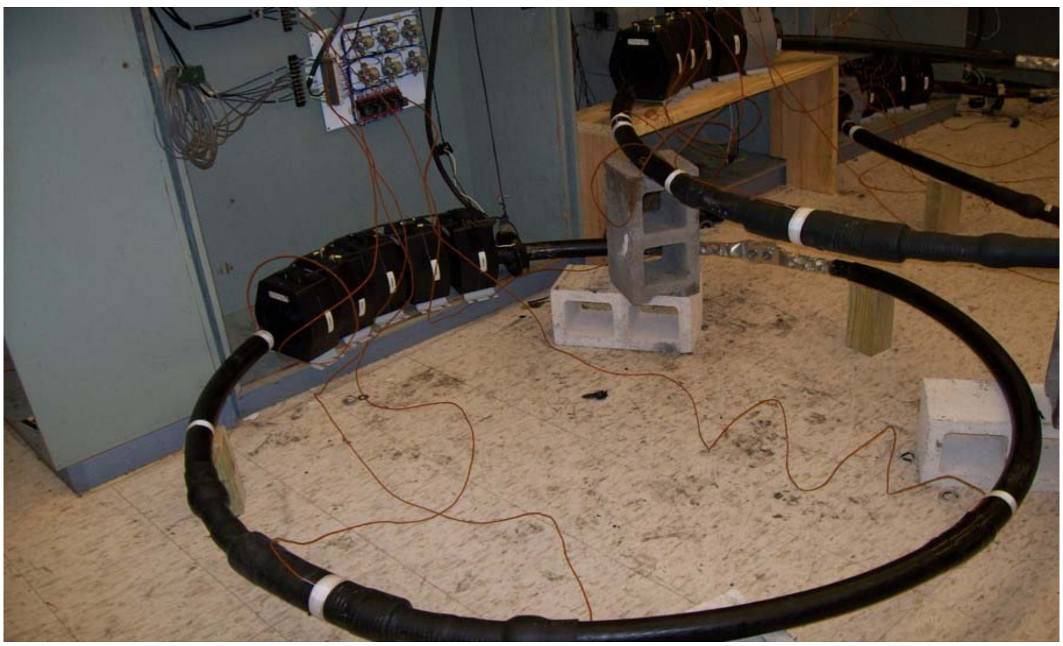
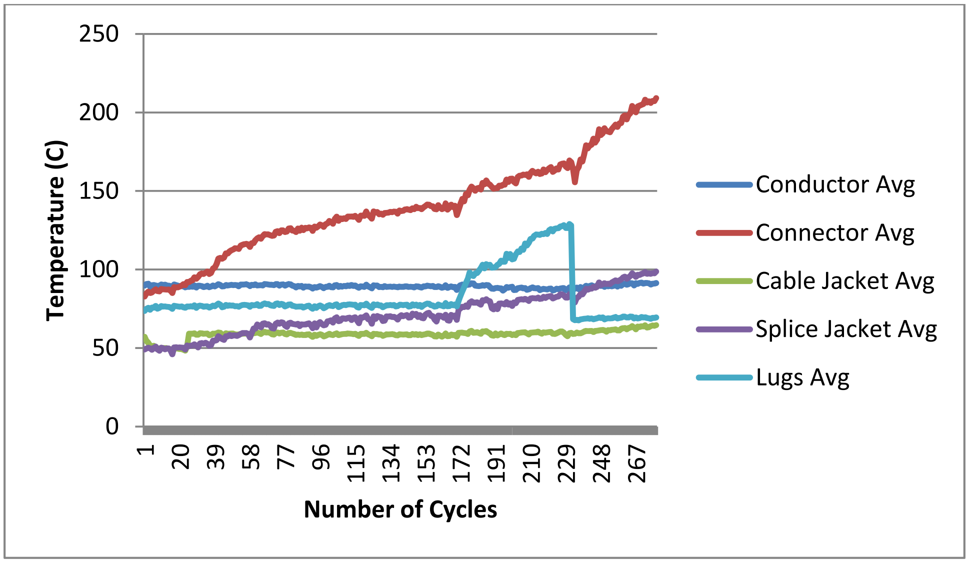


