PLP Model TLSP-795 Splice Connector
Current Cycle Qualification Test

Preformed Line Products
Purchase Order 50167

NEETRAC Project Number: 04-091

November, 2004

Requested by: John Olenik
PLP

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SUMMARY:

Preformed Line Products contracted with NEETRAC to perform the ANSI C119.4 current cycle qualification tests on a connector for 3M's 795 kcmil ACCR conductor. The ANSI C119.4 methods and acceptance criteria were modified to reflect the operating temperature limits for ACCR conductor. The connector performed well by running much cooler than the conductor. The connector met the temperature stability criterion, but marginally failed to meet the resistance stability criterion. It is considered likely that small resistance variation is a characteristic of the formed wire connector design. The ANSI stability criterion is intended for compression connectors, and may not properly measure performance of the formed wire design. There is no evidence of performance degradation after 500 cycles from room temperature to 240^{o} C, and 100 additional cycles from room temperature to 300^{o} C.

KEY FINDINGS

1) The splice excels on ANSI criterion 1 (low operating temperature). The splice is massive relative to the control conductor, and runs typically 173 degrees cooler than a 240^{o} C conductor, and 220 ^{o} C cooler than a 300^{o} C conductor.

2) The splice meets ANSI criterion 2 (temperature stability). Changes in control conductor temperature appear to affect the temperature stability more than changes in the splice temperature.

3) The splice marginally fails criterion 3 (resistance stability). However, there is no evidence of performance degradation. Splice resistance is characteristically low, and small variations within a narrow range may be a characteristic of the formed wire design.

SAMPLES

1) 15 meters (60 feet) of 795 ACCR conductor

2) One (1) PLP Model TLSP-795 full-tension splice connector for 795 ACCR (special design)

PROCEDURE

Testing was conducted in accordance with a NEETRAC procedure entitled "PRJ04-091, CONFIDENTIAL – ANSI C119.4 – 500 Cycle Testing on TLSP-795 Full Tension Splice". The procedure controls all technical and quality management details for the project.

The splice and ACCR conductor sample were provided by PLP. The test sample was constructed in accordance with the following procedure:

1) Stainless steel automotive-style hose clamps were applied to the conductor on both sides of any cut to keep the strands locked in the "as manufactured" position.
2) The conductor OD was thoroughly abraded using a conductor V-brush.
3) Immediately following wire-brushing, Alcoa Filler Compound (AFC) was liberally applied to the conductor OD to prevent oxidation of the fresh aluminum surface. AFC is a gritted inhibitor compound specified for Alcoa compression connectors. PLP directed that it be used for the formed-wire splice.
4) Inner and outer splice rods were hand-wrapped to join two conductor sections in accordance with PLP installation instructions. The rods were started at the center, and wrapped towards the free-span end of the splice.
5) The sample free ends were unstranded (broomed) outboard of hose clamps installed to keep the conductor strands locked in the "as-manufactured" position. The broomed ends were fitted with a special cast-resin fitting. The fitting is a NEETRAC design normally used for tension testing of ACSR and ACCR conductors. The cast resin ensures that all conductor strands are loaded equally, and in the position preserved by the hose clamps applied when the sample was cut from the reel. The end fittings were positioned to provide for a bare four foot conductor section to use as the "control" conductor as defined in ANSI C119.4.
6) The sample was installed in a sustained load frame, and pulled to 15% of the conductor's rated breaking strength. 3M's published RBS for 795 ACCR conductor is 31,134 lb. Tension level used for the test was 4,670 lb. A lead-screw under feedback control was used to maintain tension to compensate for creep and temperature changes. A dead band of +/- 300 lb (+/- 0.1% RBS) was programmed to permit some tension variation during the test.
7) The test system was instrumented for tension, temperature, and load actuator movement. An automatic data acquisition system recorded all parameters except for current on a two-minute interval for the duration of the test. The loop current was measured with a hand-held clamp-on ammeter, and recorded manually. Thermocouple temperature sensors were installed by prying open the conductor strands, inserting a sheathed thermocouple, and then letting the strand clamp the probe in position. Temperature sensors were placed in the following locations:
    a. Ambient (in an aluminum bar remote from the direct influence of the hot sample)
    b. Control surface at center of span
    c. Control core at center of span
    d. Splice, center in first layer of rods
    e. Splice, center, in second layer of rods
    f. Splice, center, at conductor surface
    g. Splice, center, and conductor core
    h. Conductor surface, north end at last rod
    i. Conductor surface, south end, at last rod
    j. Conductor surface, six (6) inches from last rod, south end
    k. Conductor surface, twelve (12) inches from last rod, south end

l. Conductor surface, eighteen (18) inches from last rod, south end
m. Conductor surface, twenty-four (24) inches from last rod, south end
n. Splice, 1 st layer, six (6) inches from end of 1 st layer rods, south end
o. Splice, 1 st layer, six (6) inches from end of 2 nd layer rods, south end
p. Splice, 2 nd layer, six (6) inches from end of 2 nd layer rods, south end

