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POWERTECH LABS INC.

CONNECTABILITY TESTING OF COPPER AND ALUMINUM WIRING, PHASE 2:

Current Cycling Tests – Mechanical Connectors

PROJECT PL-00236

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1. EXECUTIVE SUMMARY

The objective of this study was to compare the electrical connectability of #1 AWG copper and #2/0 AWG 8000 series aluminum wire for use in low-voltage electrical power distribution applications. This report describes the current cycling test component on mechanical screw-type connector samples. The test connectors were standard single screw lug connectors obtained from local industrial electrical suppliers. The aluminum wire test samples were prepared with and without abrasion of the conductor surface, with and without oxide inhibitor applied to the conductor, and with the set screw tightened to 70%, 100%, and 125% of the rated torque. The copper wire samples were prepared without abrasion and without oxide inhibitor, and with the set screw tightened to 70%, 100%, and 125% of the rated torque.

The wire and connector samples were subjected to accelerated ageing by current cycling using the test procedures outlined in IEC 61238-1 as a guide. Test samples were subjected to 1500 current cycles in a high humidity environment with the temperature of the conductor cycling from room temperature to 100°C rise above ambient and back to room temperature in a period of 2.25 hours. Short circuit current was also applied to each sample after 200 current cycles were completed. The dc resistance and peak temperature of each sample was monitored during the test.

The overall conclusions from the testing are as follows:

1. The **copper mechanical connectors on copper wire** had the most stable resistance and temperature readings, and performed the best during the test.

2. The **aluminum (dual rated) mechanical connectors on copper wire** performed relatively poorly during the test, with 1/3 of the samples failing or showing elevated resistance and temperature levels by the end of the test.

3. The **aluminum (dual rated) mechanical connectors on aluminum wire** performed very poorly during the test, and had a very high failure rate even before the mid-point of the test. Over 90% of the samples had either failed or showed elevated resistance and temperature levels by the end of the test. There was no clear correlation between conductor preparation method, torque level, and failure, except that the connectors that had been torqued to 125% of the rated torque level performed marginally better than the others.

2. INTRODUCTION

The objective of this study is to compare the electrical connectability of copper and aluminum wire for use in low-voltage (<1000 V) electrical power distribution applications. The wire and connector samples used in the testing were obtained from local North American suppliers. The work was done at the request of the International Copper Association Ltd. (ICA), and was carried out at Powertech Labs, Surrey, B.C, Canada from July 2013 to February 2014.

This report describes the Phase 2 (current cycling test) component of the testing on mechanical screw-type connector samples.

3. TEST SAMPLES

3.1 WIRE

The wire was obtained from a local industrial supplier (Texcan) by Powertech Labs. The wire was standard, stock product that was supplied in the absence of specifying the manufacturer when ordering.

The wire samples used for the testing are listed below in Table 1.

Table 1. Wire samples used in the testing.

Manufacturer	Size	Type	Model	Rating	Voltage
BICC	1 AWG	Copper	Not marked	RW90	600V
Alcan	2/0 AWG	Aluminum Alloy	NUAL	RW90	600V

3.2 CONNECTORS

Connectors were obtained for the tests from local suppliers. The connectors were standard, commonly available types from standard industrial electrical suppliers, and included the following types:

- Single screw mechanical lug connectors, CU rated, copper or brass body (plated)
- Single screw mechanical lug connectors, AL/CU dual rated, aluminum body

A typical sample connector is shown in Figure 1.

Figure 1. Typical connector sample (AL/CU dual rated shown).

3.3 SAMPLE ASSEMBLIES

The test sample assemblies consisted of short lengths of bare wire terminating in an electrical connector at one end, and a current equalizer at the other end. The layout of a typical sample is shown in Figure 2.

Reference (control) conductor samples with no connector were also included in the testing. Two reference samples of each conductor size and type were used.

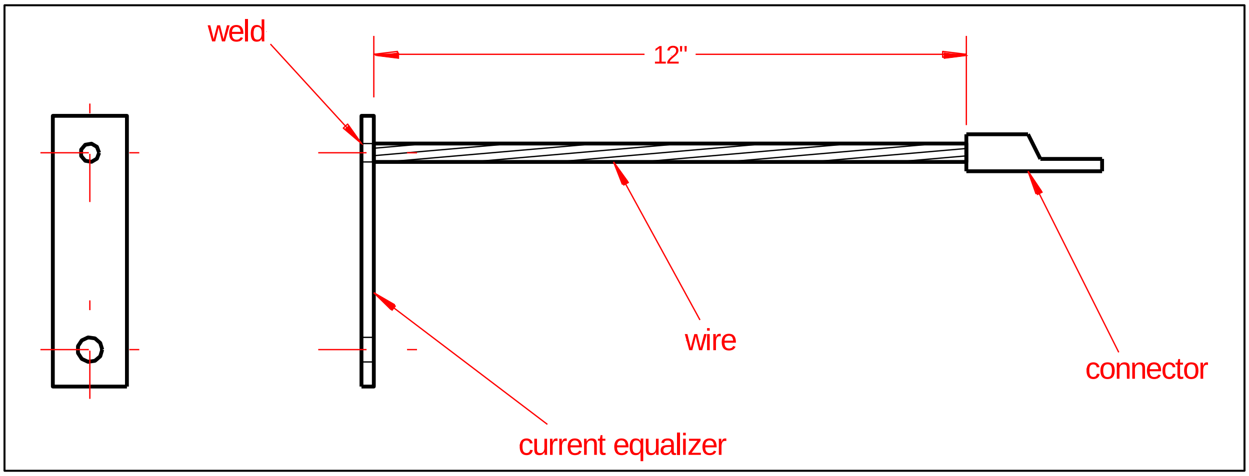

Figure 2. Typical connector test sample.

3.4 CONNECTOR PREPARATION

The samples included an equal number of connectors that were tightened to each of the following three torque values:

- 70% of rated torque.
- 100% of rated torque.
- 125% of rated torque.

Where used, contact lubricant (oxide inhibitor), was applied on the connection barrel and/or conductor as directed in the manufacturer's installation instructions. A commonly available product was selected. Neither oxide inhibitor nor any other lubricant was used on the screw threads.

Each copper wire sample was prepared with no wire brushing or abrasion of the wire or connector, and no oxide inhibitor was used.

For the aluminum wire samples, three different preparation methods were used:

1. Wire brushing/abrasion of the bare wire surface, and application of oxide inhibitor.
2. Application of oxide inhibitor only.
3. No oxide inhibitor and no abrasion.

A summary of the combinations of preparation methods for each sample is given in Table 2.

3.5 TEST LOOP ASSEMBLY

The test sample assemblies were elevated on wooden rails, 3 ft. from the laboratory floor, and connected together into a series loop so that the same current level could be passed through all samples simultaneously. Samples were suspended in free air so that cooling would be by natural convection. The plan view layout of the test loop is shown in Figure 3, and a circuit schematic is shown in Figure 4. A photograph of some of the samples in the test is shown in Figure 5.

Table 2. Sample preparation used for the current cycle tests.

Type	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Total No. Units
Control	#1 Cu	---	---	---	---	2
Control	2/0 Al	---	---	---	---	2
Mechanical	#1 Cu	AL/CU	N	N	125%	4
Mechanical	#1 Cu	AL/CU	N	N	100%	4
Mechanical	#1 Cu	AL/CU	N	N	70%	4
Mechanical	#1 Cu	CU	N	N	125%	4
Mechanical	#1 Cu	CU	N	N	100%	4
Mechanical	#1 Cu	CU	N	N	70%	4
Mechanical	2/0 Al	AL/CU	Y	Y	125%	4
Mechanical	2/0 Al	AL/CU	N	Y	125%	4
Mechanical	2/0 Al	AL/CU	N	N	125%	4
Mechanical	2/0 Al	AL/CU	Y	Y	100%	4
Mechanical	2/0 Al	AL/CU	N	Y	100%	4
Mechanical	2/0 Al	AL/CU	N	N	100%	4
Mechanical	2/0 Al	AL/CU	Y	Y	70%	4
Mechanical	2/0 Al	AL/CU	N	Y	70%	4
Mechanical	2/0 Al	AL/CU	N	N	70%	4

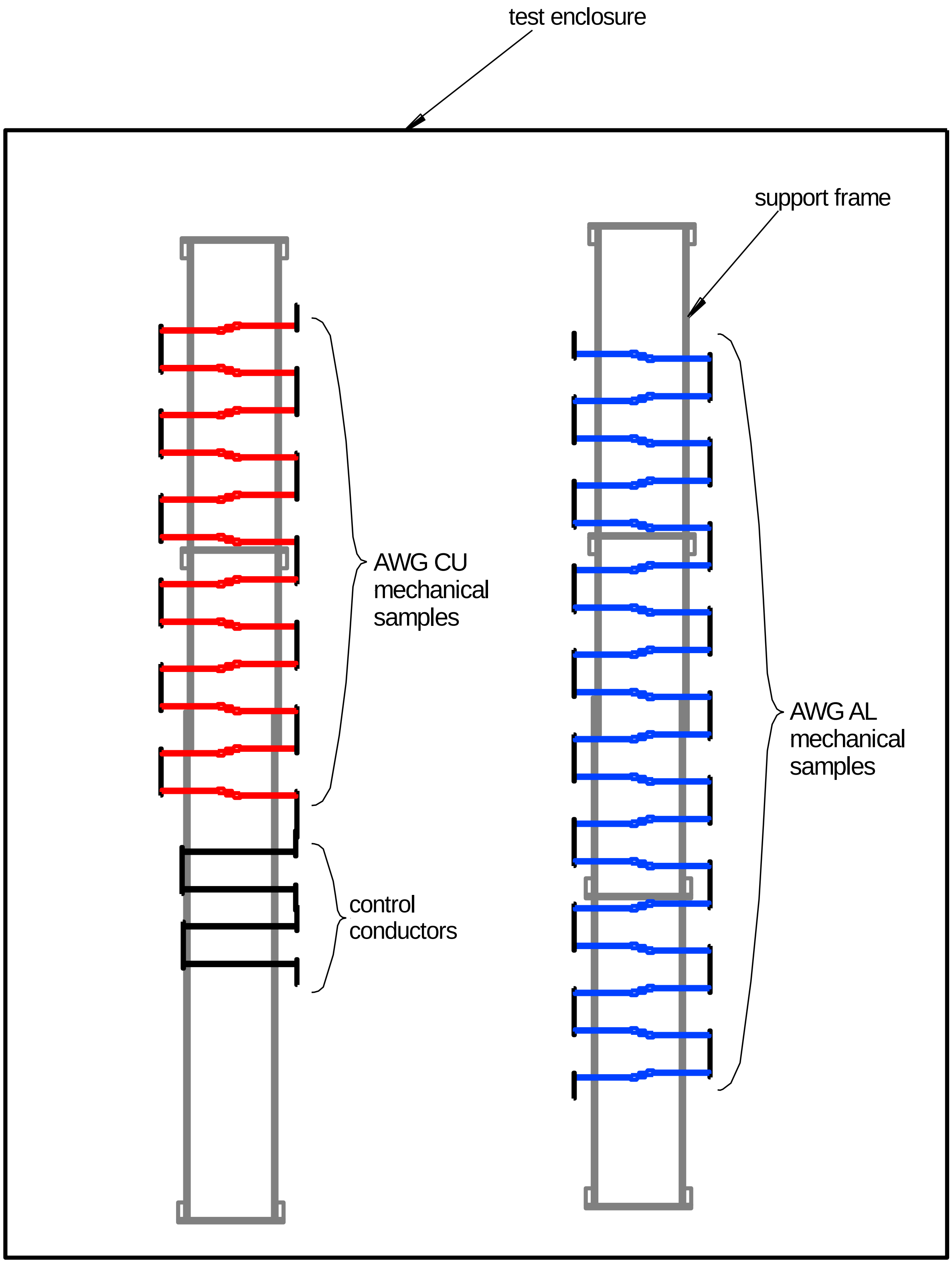

Figure 3. Test loop sample layout, plan view (not to scale). Current jumpers between rows of samples and are not shown.

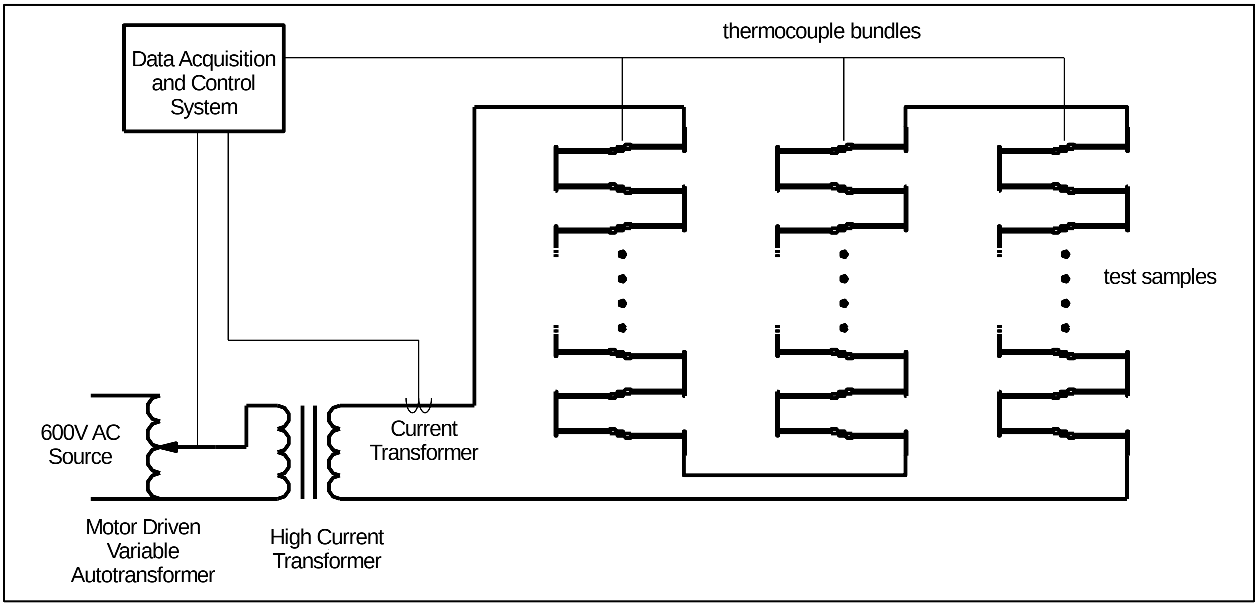

Figure 4. Circuit schematic for the test loop.