Figure 1. Picture of Current Cycling Experimental Loop Set-Up

Test Data

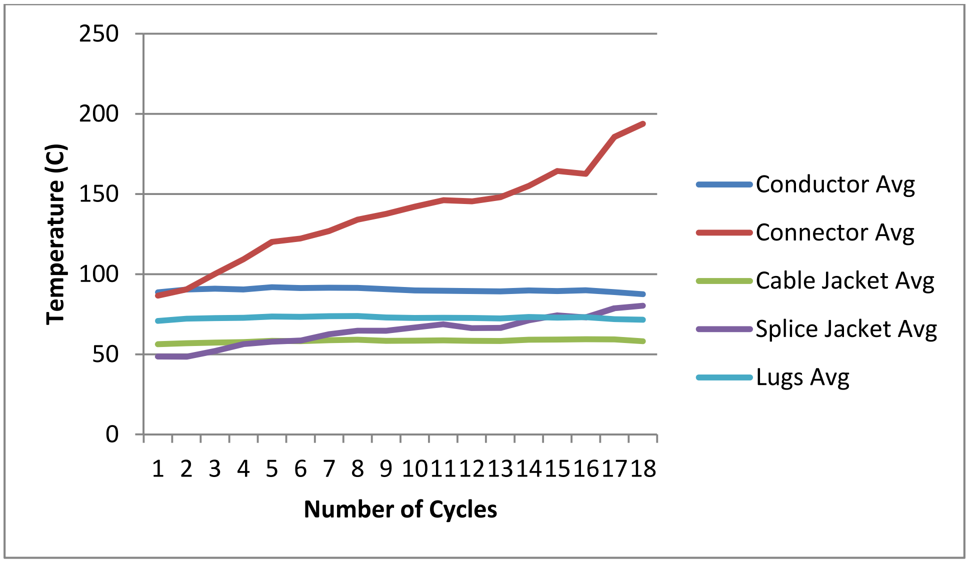
The following Graph 1 shows the data obtained for Sample A compression connector with wire brushing of the conductor during installation. The conductor temperature was held constant at 90°C, but the connector and splice jacket temperature trended upwards over time with increasing cycles. This loop ran for over nine months, until the connector temperature consistently exceeded 200°C and then the test was stopped. Figure 2 shows the inspection of the connector and cable insulation after current cycling. The cable insulation clearly showed discoloration as a result of the extended period of high connector temperatures.



Graph 1. Sample A Using a Compression Connector with Wire Brushing During Installation

Figure 2. Sample A Inspection of Connector and Cable Insulation After Load Cycling

The next Graph 2 shows the data obtained from Sample B using a compression connector without wire brushing during installation. Graph 2 shows that the non-wire brushed compression connector only lasted 18 days in this test before the connector temperature under the joint reached 225^{o}C and shut down the test. The Connector jumped over 20^{o}C per hour right before it tripped. So last plotted value shows to be less than 225^{o}C. These results reinforce the importance of wire brushing conductors before compression connector installation. The splice body was removed and inspected after cycling and the sample is shown in Figure 3. The cable insulation near the connector showed minimal discoloration even though the connector temperature reached 225^{o}C due to the short duration of the sample at the higher temperatures.