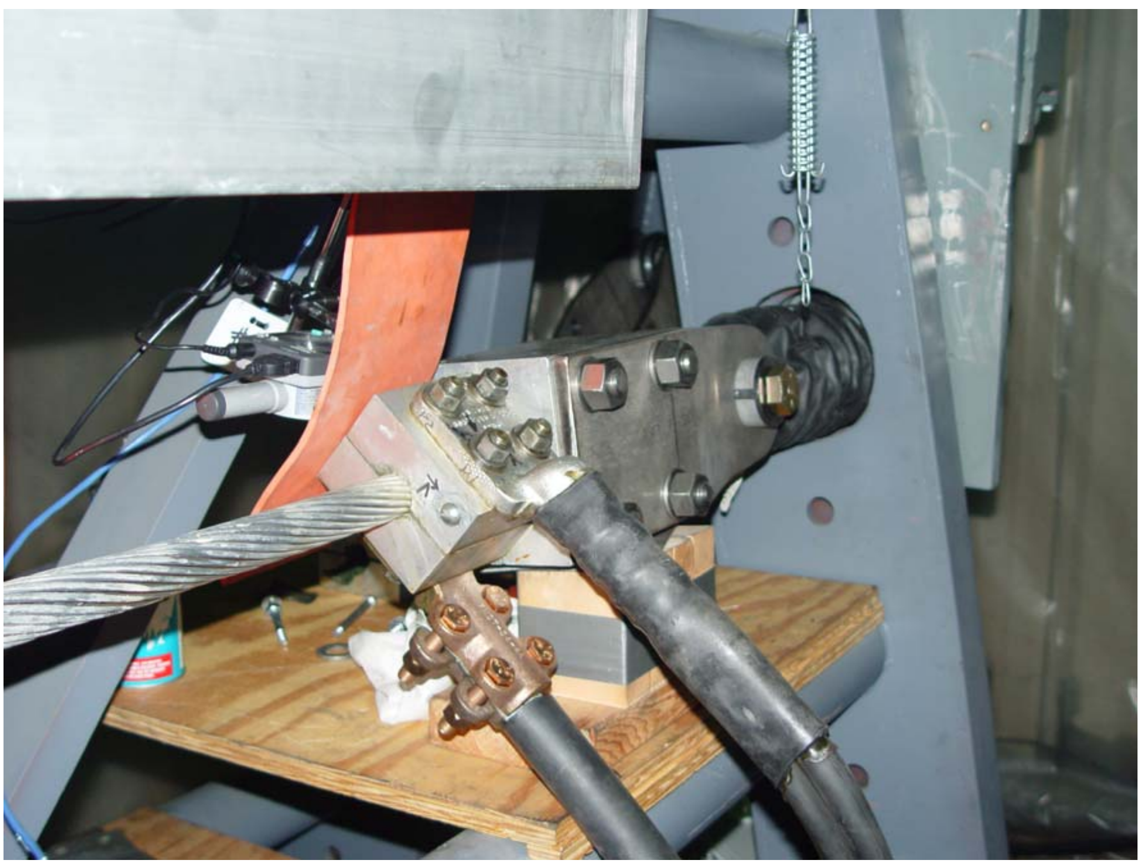
8) A high-current AC power supply was connected to the loop. Current was adjusted to obtain a steady-state control conductor surface temperature of 240° C. Current measured 1780 Amperes for the required steady-state temperature. Loop current was not adjusted during the test, because previous experience with other 3M test loops showed that current adjustments resulted in problems meeting the nominal temperature stability criteria in ANSI C119.4. Cycle timing was set for 90 minutes on and 90 minutes off, in accordance with the requirements of ANSI C119.4.
9) For pre-conditioning, 25 complete temperature cycles (3 days) were completed to ensure the conductor creep was near final, and the splice components were completely settled.
10) Initial resistance was measured for both the control conductor and the splice. Splice resistance was measured between equalizers located 2 feet outboard of the splice, in accordance with the ANSI C119.4 requirements.
11) The test was run for 500 complete thermal cycles. The test was cooled to ambient, and resistance measured at cycles 25, 50 75, 100, 125, 165, 205, 250, 325, 405, and 500 as stipulated in ANSI C119.4.
12) After 500 complete thermal cycles to 240° C, the loop current was adjusted to raise the control conductor surface temperature to 300° C. One hundred thermal cycles were completed at the higher temperature.

The profile differs from the ANSI C119.4 in the following respects:

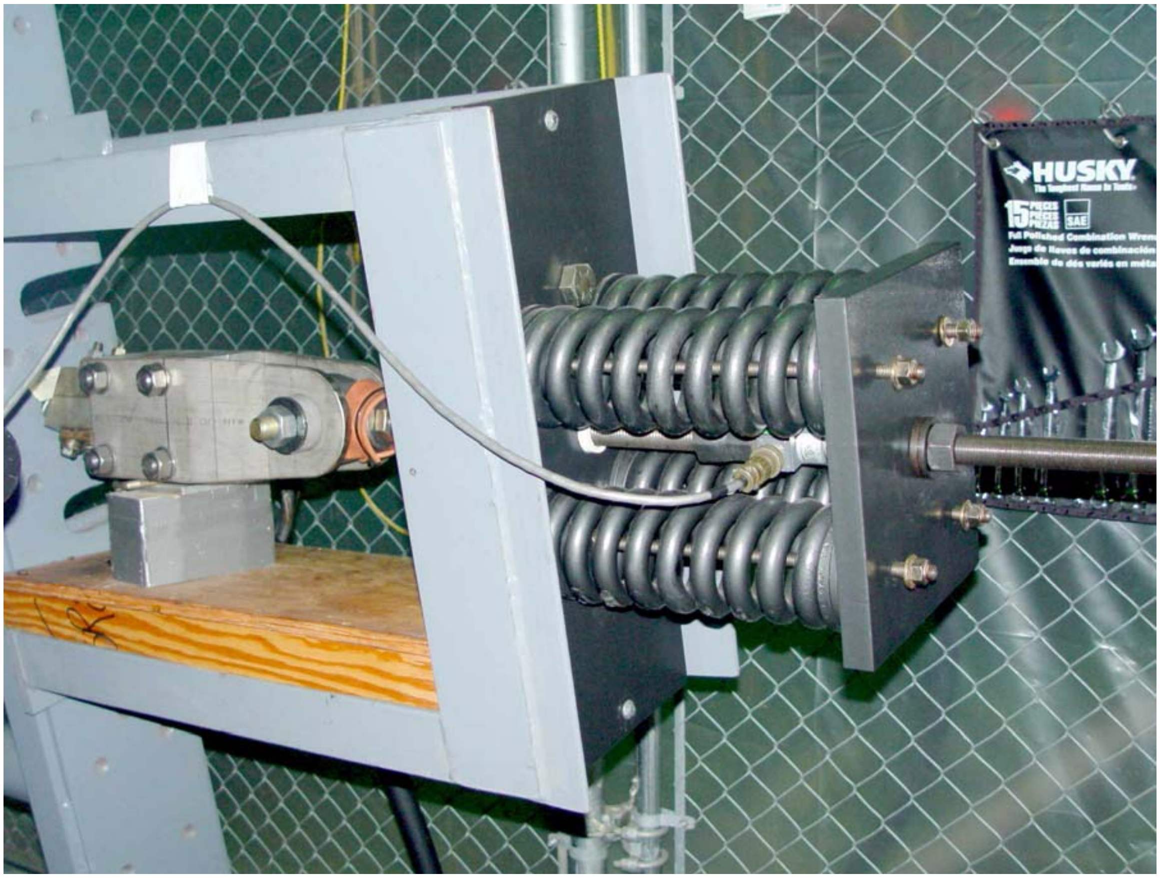
1) Control conductor temperature was 240° C, instead of 100° C rise above ambient (typical control conductor temperature is 123° C).
2) At the end of the standard 500 thermal cycles, 100 additional cycles were completed with the control conductor maximum temperature of 300° C.