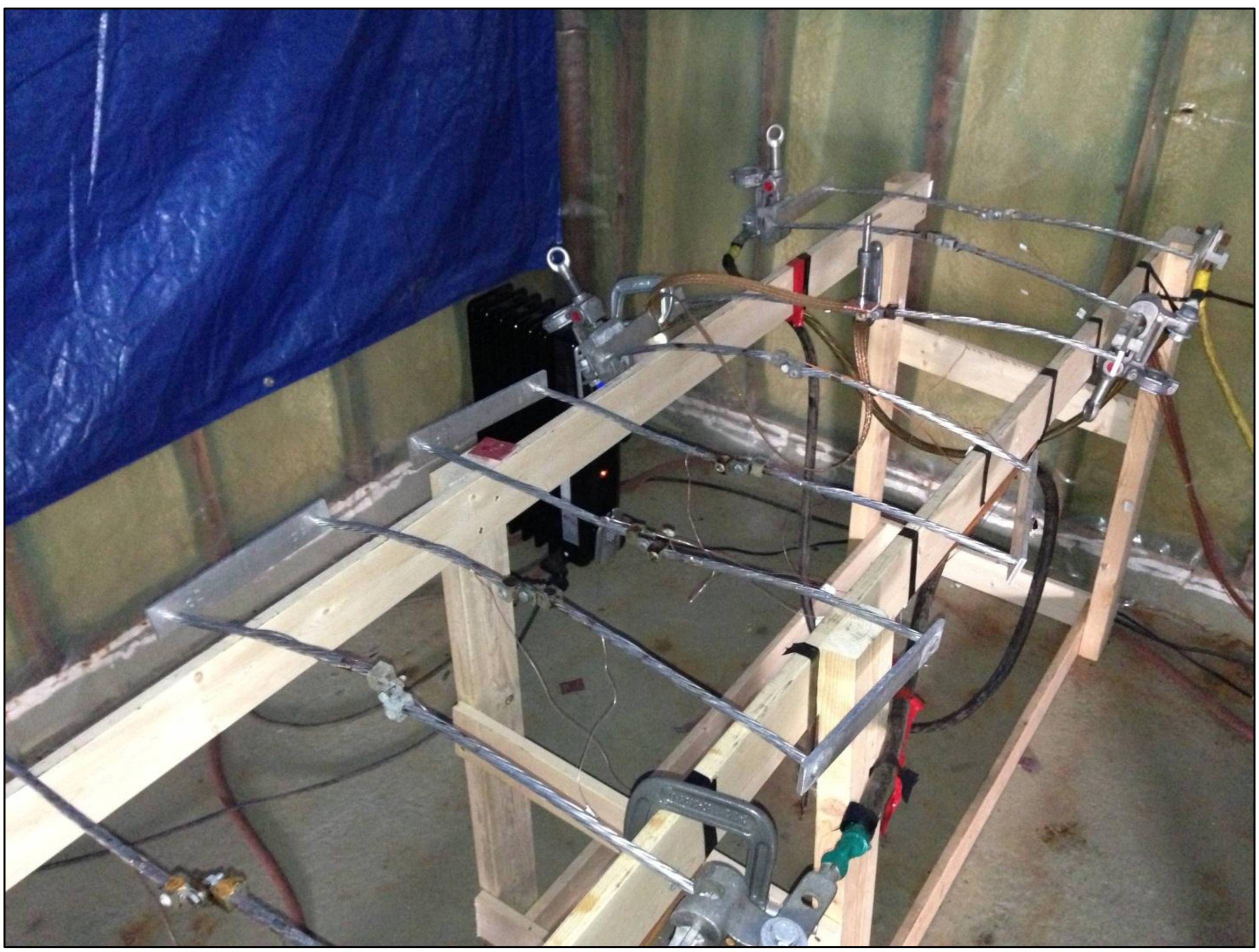

Figure 5. Samples set up for the test.

3.6 SAMPLE LABELLING

Samples were labelled as indicated in Table 3.

Table 3. Sample labelling for all samples.

Sample No.	Inhib-itor	Abra-sion	Torque	Conductor	Type	Con-nector Rating	Manufact-urer	Model
CCtrl1	---	---	---	#1 Cu	Control	---	Table Content Redacted	---
CCtrl2	---	---	---	#1 Cu	Control	---		---
ACtrl1	---	---	---	2/0 Al	Control	---		---
ACtrl2	---	---	---	2/0 Al	Control	---		---
CM1	N	N	125%	#1 Cu	Mechanical	AL/CU		KA26U
CM2	N	N	125%	#1 Cu	Mechanical	AL/CU		KA26U
CM3	N	N	100%	#1 Cu	Mechanical	AL/CU		KA26U
CM4	N	N	100%	#1 Cu	Mechanical	AL/CU		KA26U
CM5	N	N	70%	#1 Cu	Mechanical	AL/CU		KA26U
CM6	N	N	70%	#1 Cu	Mechanical	AL/CU		KA26U
CM7	N	N	125%	#1 Cu	Mechanical	AL/CU		ADR21
CM8	N	N	125%	#1 Cu	Mechanical	AL/CU		ADR21
CM9	N	N	100%	#1 Cu	Mechanical	AL/CU		ADR21
CM10	N	N	100%	#1 Cu	Mechanical	AL/CU		ADR21
CM11	N	N	70%	#1 Cu	Mechanical	AL/CU		ADR21
CM12	N	N	70%	#1 Cu	Mechanical	AL/CU		ADR21
CM13	N	N	125%	#1 Cu	Mechanical	CU		KLU125
CM14	N	N	125%	#1 Cu	Mechanical	CU		KLU125
CM15	N	N	100%	#1 Cu	Mechanical	CU		KLU125
CM16	N	N	100%	#1 Cu	Mechanical	CU		KLU125
CM17	N	N	70%	#1 Cu	Mechanical	CU		KLU125
CM18	N	N	70%	#1 Cu	Mechanical	CU		KLU125
CM19	N	N	125%	#1 Cu	Mechanical	CU		STC1102
CM20	N	N	125%	#1 Cu	Mechanical	CU		STC1102
CM21	N	N	100%	#1 Cu	Mechanical	CU		STC1102
CM22	N	N	100%	#1 Cu	Mechanical	CU		STC1102
CM23	N	N	70%	#1 Cu	Mechanical	CU		STC1102
CM24	N	N	70%	#1 Cu	Mechanical	CU		STC1102

Sample No.	Inhib-itor	Abra-sion	Torque	Conductor	Type	Con-nector Rating	Manufact-urer	Model
AM1	Y	Y	125%	2/0 Al	Mechanical	AL/CU	Table Content Redacted	KA26U
AM2	Y	Y	125%	2/0 Al	Mechanical	AL/CU		KA26U
AM3	Y	N	125%	2/0 Al	Mechanical	AL/CU		KA26U
AM4	Y	N	125%	2/0 Al	Mechanical	AL/CU		KA26U
AM5	N	N	125%	2/0 Al	Mechanical	AL/CU		KA26U
AM6	N	N	125%	2/0 Al	Mechanical	AL/CU		KA26U
AM7	Y	Y	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM8	Y	Y	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM9	Y	N	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM10	Y	N	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM11	N	N	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM12	N	N	100%	2/0 Al	Mechanical	AL/CU		KA26U
AM13	Y	Y	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM14	Y	Y	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM15	Y	N	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM16	Y	N	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM17	N	N	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM18	N	N	70%	2/0 Al	Mechanical	AL/CU		KA26U
AM19	Y	Y	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM20	Y	Y	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM21	Y	N	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM22	Y	N	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM23	N	N	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM24	N	N	125%	2/0 Al	Mechanical	AL/CU		ADR21
AM25	Y	Y	100%	2/0 Al	Mechanical	AL/CU		ADR21
AM26	Y	Y	100%	2/0 Al	Mechanical	AL/CU		ADR21
AM27	Y	N	100%	2/0 Al	Mechanical	AL/CU		ADR21
AM28	Y	N	100%	2/0 Al	Mechanical	AL/CU		ADR21
AM29	N	N	100%	2/0 Al	Mechanical	AL/CU		ADR21
AM30	N	N	100%	2/0 Al	Mechanical	AL/CU		ADR21

Sample No.	Inhib-itor	Abra-sion	Torque	Conductor	Type	Con-nector Rating	Manufact-urer	Model
AM31	Y	Y	70%	2/0 Al	Mechanical	AL/CU	Table Content Redacted	ADR21
AM32	Y	Y	70%	2/0 Al	Mechanical	AL/CU		ADR21
AM33	Y	N	70%	2/0 Al	Mechanical	AL/CU		ADR21
AM34	Y	N	70%	2/0 Al	Mechanical	AL/CU		ADR21
AM35	N	N	70%	2/0 Al	Mechanical	AL/CU		ADR21
AM36	N	N	70%	2/0 Al	Mechanical	AL/CU		ADR21

4. TEST PROCEDURE

The wire and connector samples were subjected to accelerated ageing by current cycling. The test procedure IEC 61238-1 (2003-05), “Compression and mechanical connectors for power cables for rated voltages up to 30 kV (Um = 36 kV)”, was used as a guide, with modifications and details as listed below:

- 4 samples of each configuration were tested. The numbers of samples of each type used are given in Table 2.
- Welded equalizers were prepared and samples were connected together palm-to-palm in accordance with ANSI C119.4-2011.
- Samples were subjected to 1500 heating/cooling cycles, each consisting of 1 hour of heating by applying high current followed by 1.25 hours of natural cooling with no current applied.
- The current level was determined at the start of the test as the current required to heat the control (reference) conductor samples to a temperature rise of 100-105°C above ambient temperature. A current level of 280 A was used for the test.
- One application of short-circuit current was applied to each sample after the 200th current cycle to achieve 250°C to 270°C on the reference conductor. Samples were tested in groups, by location in the test loop.
- Sample assemblies were tested in an enclosure with an ambient temperature of 25-30°C during the test.
- The test was conducted in a high humidity environment (>90% RH, non-condensing). Humidity was maintained using atomizing sprayers which operated on a 20% duty cycle.
- Connector DC resistance was measured approximately every 100 cycles or less, and the temperature of connectors and reference conductors was monitored during the test.
- Peak temperature rise values for each connector were measured using thermocouples attached to the surface of the connector body with thermally conductive epoxy.
- Connection performance was evaluated by the change in the corrected dc resistance and temperature rise above the control conductor temperature over the course of the test.

5. TEST RESULTS

5.1 TEMPERATURE CYCLE

The samples completed 1500 current cycles total, with a typical heat/cooling current cycle shown in Figure 6. The small oscillations in the temperature were caused by the humidification atomizers turning on and off, which temporarily cooled the ambient temperature slightly.

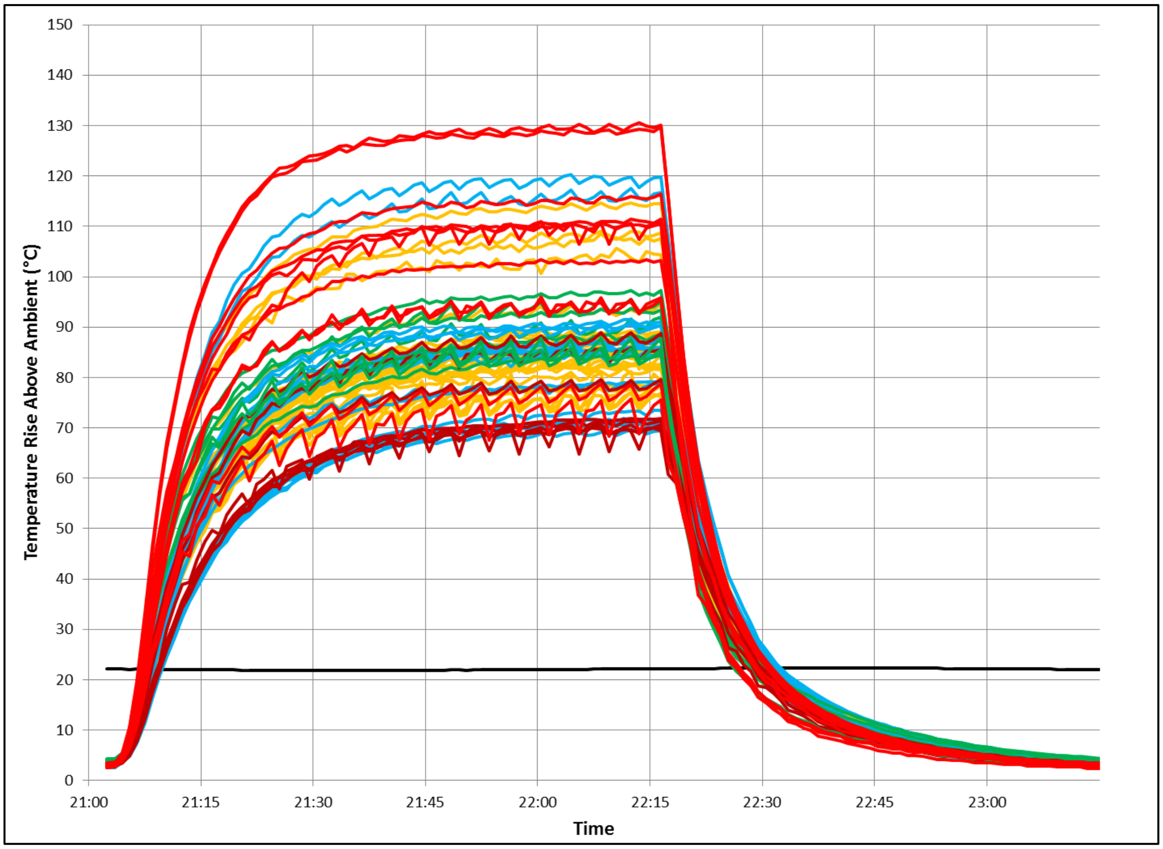

Figure 6. Typical heating/cooling cycle.