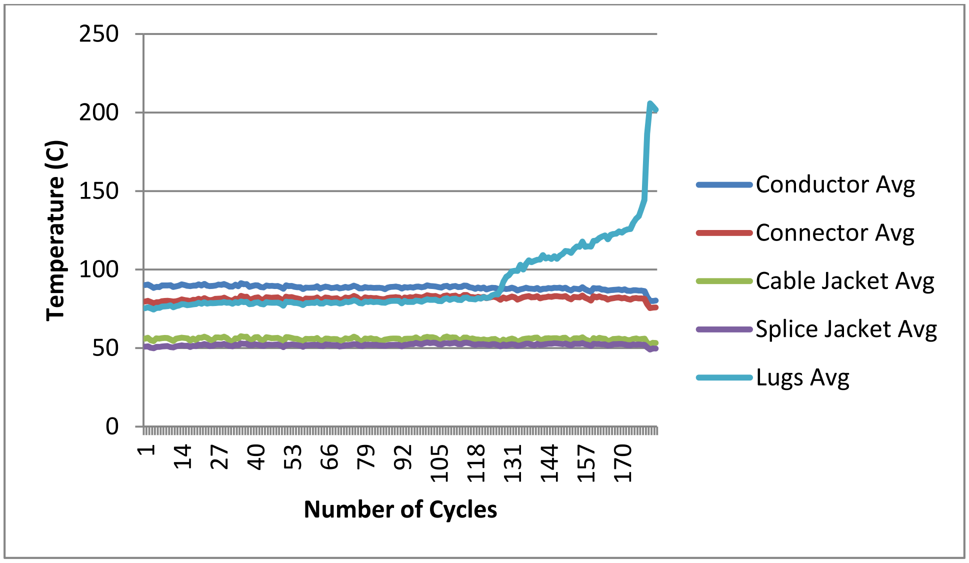


Graph 2. Sample B Using a Compression Connector without Wire Brushing During Installation

Figure 3. Sample B Inspection of Connector and Cable Insulation After Load Cycling

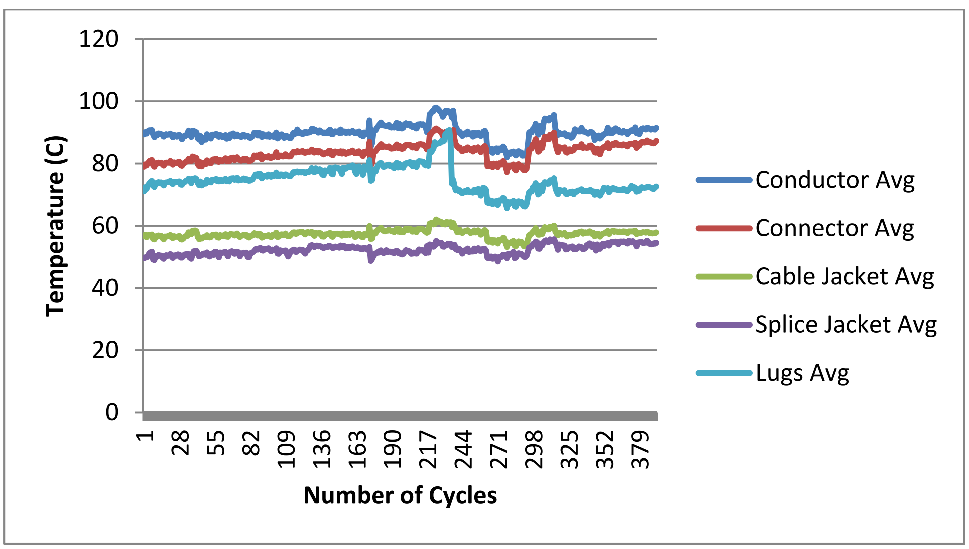
The following Graph 3 shows the results for Sample C using a 1000-1250 shearbolt connector and wire brushing before installation. This test ran for approximately six months and the connector temperature was cooler than the conductor temperature for the entire length of the test. The testing of this loop was ended because of issues with the lugs, which thermally ran away.

When the lug thermally ran away about two feet of cable on each end was damaged and could not be re-used. So the loop was too short to continue the test.