Photographs 1 through 4 show the connector test loop during the test.

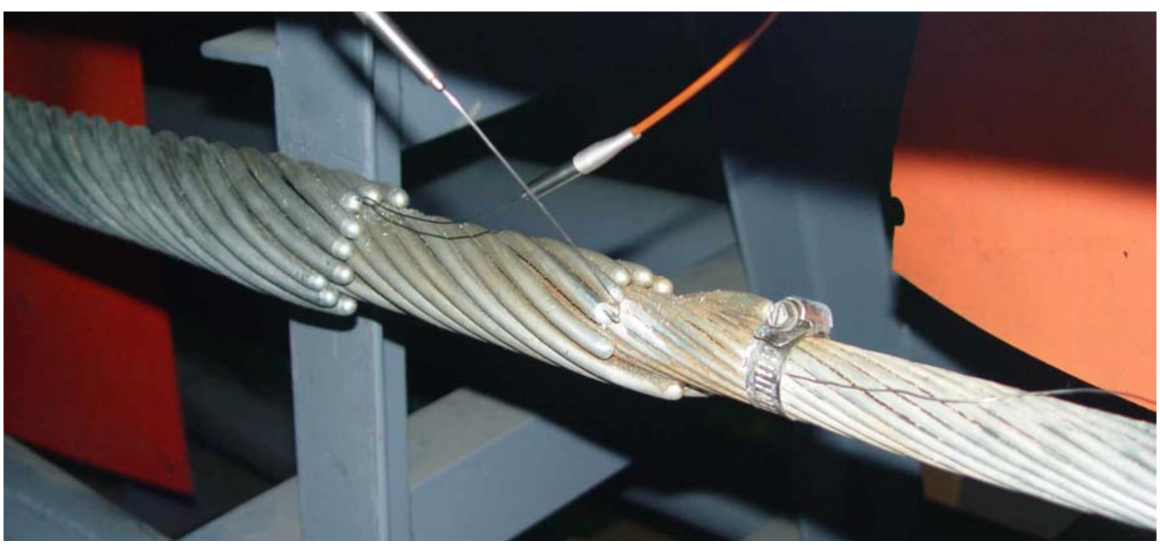
Photograph 1, long view of the splice sample under test



Photograph 2, current termination (foreground), and resin fitting (background)



Photograph 3, end opposite load actuator. Load cell is located in center of spring cluster


Photograph 4, splice end showing thermocouple installation

RESULTS

Figure 1 shows a typical heat-up and cool-down cycle for the splice sensors, control conductor, and room ambient. Figure 2 shows typical data for the 300° C phase of the test. ANSI C119.4 requires a 500-cycle test for connector qualification. The extra 100 cycles at 300 ° C were specified to demonstrate performance in excess of the ANSI requirements.