5.2 SAMPLE RE-TORQUING

The initial test plan was to apply the required torque values when setting up the connectors at the beginning of the test, and leave the connectors in this state throughout the test. However, a large number of the aluminum wire connectors were found to be very loose (practically zero residual torque) after the application of short circuit current after 200 cycles. It was decided that, in order to continue the comparative test, all connectors would be retightened to the original starting torque levels. In a normal current cycling test the connectors would not be touched after the initial torque was applied. However, the test would not have continued to completion had the samples not been retightened.

5.3 SAMPLE FAILURES

During the test a number of connectors 'failed' by exceeding a peak temperature level that was considered unsafe to allow them to continue with the testing. Although the connectors were still intact (i.e., the conductor had not melted or separated from the connector), they were bypassed using shunt jumpers in order to allow the test to continue. Generally, the temperature level that was considered too high to safely continue was 250°C. An example of a bypassed sample is shown in Figure 7.

In one case a connector actually failed completely by melting through the conductor during the short-circuit test (see Figure 8). This sample was removed from the test.

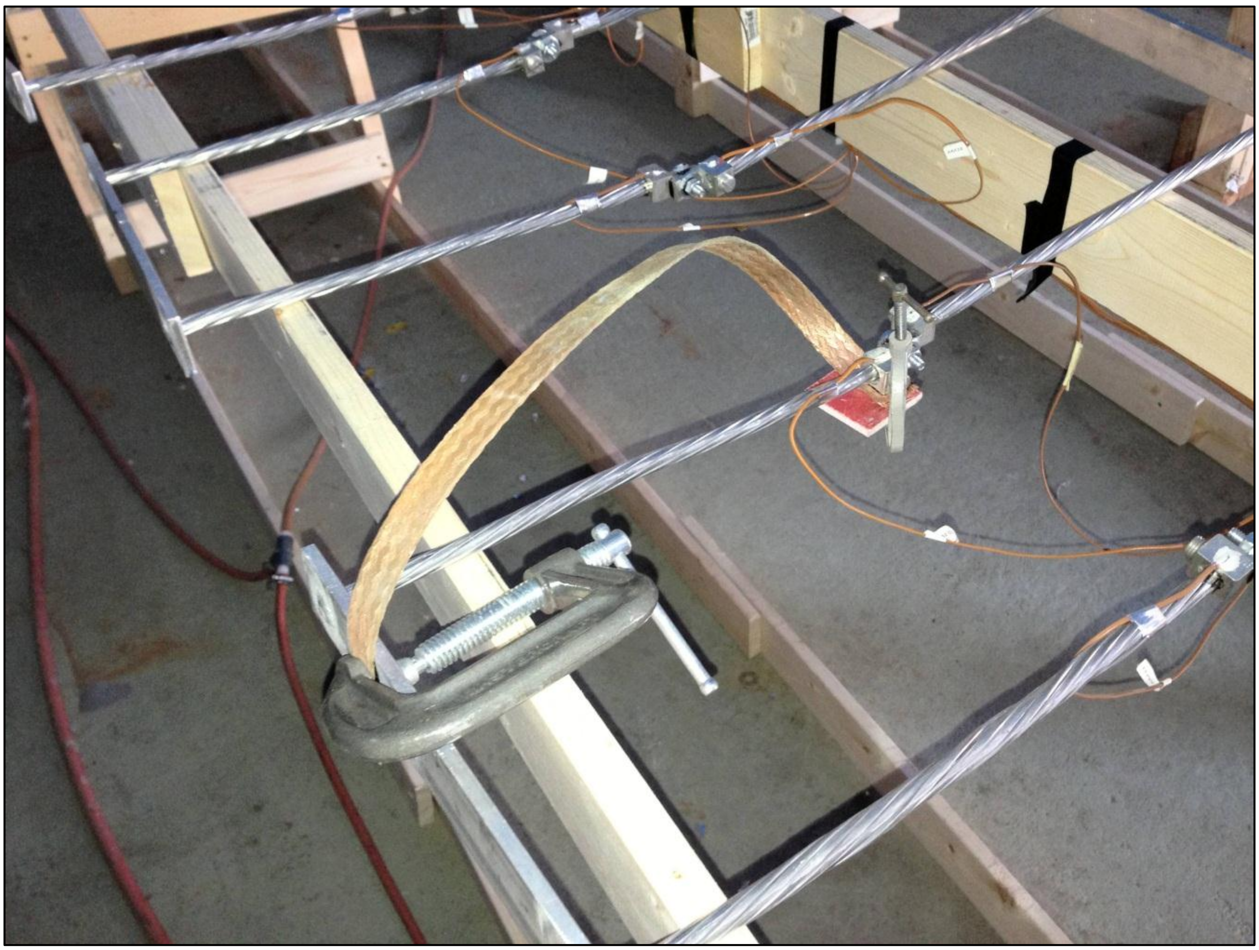

Figure 7. Sample bypassed using a shunt jumper due to overheating during testing.

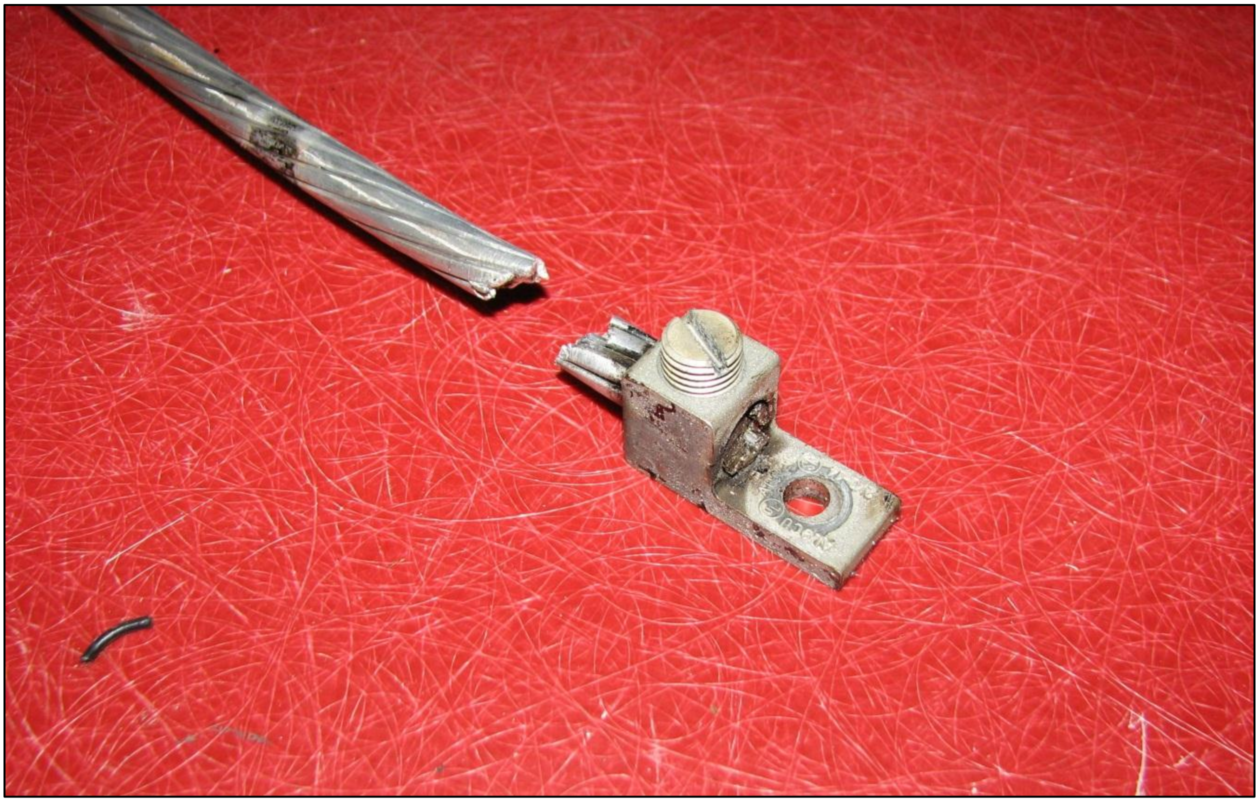

Figure 8. Sample AM32 that failed during the short-circuit test.

5.4 DC RESISTANCE AND PEAK TEMPERATURE RISE VALUES

DC resistance values were recorded and corrected for temperature to 20°C[1]. For comparison, samples were grouped by wire type, connector type, and preparation. The resistance data for each group of connectors is plotted in Figure 9 through Figure 24.

Peak temperature rise above ambient values are the maximum temperatures reached by each connector in the selected cycles, minus the ambient temperature during that cycle. The peak temperature rise above ambient data is plotted in Figure 25 through Figure 40.

[1] Temperature correction is a standard calculation that uses the following formula to calculate the resistance corrected to 20°C. This compensates for minor variations in the temperature at which the connector resistance was measured.

Corrected Resistance $R_c = R_m \times \frac{1}{1+\alpha(\theta-20)}$

α = temperature coefficient of resistance

= 0.004 °C^{-1}

θ = connector temperature at the time of measurement

Comments on the plots:

- Samples that overheated and were bypassed with a shunt jumper are labelled with the prefix 'BP'. Bypassed samples had no further resistance and temperature measurements recorded for the remainder of the test, and are considered to have 'failed' the test.
- Samples that failed by melting through of the conductor are labelled with the prefix 'F'.
- The measurement made before the short-circuit test is labelled as '200' in the legend.
- The measurement made after the short-circuit test is labelled as '200SC' in the legend.
- There are occasional gaps in the peak temperature rise data, which are due to thermocouples that became dislodged.
- The fluctuations in the resistances and temperatures of the control samples give an indication of the error limits of the readings and the normal random variations due to methodology.

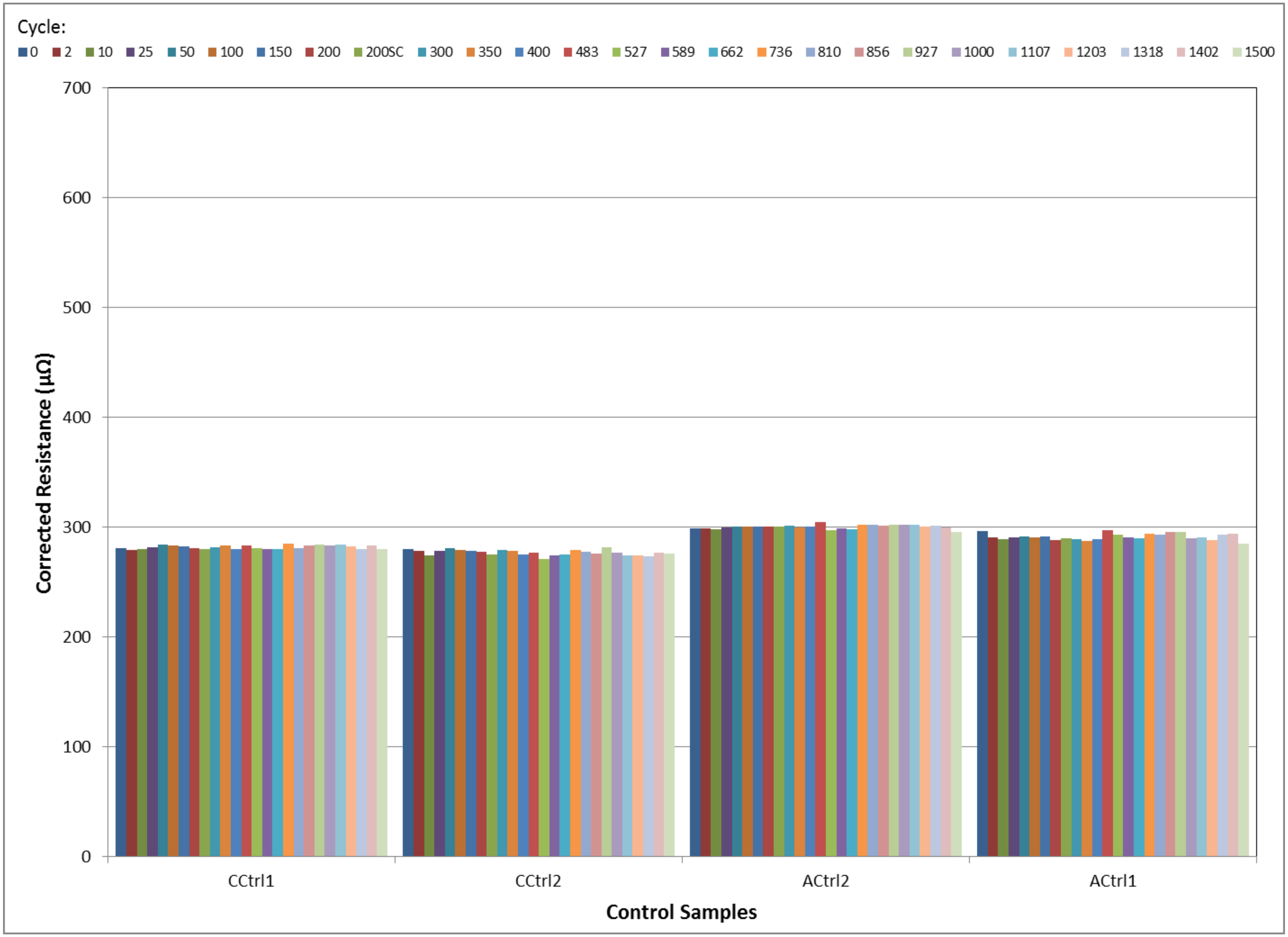

Figure 9. DC resistance of control conductor samples, corrected to 20°C.