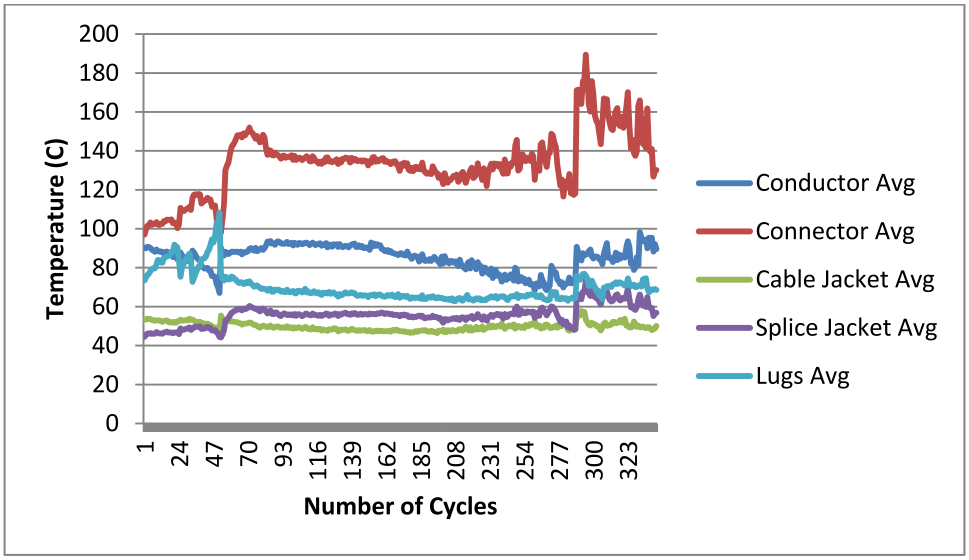
Graph 3. Sample C Using 1000-1250 Shearbolt Connector with Wire Brushing During Installation

The following Graph 4 shows the test results for Sample D using a 1000-1250 shearbolt connector without wiring brushing during installation. The connector temperature has remained consistently below the temperature of the conductor and there is no appreciable difference in connector temperature compared to the shearbolt connector in Sample C using wiring brushing during installation. Middle of testing we had lug issues, so lugs were replaced and crimped on. The test was ended after eleven months, as the test equipment was needed for other testing.



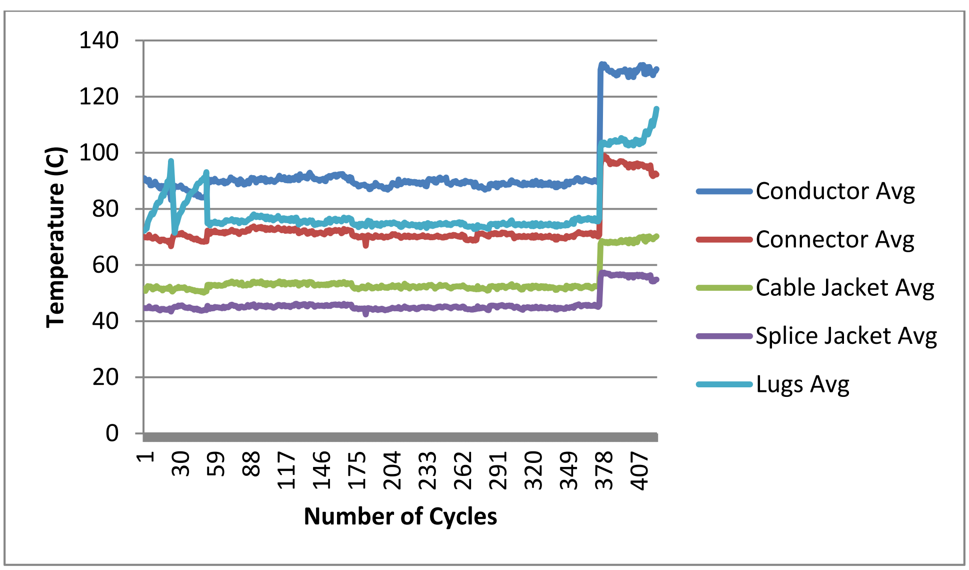
Graph 4. Sample D Using 1000-1250 Shearbolt Connector without Wire Brushing During Installation

The following Graph 5 shows the data obtained for Sample E compression connector with wire brushing of the conductor during installation. The conductor temperature was held constant at 90°C, but the connector is running hotter than the conductor.



Graph 5. Sample E Using a Compression Connector with Wire Brushing During Installation

The following Graph 6 shows the results for Sample F using a 1/0-350 shearbolt connector and wire brushing before installation. The connector temperature was cooler than the conductor temperature for the entire test. The testing of this loop began with lug issues and then was corrected with connecting the loop with a shearbolt.