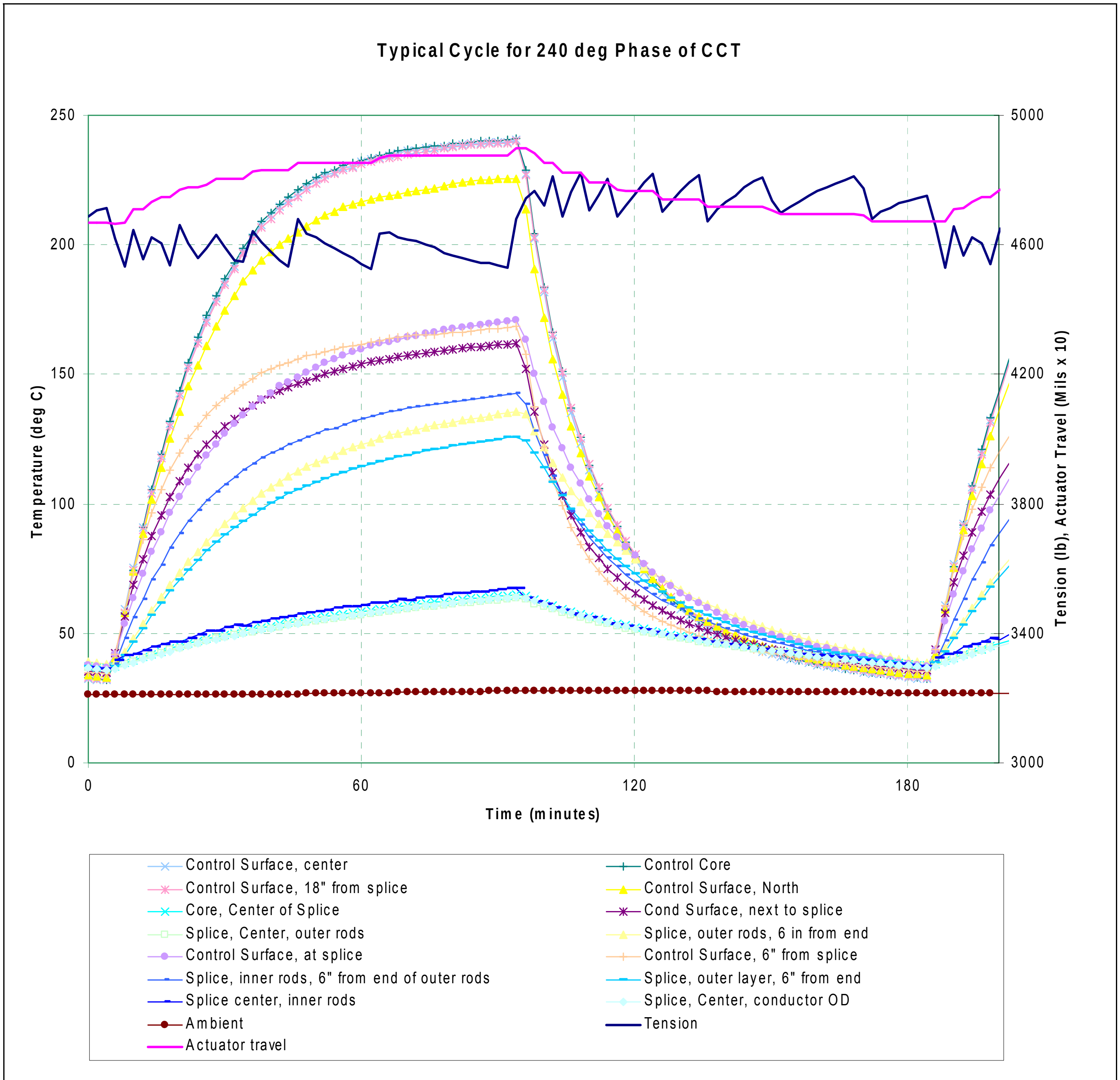


Figure 1, typical data for one complete cycle for 240° C CCT

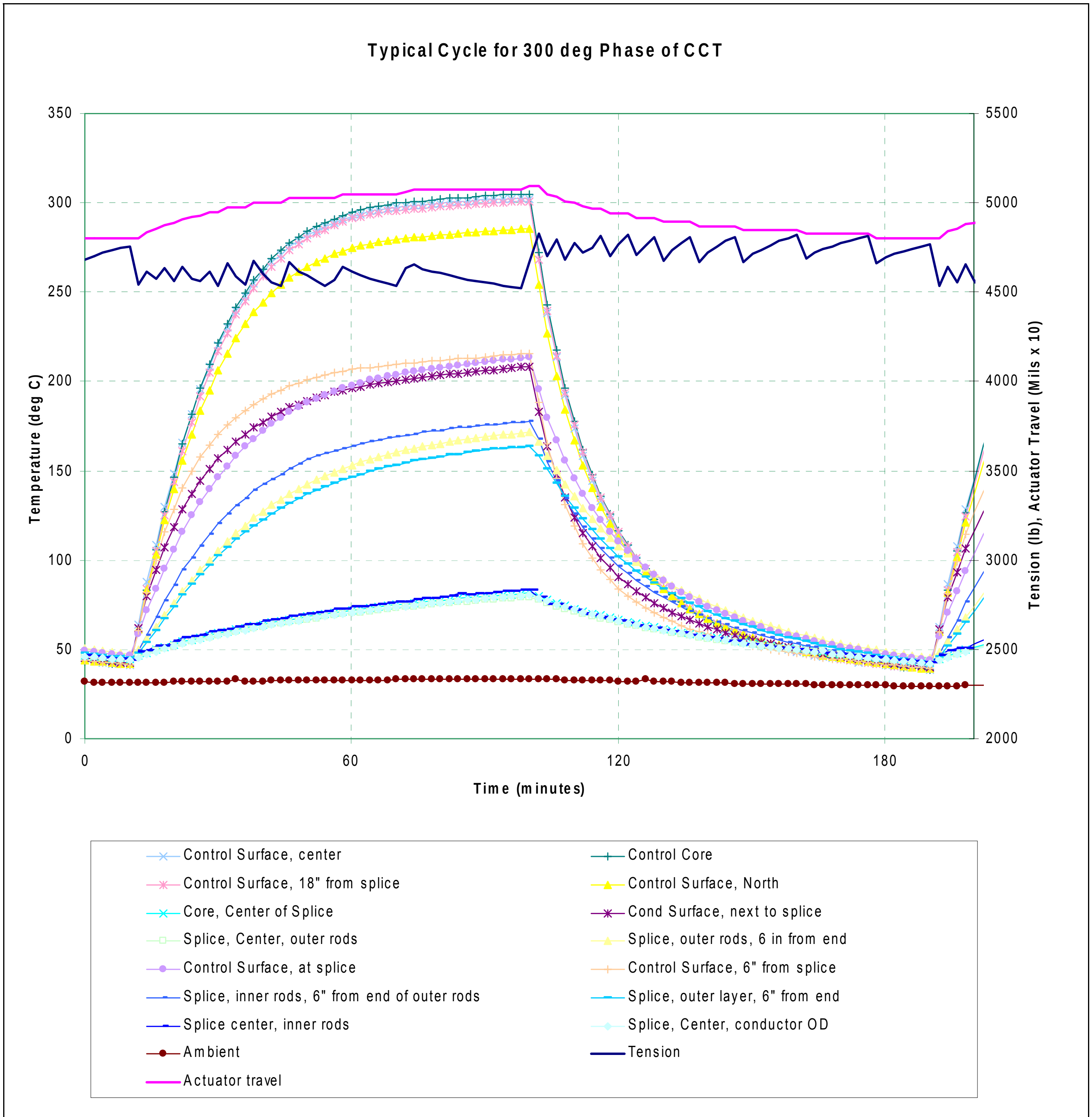


Figure 2, typical data for one complete cycle for 300° C CCT

To qualify under the ANSI C119.4 standard, a connector must display the following three attributes:

1) Connector temperature at the end of the heating cycle must not exceed the temperature of the control conductor.

2) Temperature difference between the connector and control conductor must be stable within 10° C of the average temperature difference exhibited during the 500 cycles.

3) Connector resistance must be stable during each measurement within 5% of the average resistance exhibited during the test.

Criterion 1 ensures that a connector's size (convection cooling area), and resistance (heat generation) are appropriate to ensure that annealing and other thermal effects are not more severe at the connector than in the free span. Criteria 2 and 3 are based on observations and theory that splices approaching failure begin to exhibit unstable temperature and resistance behavior well before resistance increases to the point that connector temperature exceeds the free span temperature.

Performance versus the ANSI C119.4 Acceptance Criteria:

Criterion 1: Connector temperature at the end of the heating cycle must not exceed the temperature of the control conductor.

See Figure 3 for a chart illustrating the behavior of the connector relative to the control conductor. The splice is massive relative to the control conductor, and runs typically 173 degrees cooler than a 240^o C conductor, and 220 degrees cooler than a 300^o C conductor.