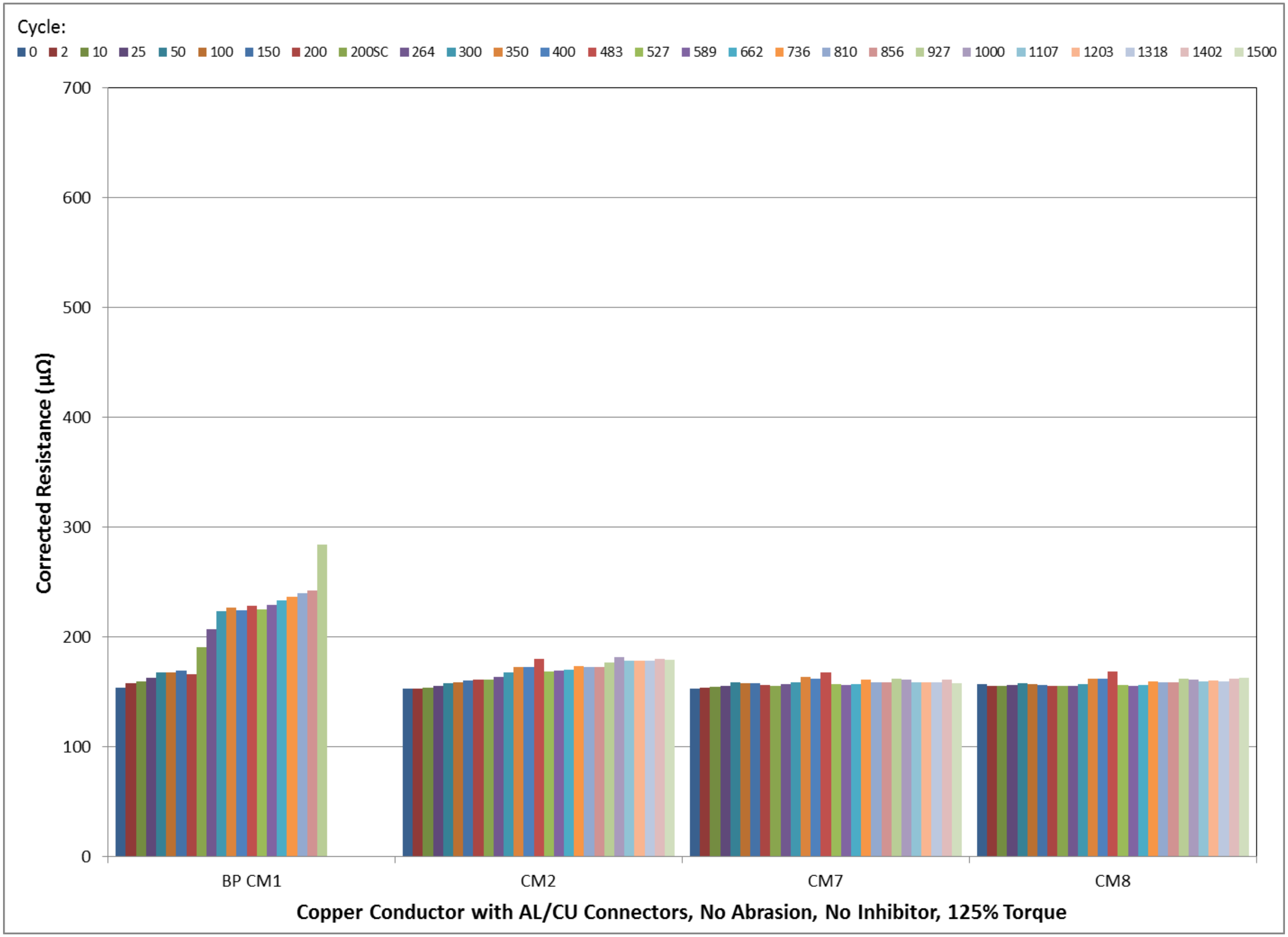

Figure 10. DC resistance of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test. Resistance values are corrected to 20°C.

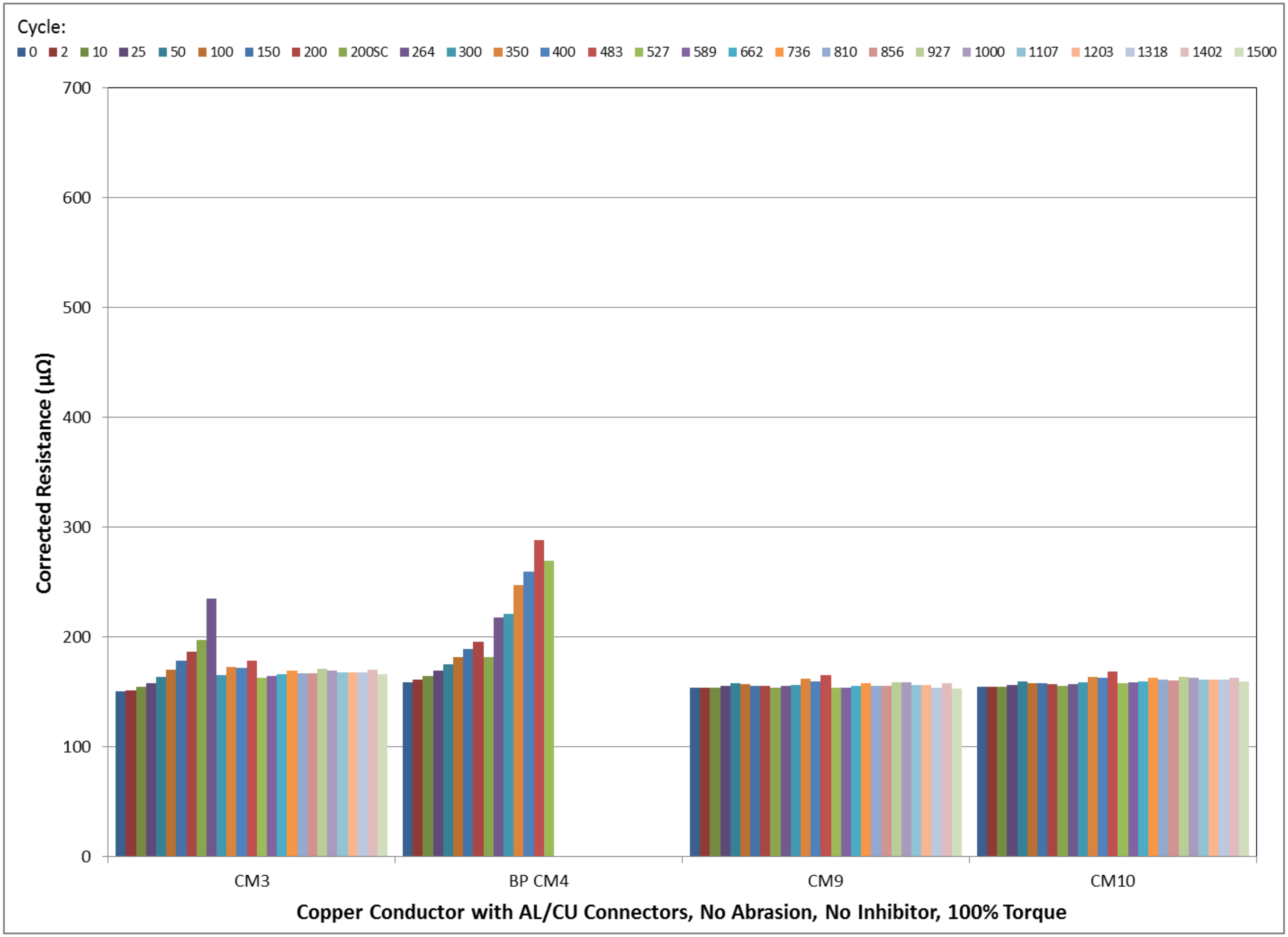

Figure 11. DC resistance of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test. Resistance values are corrected to 20°C.

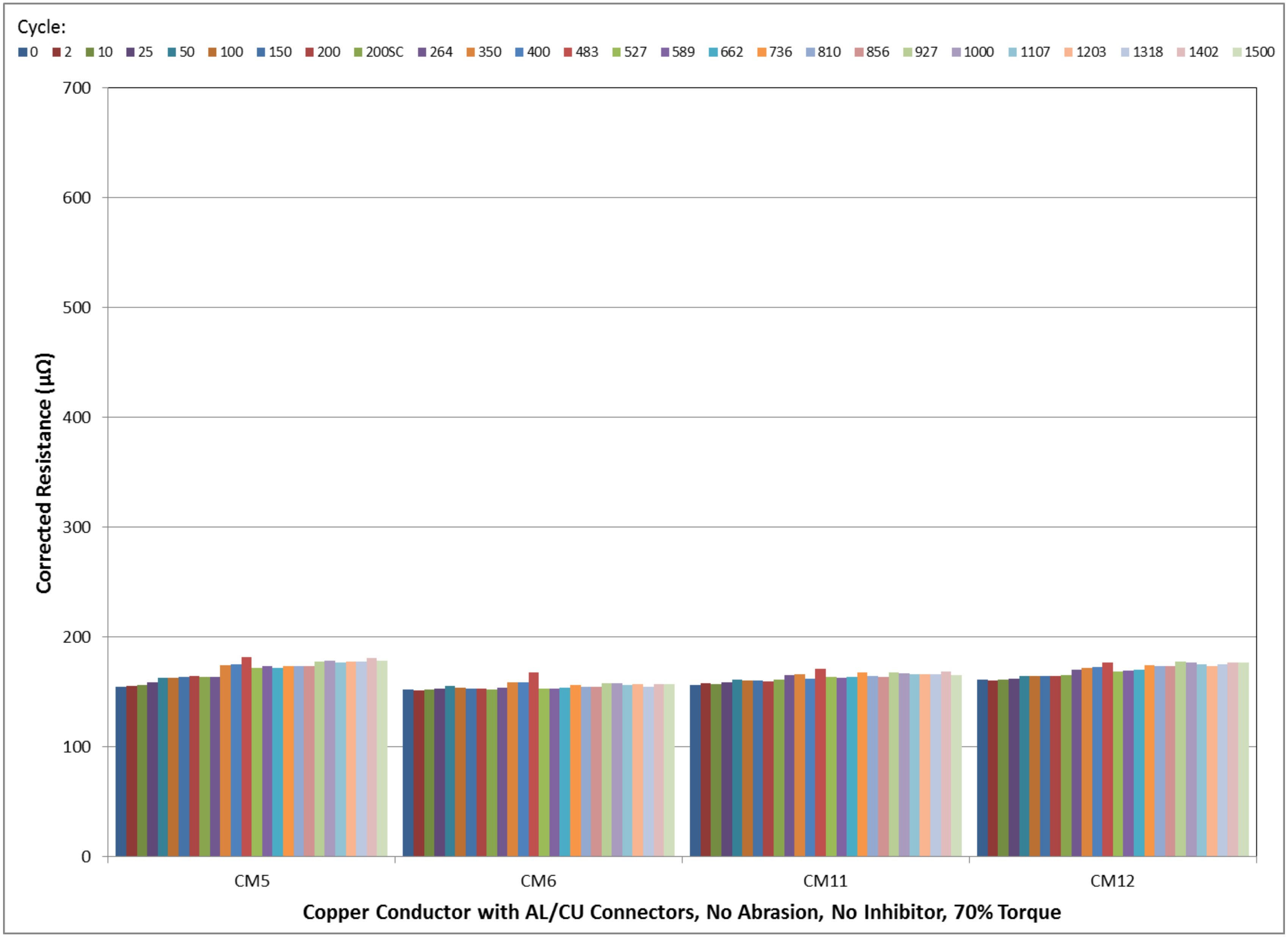

Figure 12. DC resistance of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test. Resistance values are corrected to 20°C.

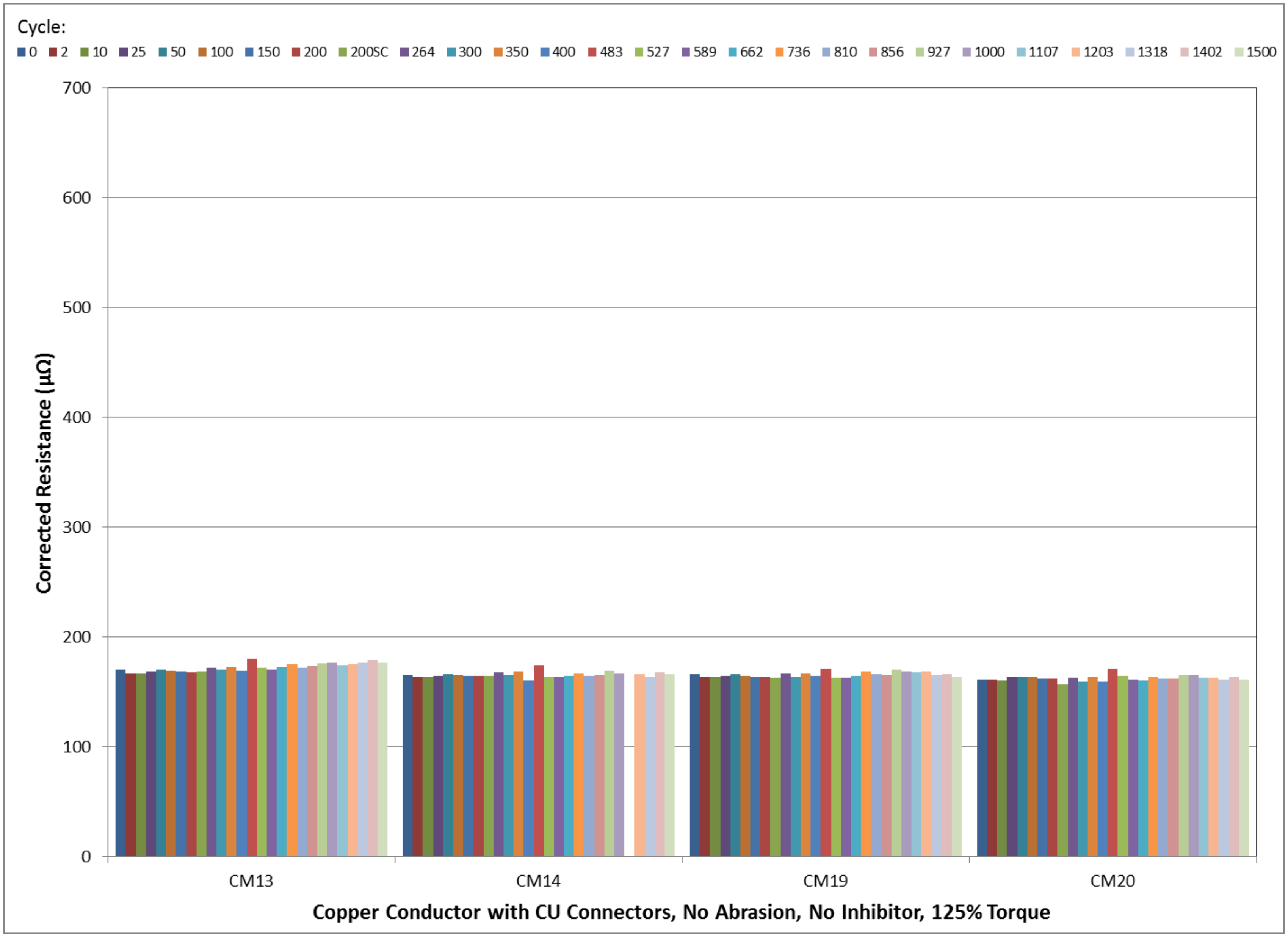

Figure 13. DC resistance of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test. Resistance values are corrected to 20°C.