Graph 6. Sample F Using 1/0-350 Shearbolt Connector with Wire Brushing During Installation

The Table 2 below summarizes the difference in temperature between the connector and conductor for the cycles shown for each test. Blue values indicate the connector temperature was lower than the conductor temperature, and red indicates the connector temperature was higher than the conductor temperature. For the compression connectors, the data indicates the importance of wire brushing during installation. However, the data also clearly indicates that the shearbolt connectors that were tested perform better than the compression connectors for both connector temperature and connector temperature stability. Wire brushing showed no impact on the shearbolt connector results.

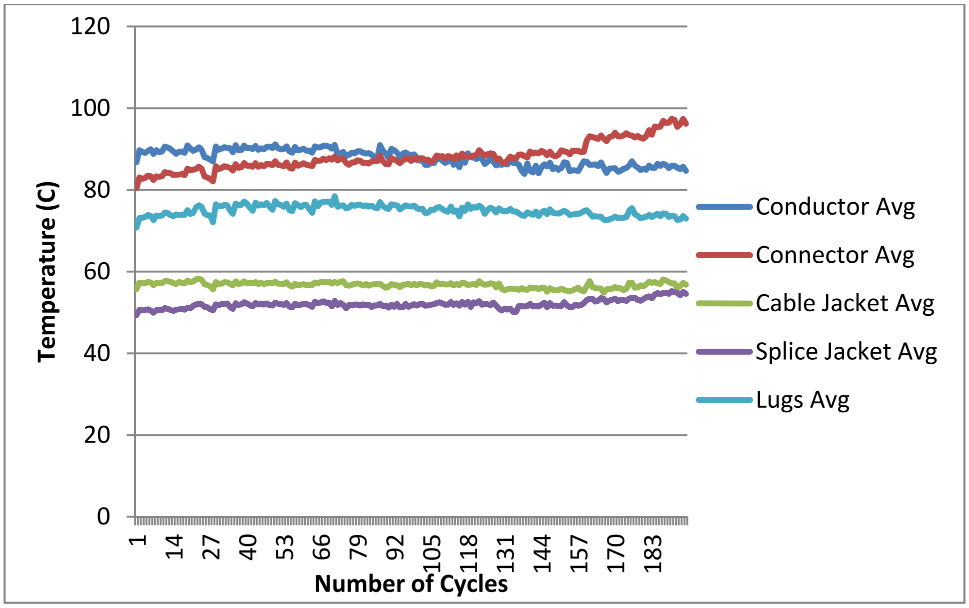
Table 2. Summary of Difference in Temperature (°C) Between Connector and Conductor

Sample	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	18th Cycle	70th Cycle
Sample A - Wire Brushed 1000 kcmil Compression Connector	**7.0**	**6.0**	**5.1**	**4.0**	**1.1**	**31.6**
Sample B - Non-wire Brushed 1000 kcmil Compression Connector	**2.0**	**0.1**	**9.3**	**18.9**	**106.4**	**N/A**
Repeat Sample B - Non-wire Brushed 1000 kcmil Compression Connector	**2.7**	**1.25**	**1.02**	**0.1**	**9.0**	**42.7**
Sample C - Wire Brushed 1000 kcmil Shearbolt Connector	**10.5**	**9.5**	**9.9**	**9.8**	**9.1**	**7.2**
Sample D - Non-wire Brushed 1000 kcmil Shearbolt Connector	**10.4**	**10.3**	**10.2**	**10.3**	**9.0**	**7.3**
Sample E – Wire Brushed 1/0 AWG Compression Connector	**6.7**	**9.7**	**10.8**	**11.0**	**17.8**	**61.7**
Sample F – Wire Brushed 1/0 AWG Shearbolt Connector	**20.9**	**21.0**	**20.5**	**19.8**	**18.4**	**18.0**