Criterion 2: Temperature difference between the connector and control conductor must be stable within 10^o C of the average temperature difference exhibited during the 500 cycles.

See Figure 4 for a chart showing the resistance temperature stability and the minimum acceptance criterion. The 10^o C temperature stability limit is intended for a control conductor temperature of 100^o C above ambient, or approximately 125^o C. At 240 ^{o} C, control conductor temperature is more variable, and the 10^o C margin is difficult to maintain even on the control conductor. The connector in this case runs much cooler than the control. Accordingly, most changes in the temperature difference are caused by change in the control conductor temperature. Figure 3 shows that the splice is stable, but the control temperature is affected by small changes in ambient conditions and in the power supply current. The temperature variations observed in Figure 4 are caused predominantly by variable control temperature. Values are recorded every cycle, but non-typical cycles were excluded to prevent values that exceeded the acceptance criterions. For example, upon start-up after the test is cooled for resistance measurements, several cycles are required before the connector reaches repeatable cycle temperature. Therefore, cycles where the control temperature was more than +/- 5 ^{o} C from the 240 ^{o} C target were not included in the evaluation. The ANSI standard has relatively sparse data collection requirements, and the cycles shown are well in excess of the minimum required. Note that readings are rejected on an objective basis (control temperature more than +/- 5^o C, and are not "hand picked" to reject failing values. This process has been necessary for qualification of compression connectors for high-temperature conductors.

Criterion 3: Connector resistance must be stable during each measurement within 5% of the average resistance exhibited during the test.

See Figure 5 for the chart illustrating the resistance stability behavior. Resistance values fall outside the ANSI C119.4 resistance stability acceptance criterion. This result is not consistent with the temperature performance, and there was no overall trend to indicate the connector was degrading. There was a close examination of the following variables to determine the cause for the apparent anomalous behavior. See discussion following Figure 5 for possible explanations.

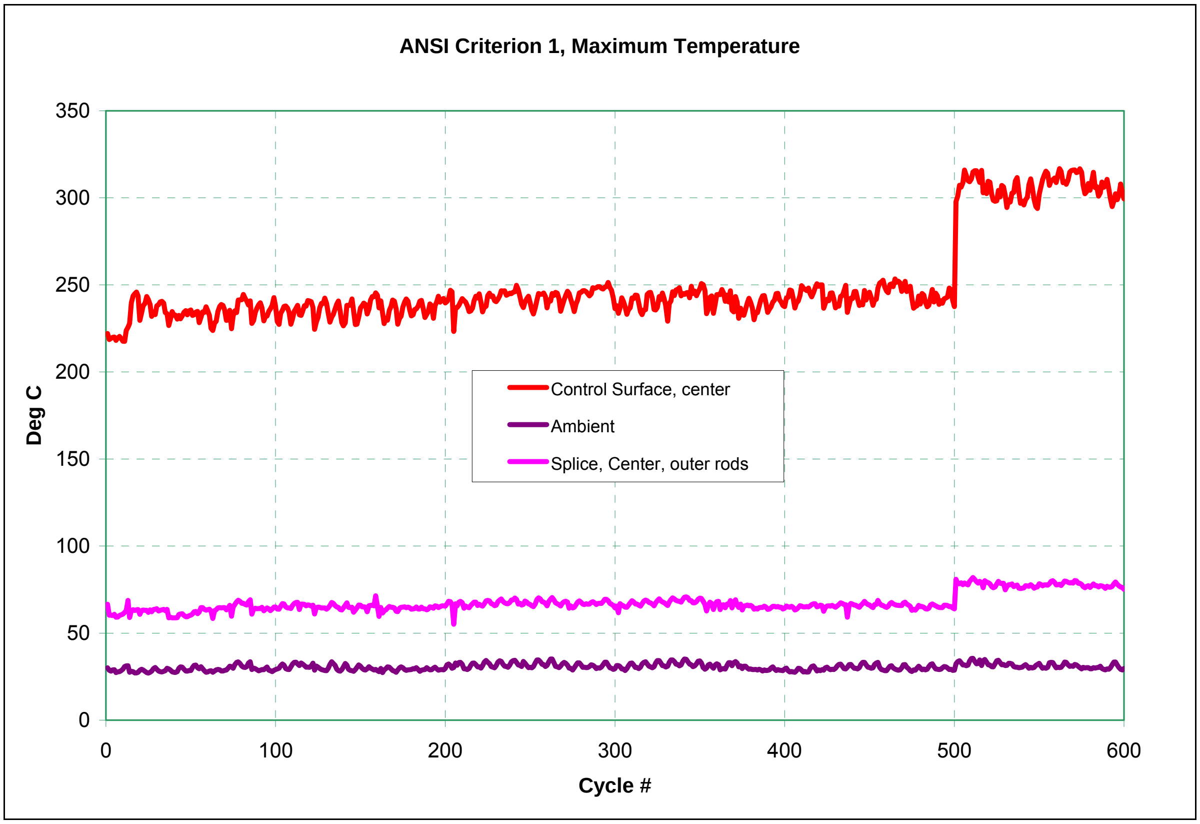


Figure 3, Connector performance under ANSI criterion 1. Data from every cycle are shown