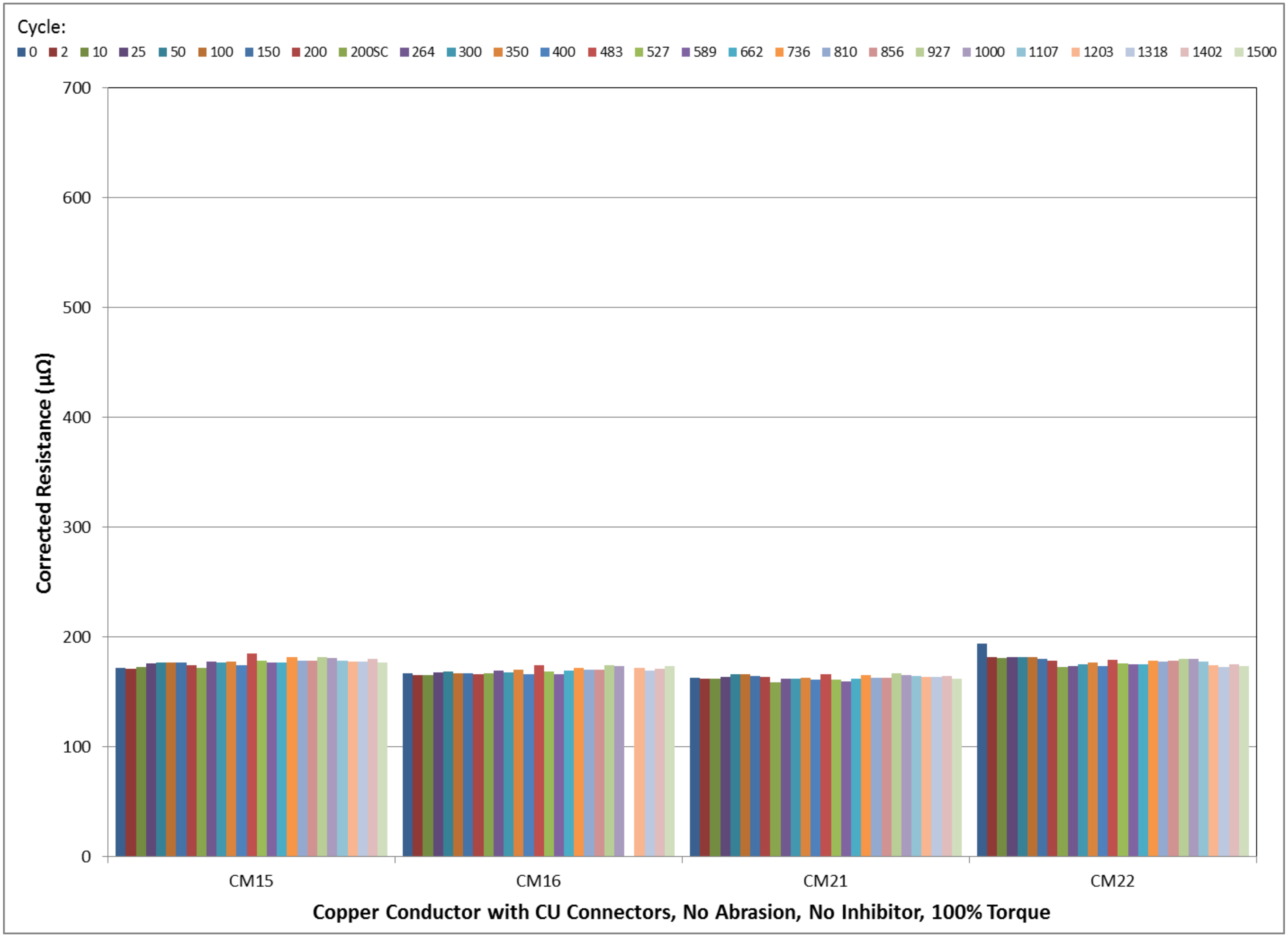

Figure 14. DC resistance of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test. Resistance values are corrected to 20°C.

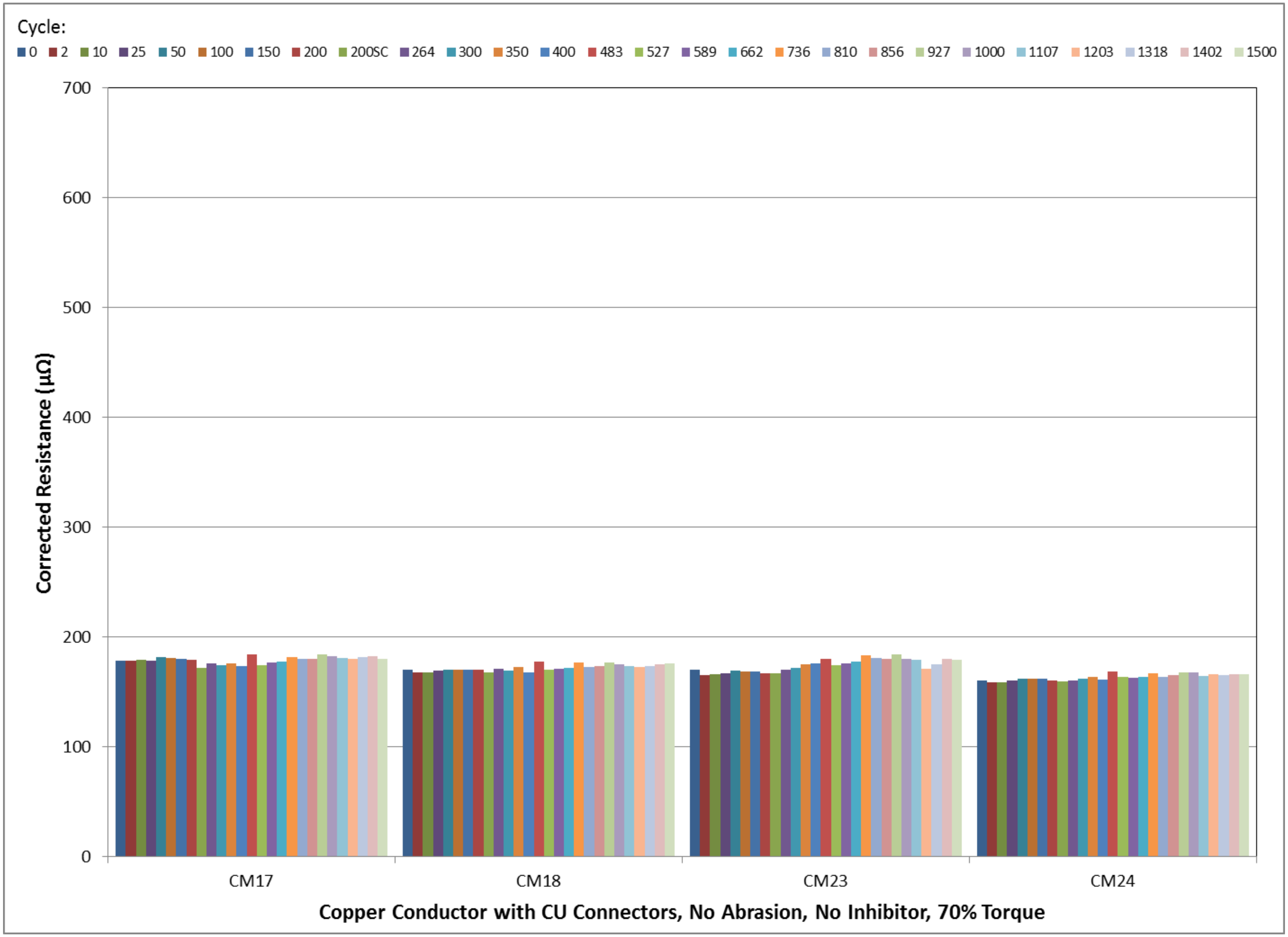

Figure 15. DC resistance of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test. Resistance values are corrected to 20°C.

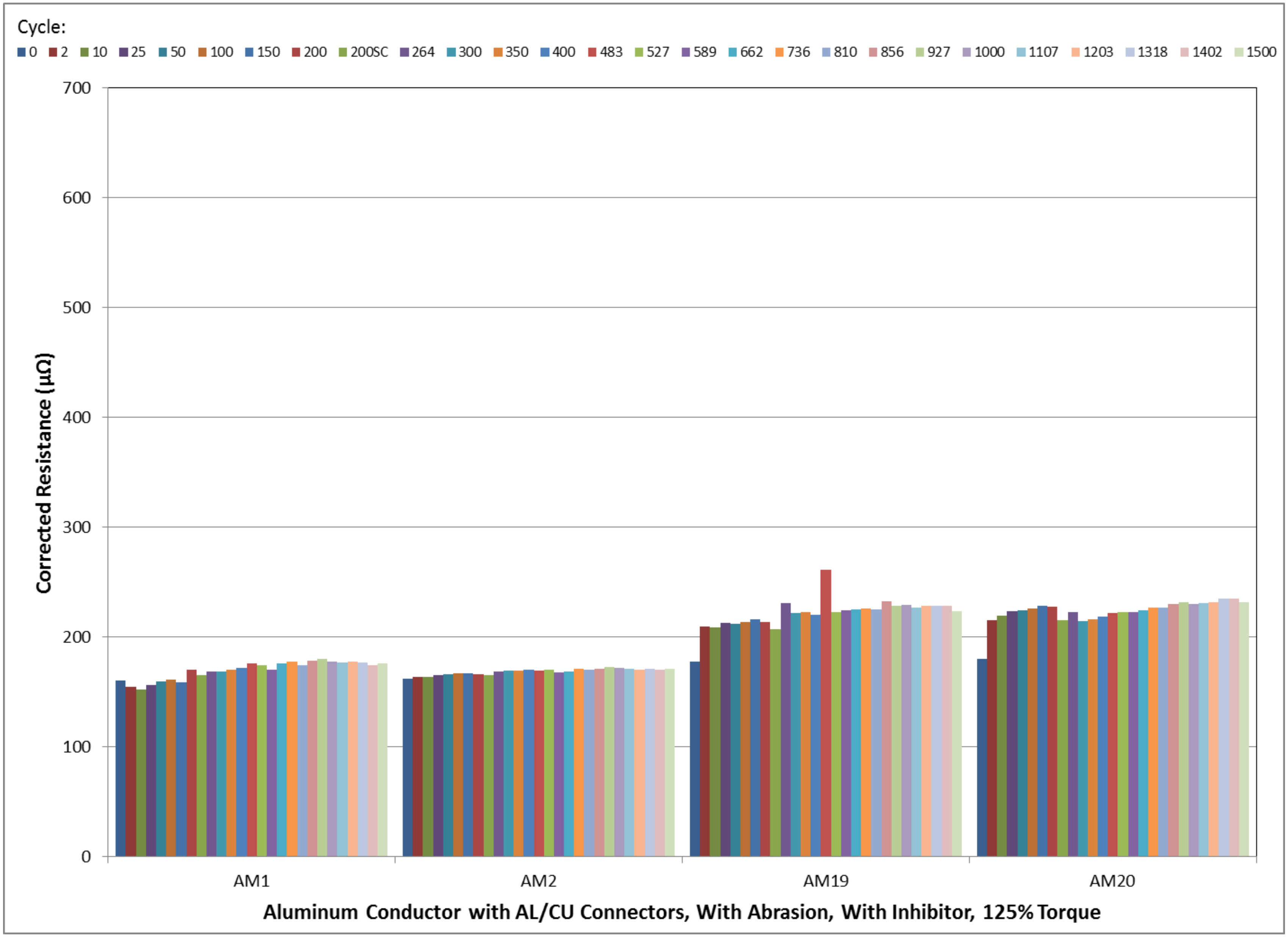

Figure 16. DC resistance of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 125% of rated torque at the start of the test. Resistance values are corrected to 20°C.