Further Investigation

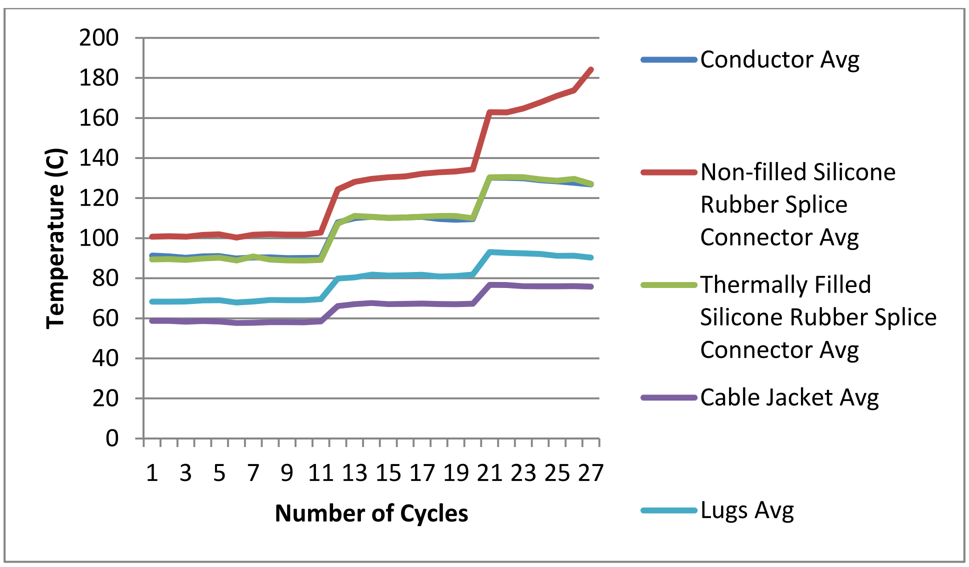
Further investigations were performed with using a wire brushed compression connector under two different 15 kV splice bodies and also using a bigger compression connector with standard silicone filled 35 kV splice. These further tests were set up like the previous long term load cycled loops and ran until 225°C was exceeded.

The following Graph 7 shows a 1000 kcmil connector under a standard silicone filled 35 kV splice during load cycling. This test was done to show that more crimps and more connector mass give connectors better performance. The test loop was on a 1000 kcmil, 35 kV, JCN underground cable with 345 mils of TRXLPE insulation and strand filled aluminum conductors.



Graph 7. Further Investigation Using Bigger Connector under Standard Silicone Filled 35 kV Splice

The following Graph 8 shows two splice bodies with the same compression connector analyzed during this test, a non-filled silicone rubber splice and a thermally filled silicone rubber splice. This test loop was on a 4/0, 15 kV, JCN underground cable with 220 mils of TRXLPE insulation and strand filled aluminum conductors. Graph 8 shows that the non-filled silicone rubber splice connector thermally ran hotter than the conductor and the thermally filled silicone rubber splice connector thermally ran at the same temperature as the conductor. This test ran for a month and then the non-filled silicone rubber connector thermally ran away and shut down the test.



Graph 8. Further Investigation Using Different Splices but Same Compression Connector

Summary

Because of the long term nature of this test and the size of the samples, there was only one sample of each configuration tested. Replication of test loops would be useful to validate and quantify differences between connectors and preparation techniques. In addition, this testing does not claim to represent the performance of all compression style connectors or all shearbolt style connectors. This evaluation is an accelerated test versus field conditions due to the current applied to the conductor. Typical field conditions will limit current loads to 600 amps or less due to system configurations and 1050 amps was used in this testing. Therefore, this test is designed as a comparison test to evaluate connector temperatures under long term cyclic loading.

However, the results indicate that connector selection and installation along with splice housing can play an important part of enabling a long term reliable underground electrical system that will experience significant load cycling. Wire brushing of conductors during installation of compression connectors appears to have a significant impact on long term compression connector performance. Additionally, the shearbolt connectors used in this test clearly showed better temperature and stability performance compared to the compression connectors and exhibited good long term performance during heavy load cycling. To ensure a reliable system evaluation of the joint and connector should be confirmed in a thermal evaluation.