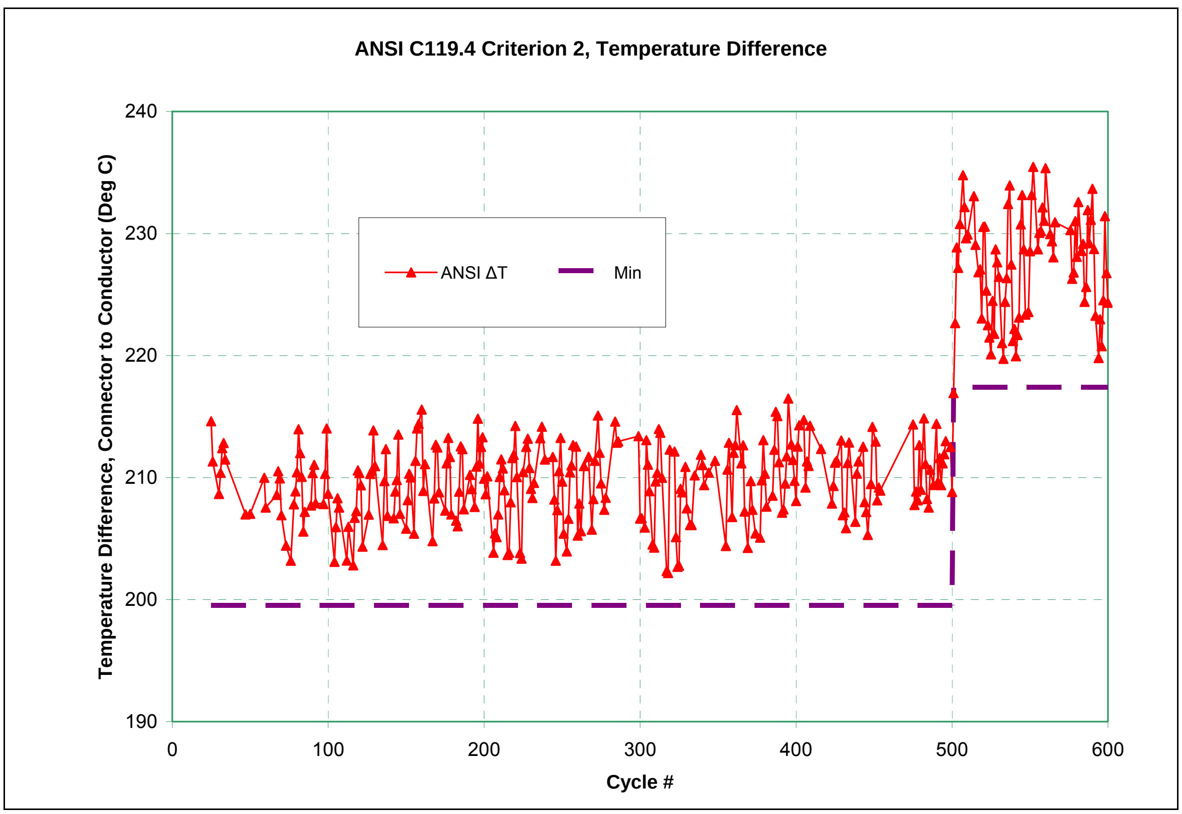


Figure 4, connector performance under ANSI C119.4 criterion 2, temperature difference. Cycles where the control temperature missed the target by more than +/- 5° C are omitted

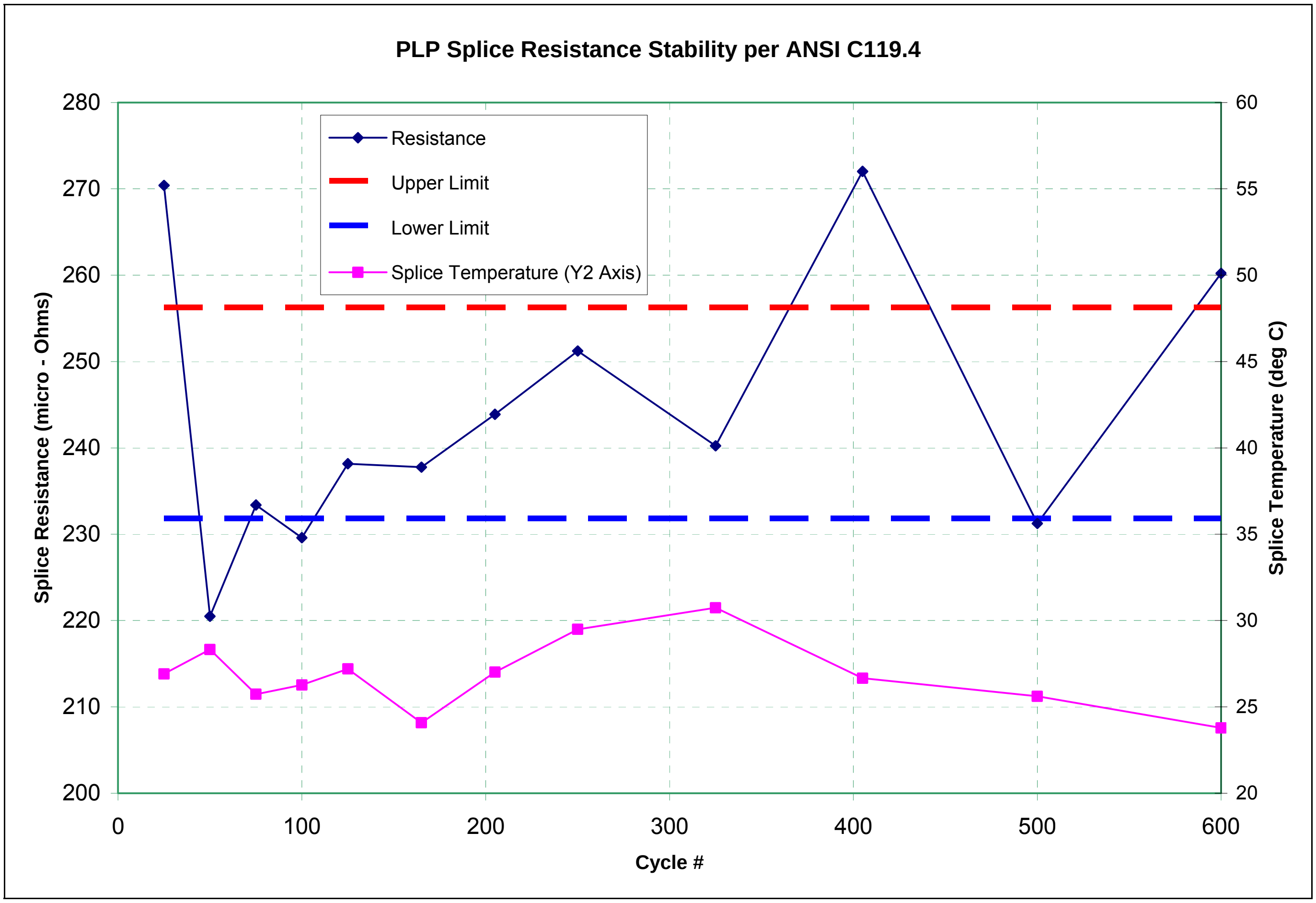


Figure 5, connector performance under ANSI C119.4 criterion 3, resistance stability

The connector technically fails the resistance stability criterion. However, the results are not consistent with splice performance on criteria 1 and 2. There was a careful investigation to determine if there was a problem with the test or the measurement method. The following were investigated:

1) Instrument drift: The AVO low resistance Ohmmeter has a temperature-stable resistance reference, and is certified accurate within +/- 0.2% of reading. The instrument was checked against a resistance standard, and no problems were found. Previous experience with the instrument has been good. Therefore, instrument problems are not considered a likely explanation.