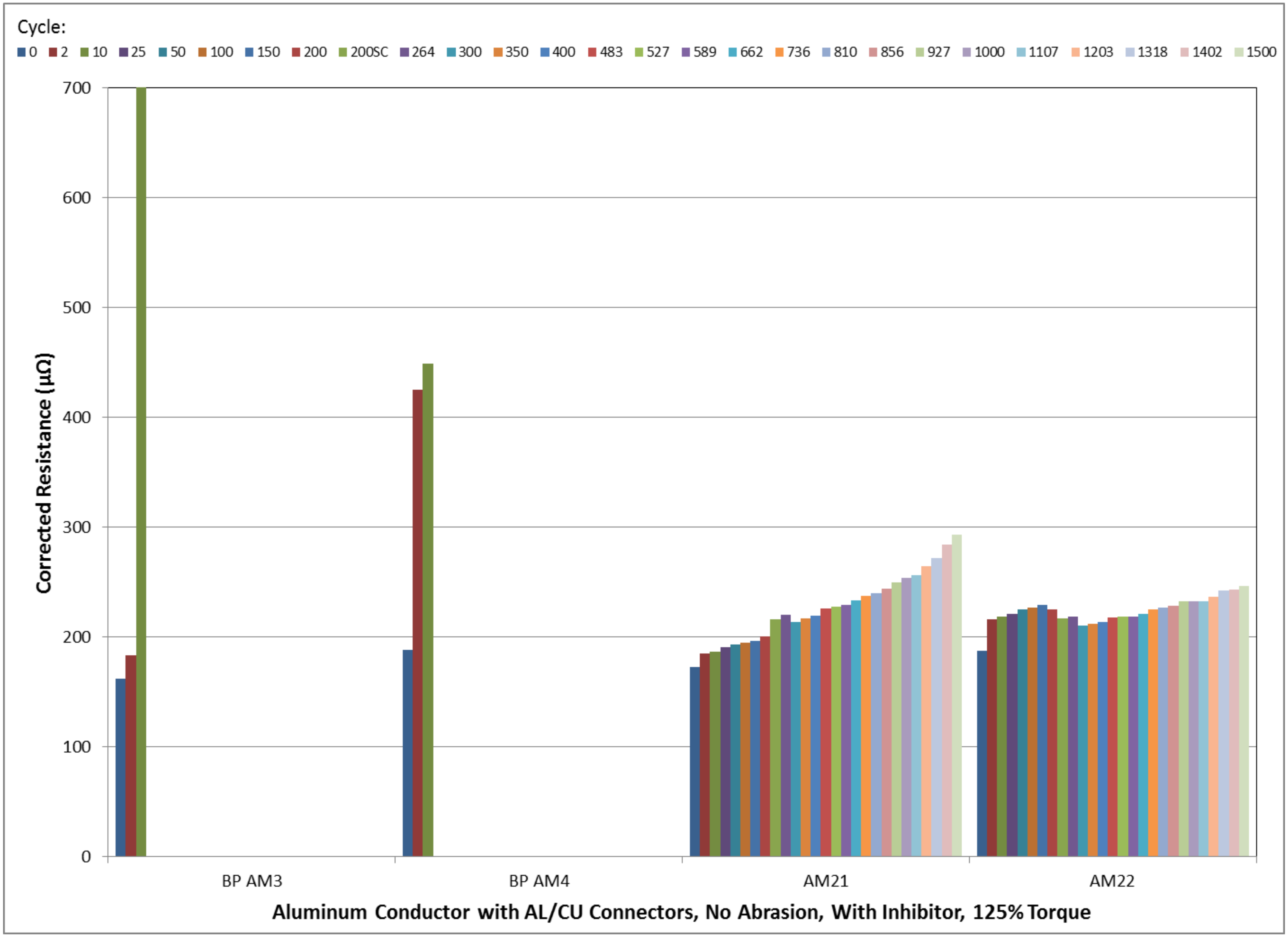

Figure 17. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 125% of rated torque at the start of the test. Resistance values are corrected to 20°C.

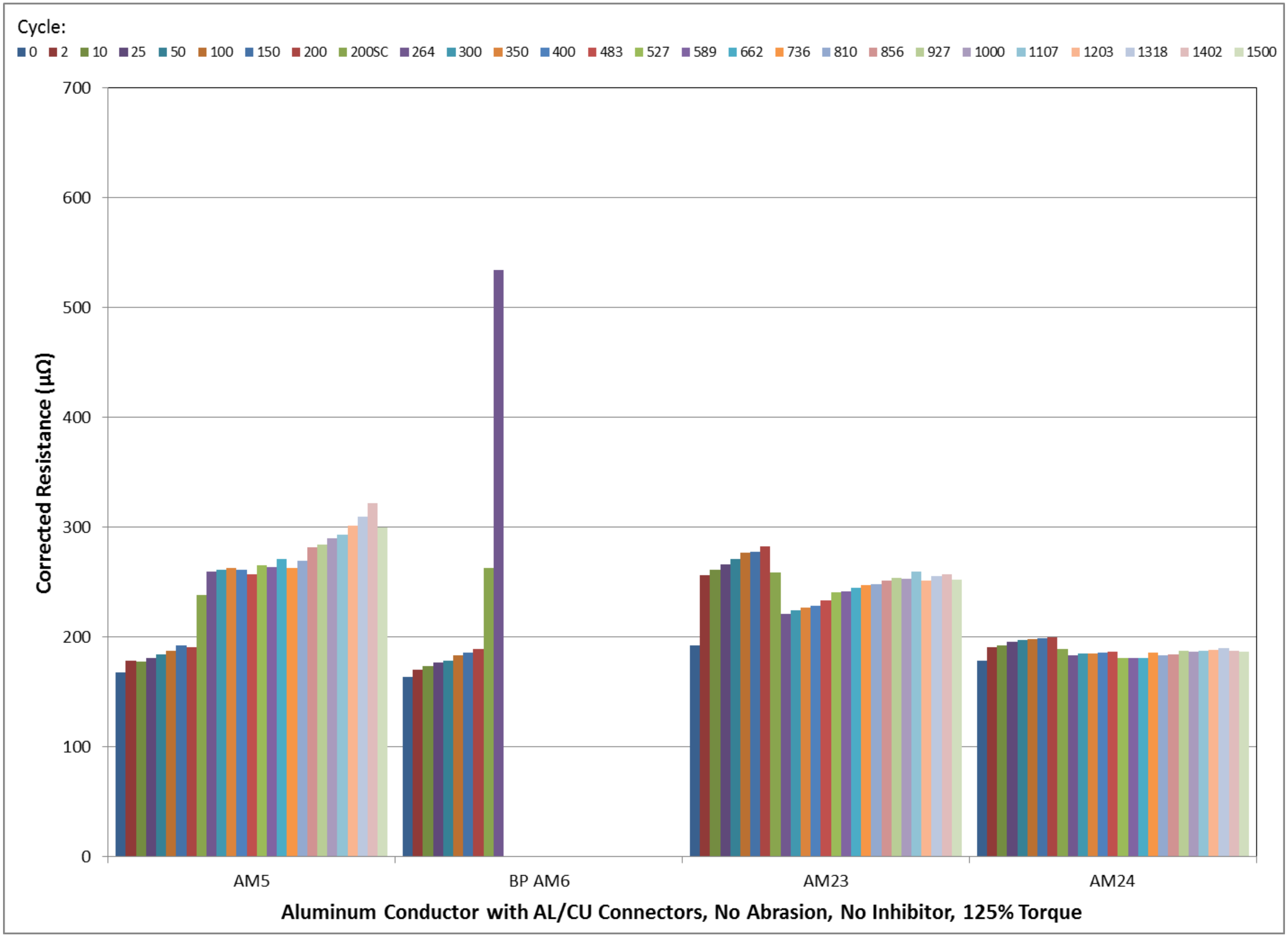

Figure 18. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test. Resistance values are corrected to 20°C.

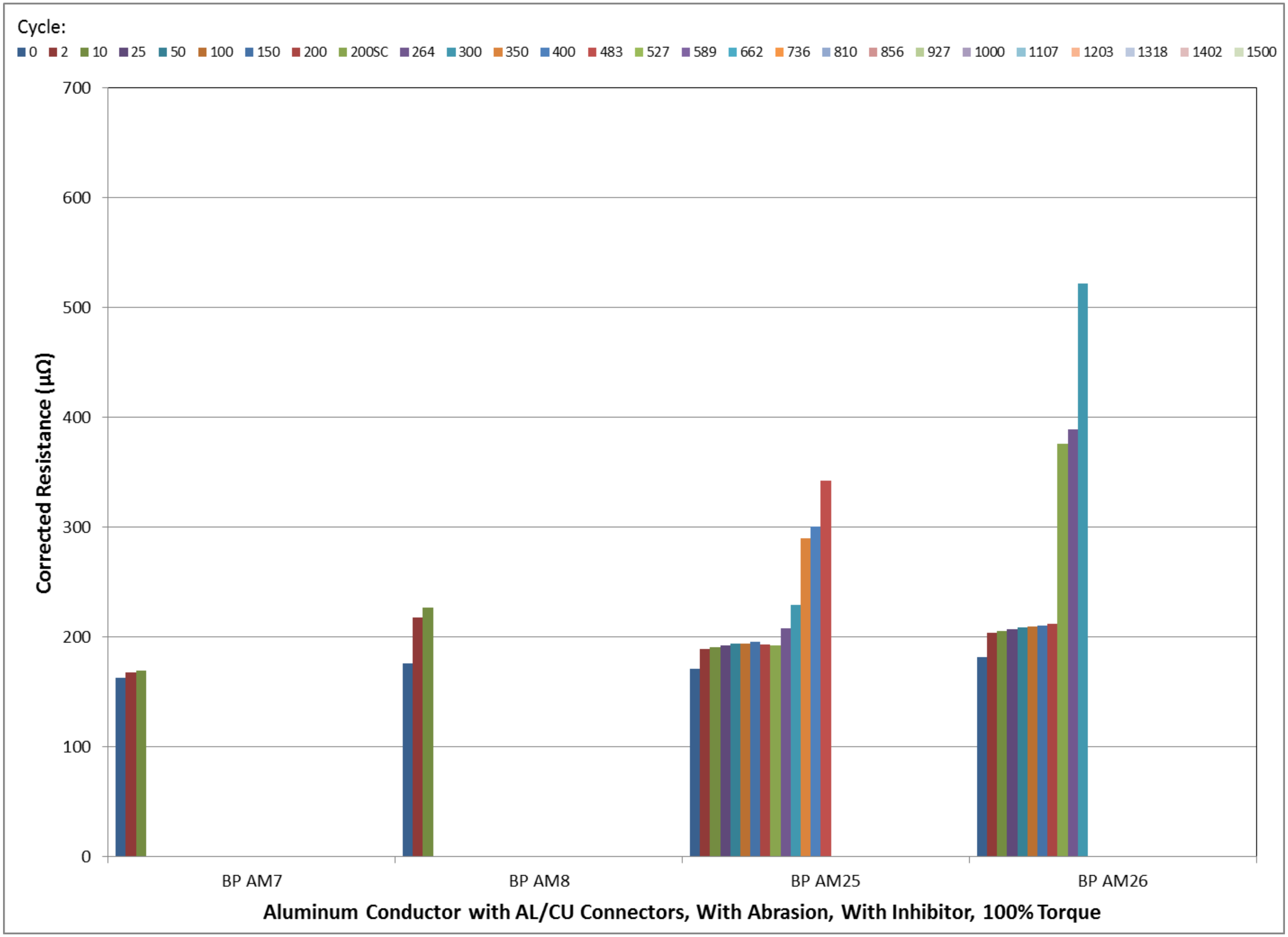

Figure 19. DC resistance of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 100% of rated torque at the start of the test. Resistance values are corrected to 20°C.

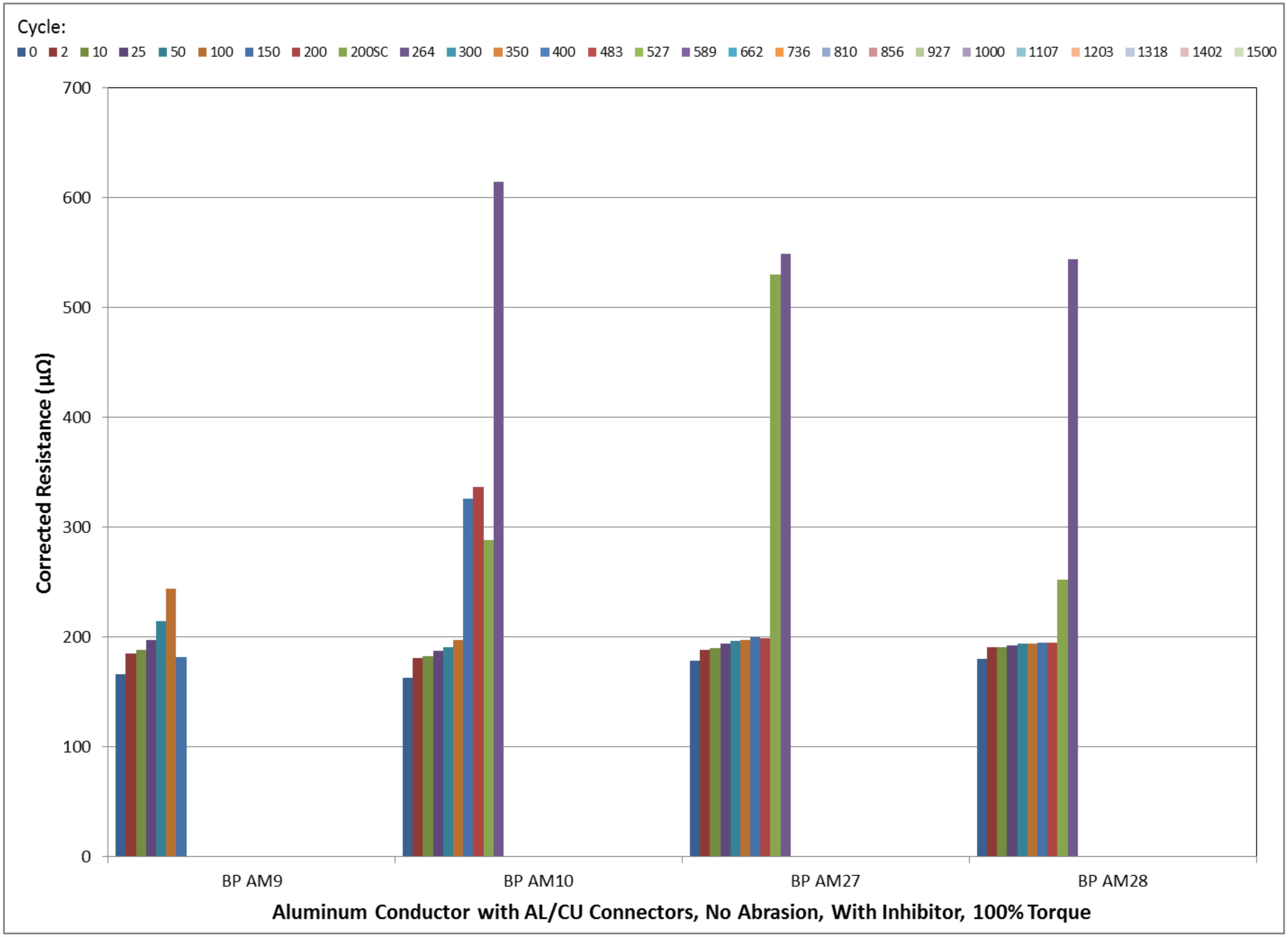

Figure 20. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 100% of rated torque at the start of the test. Resistance values are corrected to 20°C.