2) Tension effects: Tension was adjusted to a reference value each time the resistance was taken. The tension was recorded each time the resistance was taken. Checking resistance at different tension values showed minimal resistance change. Therefore, tension effects are not considered the explanation for the apparently unstable resistance readings.

3) Temperature effects: Aluminum and its alloys increase in resistance by approximately 0.4% per degree C. Experimental readings are adjusted to a reference temperature of 20^{o} C to provide for consistent comparisons. Figure 6 shows the splice resistance measured during a cool-down cycle. The line should be linear, but there is considerable curvature at high temperature. This is likely due to temperature gradients within the sample when the cooling rate is high. Near room temperature, the resistance temperature coefficient is linear, and the value is close to the 0.0036 value used for correcting resistance values to the 20^{o} C reference stipulated in ANSI C119.4.

4) Annealing effects: The aluminum-zirconium alloy used in the 3M conductor has unusual annealing properties. Most EC grade aluminum conductor materials exhibit annealing (softening) at temperatures above 90° C. Annealing affects resistance, and therefore annealing effects are a possible explanation. As part of the test, the control conductor resistance was measured each time the splice resistance was measured. Results are presented in Figure 7. As Figure 7 illustrates, even the control conductor does not meet the ANSI C119.4 resistance stability criterion. Note that in the case of the control conductor, the total resistance is very small, and normal measurement problems account for some of the apparent instability in the resistance values.

5) Sample changes: It is considered possible that a formed wire splice will not have stable resistance because the dominant current path through the numerous contact points shifts due to temperature and tension effects during the test. In a compression connector, the contacts are essentially fixed during the compression operation. The formed wire design possibly allows for microscopic movement, and that may account for resistance changes from one cycle to the next. Sample temperature remains extremely low, and there is no overall trend to indicate degradation even with the conductor operating at 300° C .

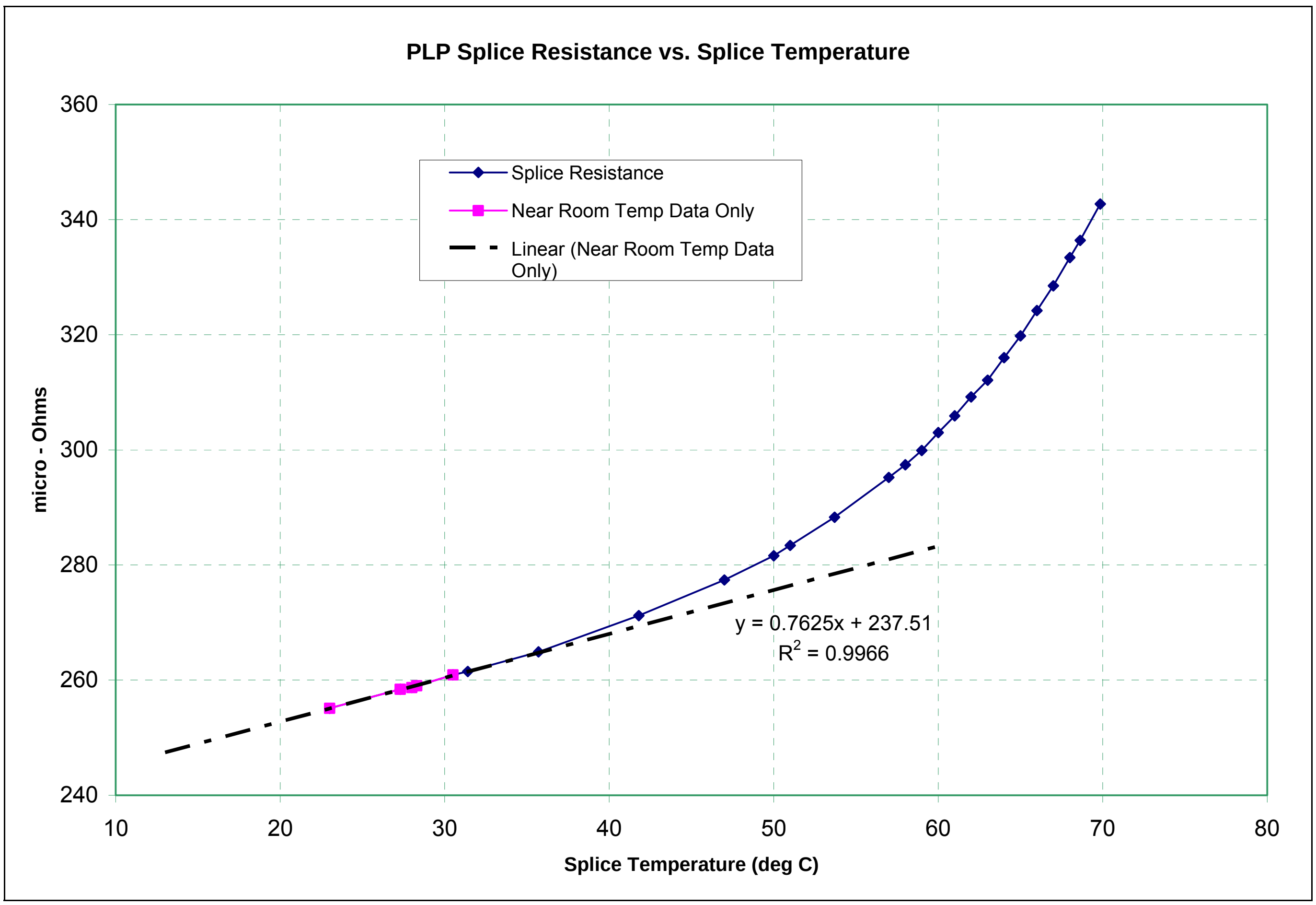


Figure 6, effect of splice temperature on resistance reading

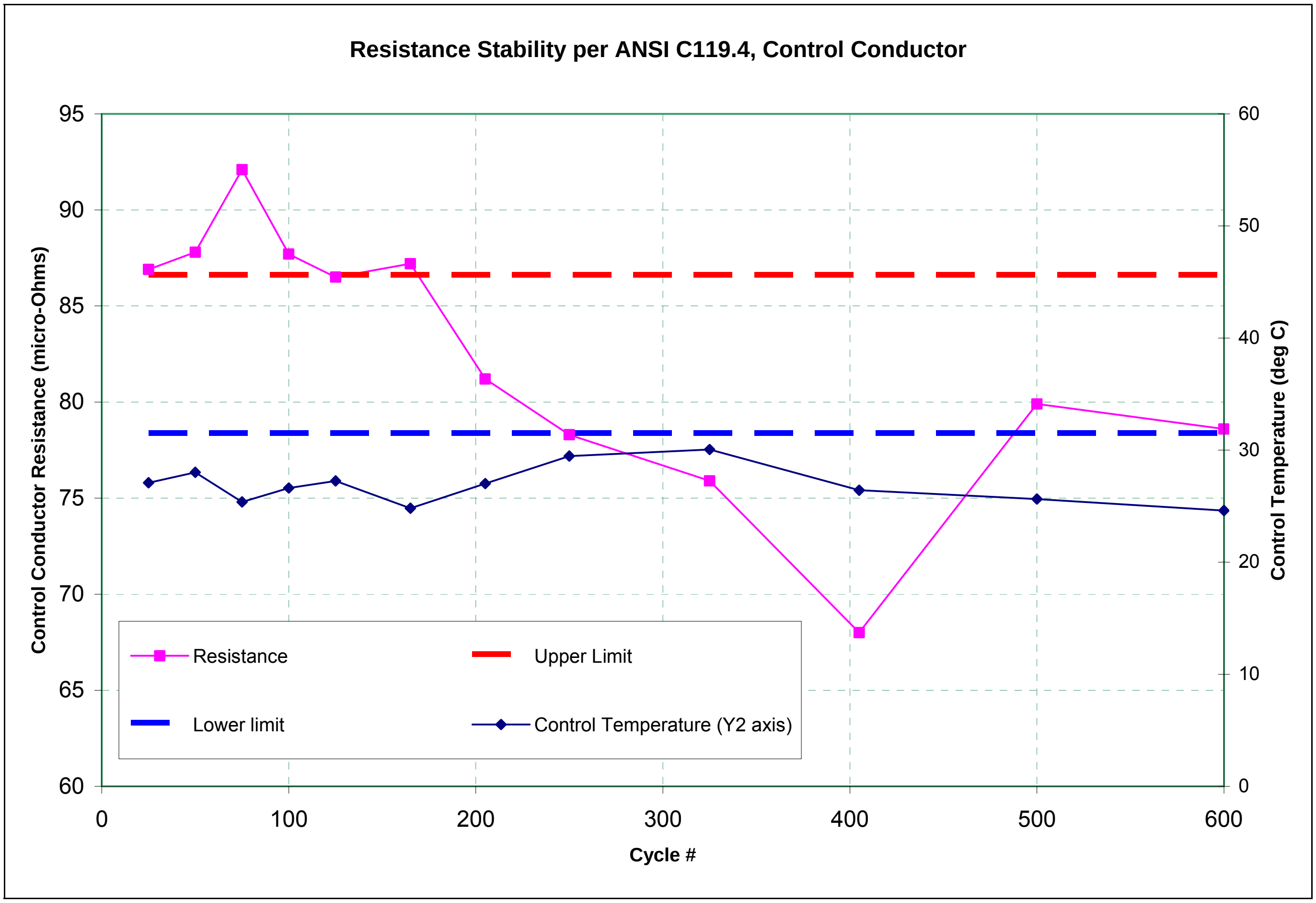


Figure 7, performance of control conductor to the ANSI resistance stability criterion
Note the total change is 0.000024 Ω, a value close to the measurement lower limits

CONCLUSION:

PLP Model TLSP-795 full-tension splice connector is considerably larger than typical compression or implosion connectors. Accordingly, the operating temperature is considerably lower than is typically seen for other connector types. Despite low operating temperatures, connector exhibits marginal performance for temperature stability, and marginally fails the ANSI criterion for resistance stability. However, there is no evidence of splice degradation after more than 500 cycles to 240^{o} C, and 100 cycles to 300^{o} C. Anomalous test results could be caused by the design of the formed-wire connector, where the electrical contacts are more mobile than those inside a compression connector. The most likely explanation for less than complete stability is microscopic movement of the numerous contact points between the formed wire rods and the conductor. The movement would be driven by temperature and tension changes as the connector is thermally cycled. There is no evidence to suggest negative performance trends. There is also no evidence from the test lines to suggest performance degradation with the PLP splice. Therefore, it is considered reasonable to assume that the connector is reliable, and strict interpretation of the ANSI criteria may not be applicable to the formed-wire design used for this connector.

EQUIPMENT LISTING

1) AVO/Biddle digital low-resistance Ohmmeter, Calibration Control # 1083
2) NEETRAC Creep/sustained load frame
3) LabView PC data acquisition system, Control # CN 3040
    a. National Instruments AT-MIO-16XE-50 computer interface card
    b. BNC 2090 voltage interface (tension measurements).
    c. Omega Engineering OMR 6018 thermocouple conditioner
4) Lebow 25,000 lb load cell and DMD 465WB conditioner, Frame “A”, Control # CN 3057
5) Mitutoyo digital position indicator, Control # CN 3042
6) Omega Engineering type T sheathed thermocouples (calibrated with CN 3040)
7) Limitorque lead-screw actuator, controlled by Measurement Computing CIO SERB-08 PC relay control board.
8) High current AC test set, Control # CN 1045.

REFERENCES AND STANDARDS LISTING

1) ANSI C119.4 - 2003, “American National Standard for Electric Connectors – Connectors for Use between Aluminum to Aluminum or Aluminum to Copper Bare Overhead Conductors”