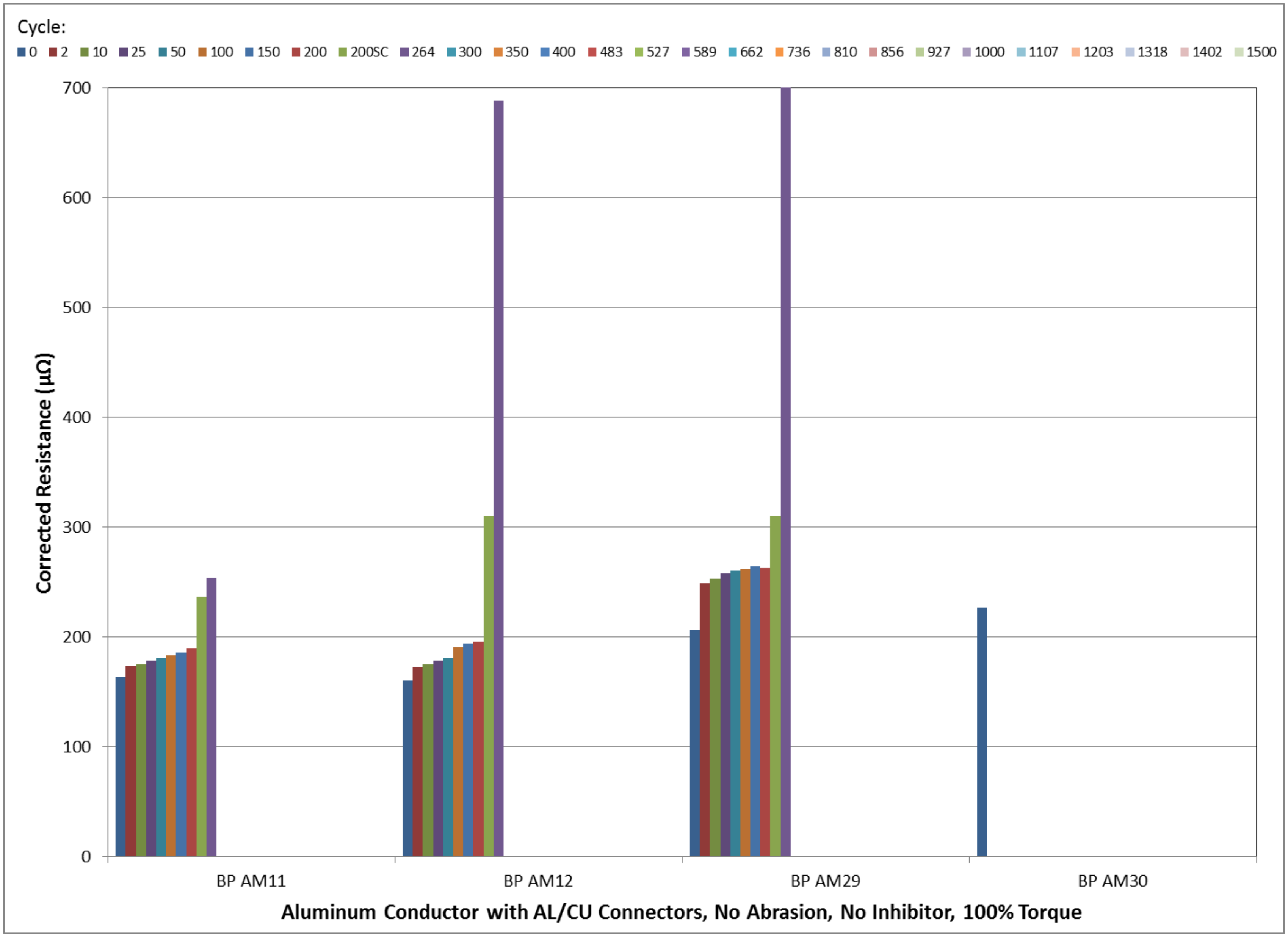

Figure 21. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test. Resistance values are corrected to 20°C.

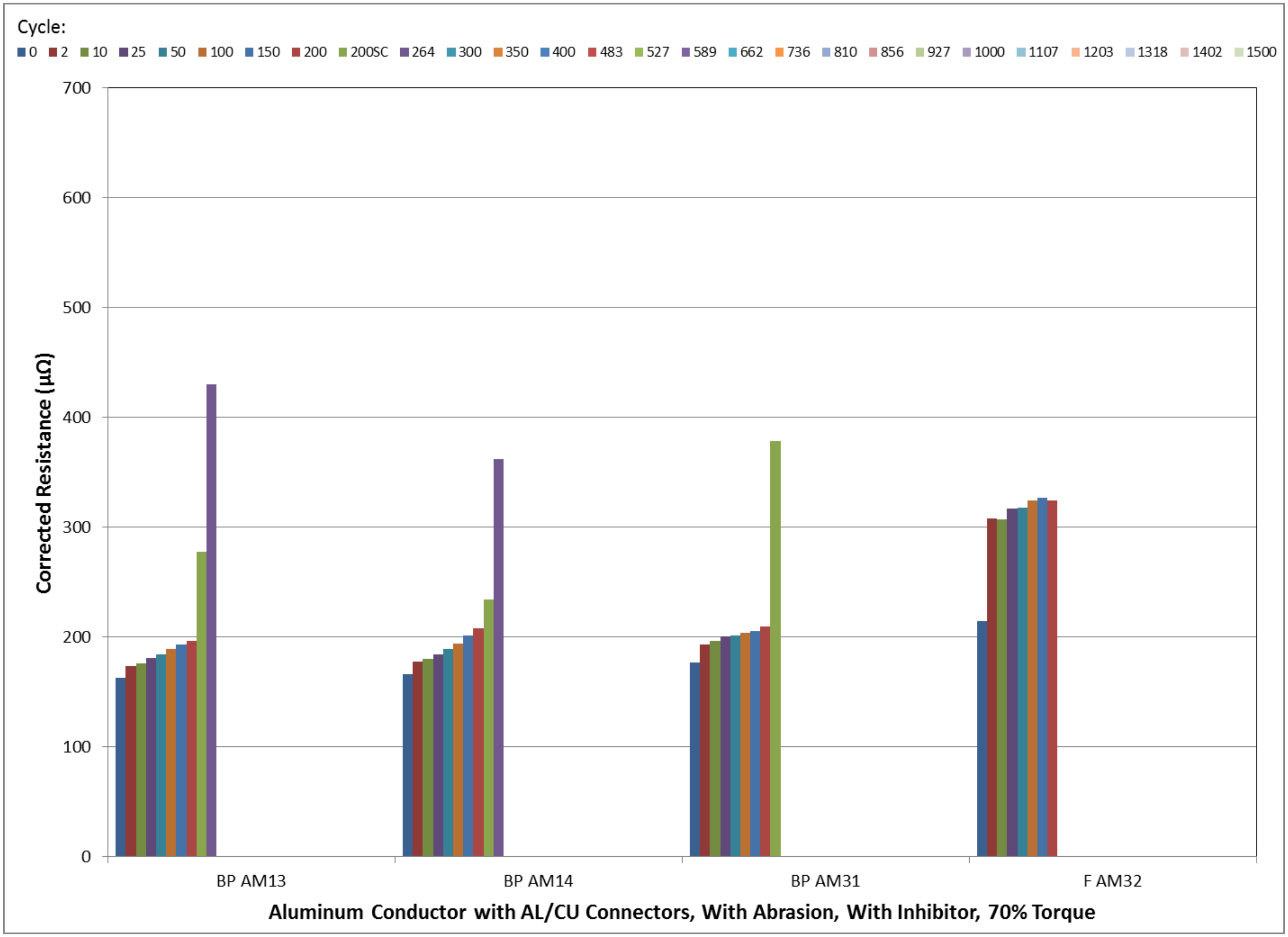

Figure 22. DC resistance of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 70% of rated torque at the start of the test. Resistance values are corrected to 20°C.

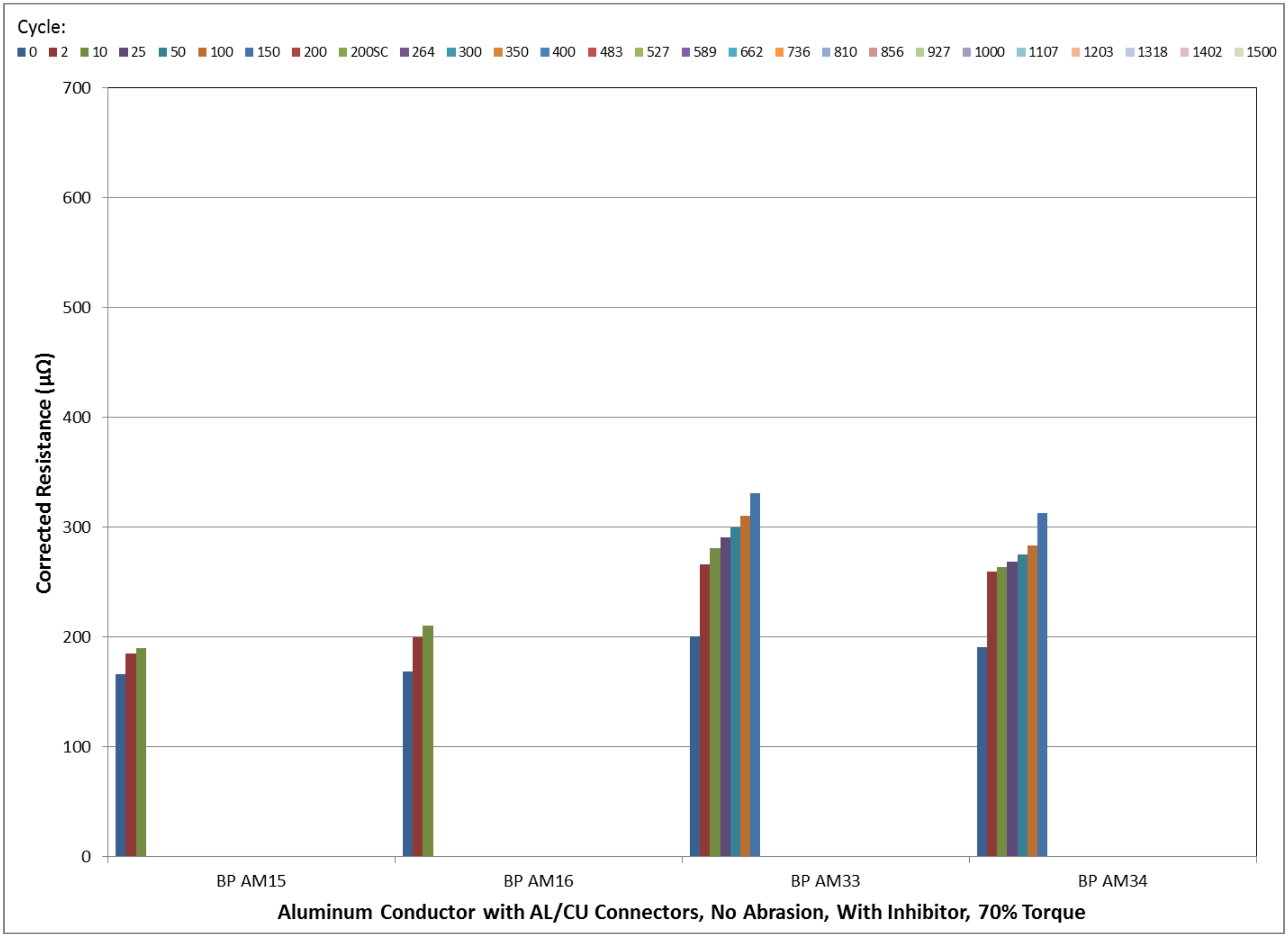

Figure 23. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 70% of rated torque at the start of the test. Resistance values are corrected to 20°C.

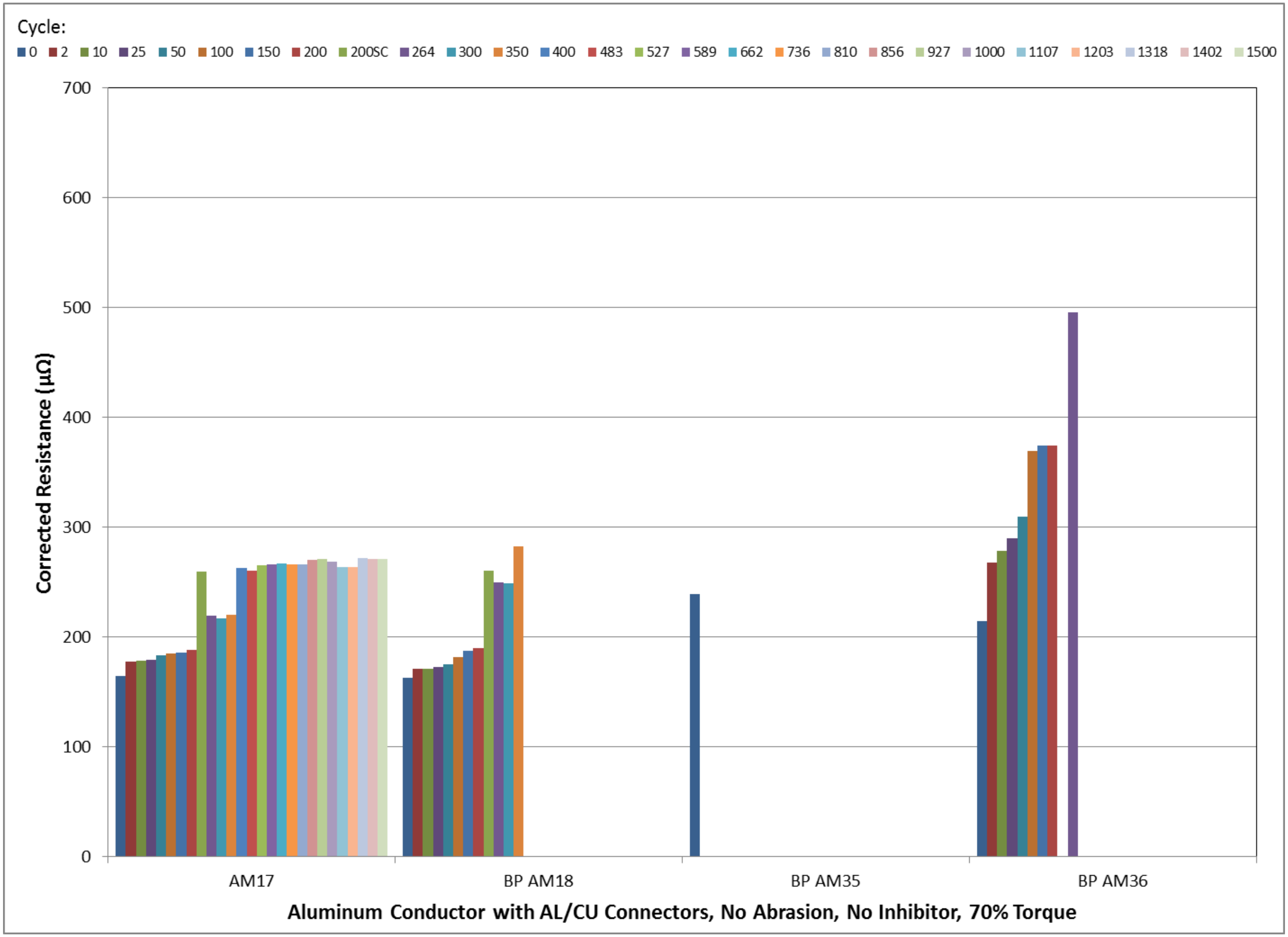

Figure 24. DC resistance of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test. Resistance values are corrected to 20°C.

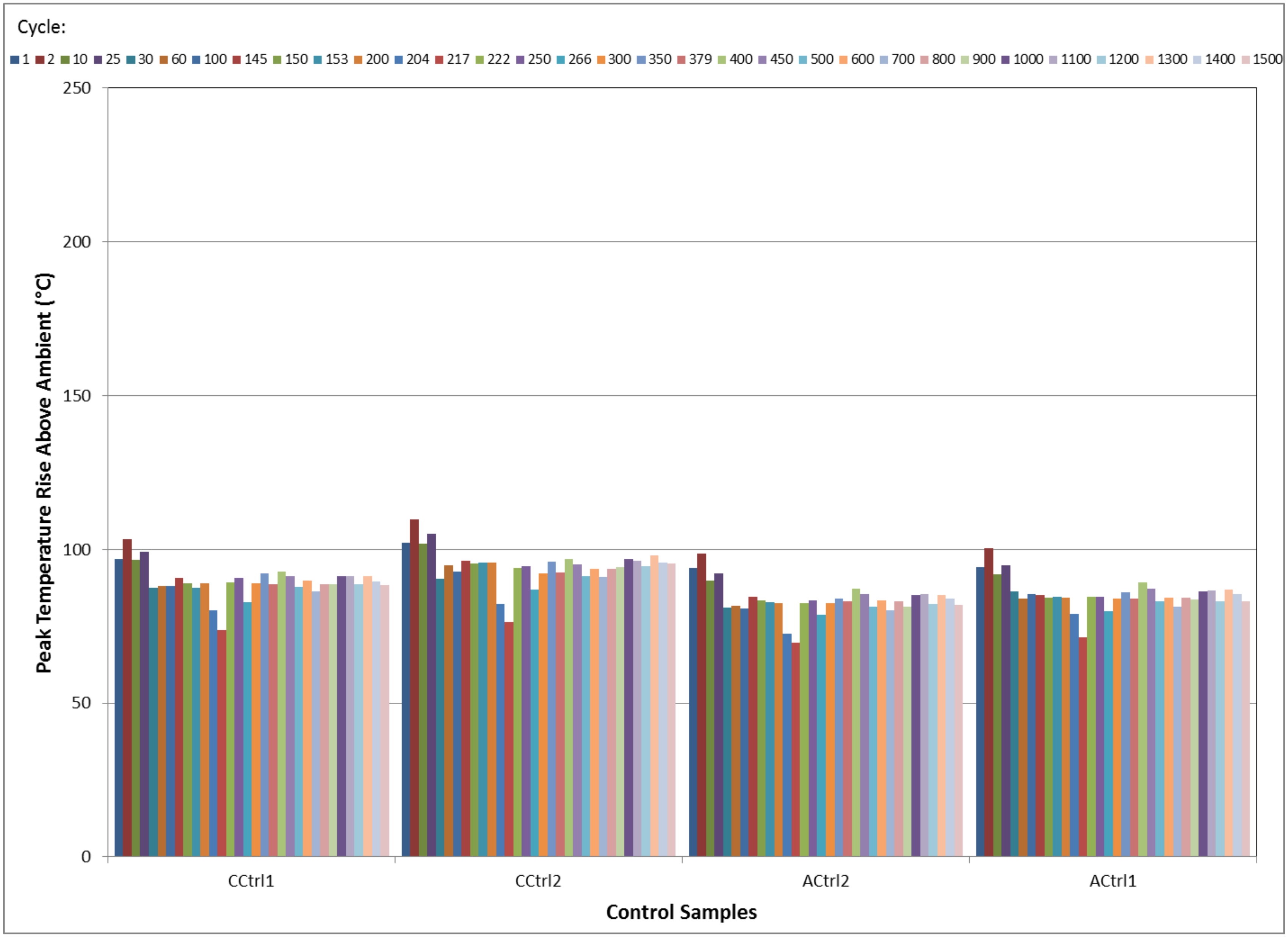

Figure 25. Peak temperature rise above ambient temperature of the control conductor samples.

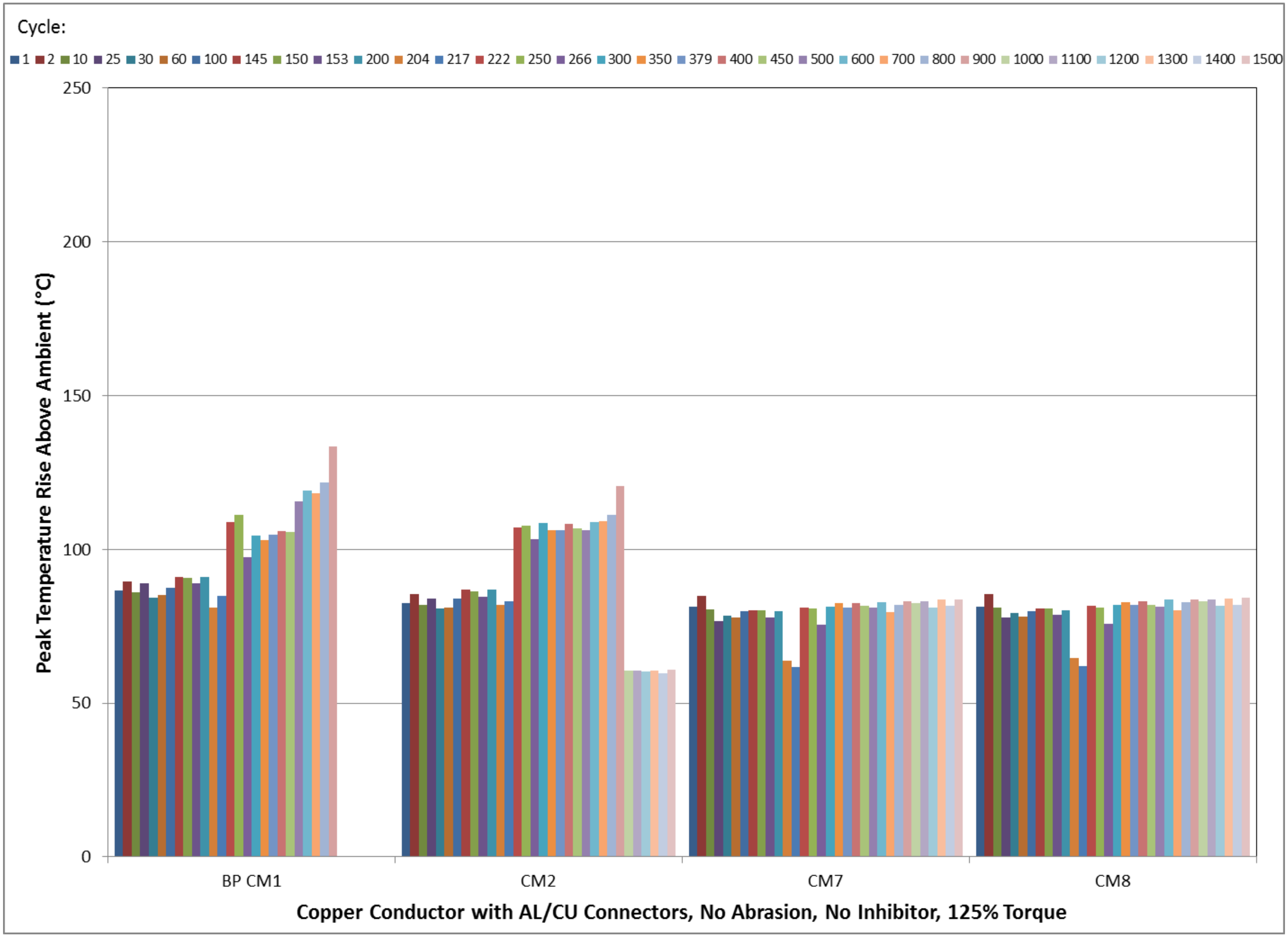

Figure 26. Peak temperature rise above ambient temperature of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test.

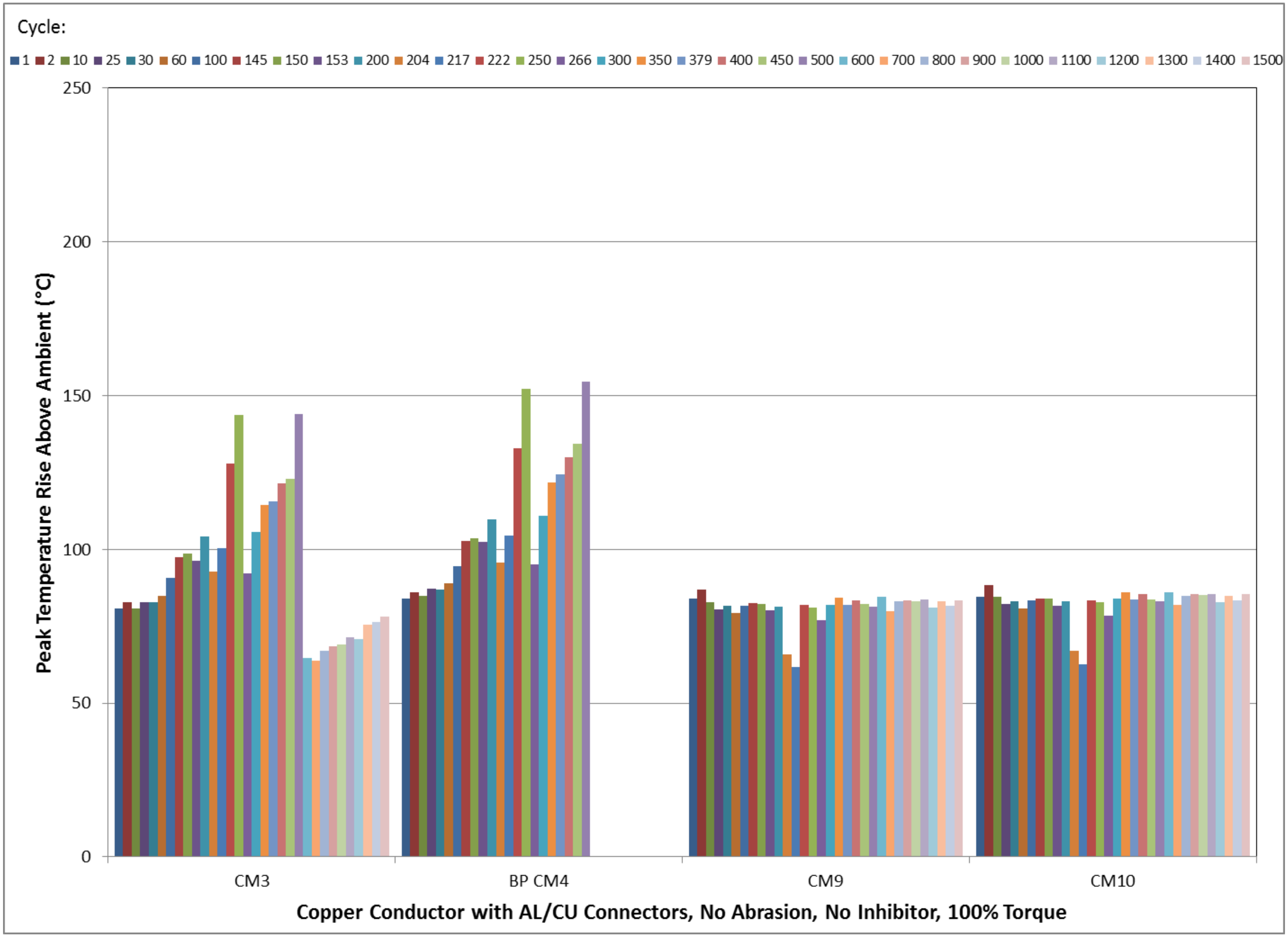

Figure 27. Peak temperature rise above ambient temperature of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test.

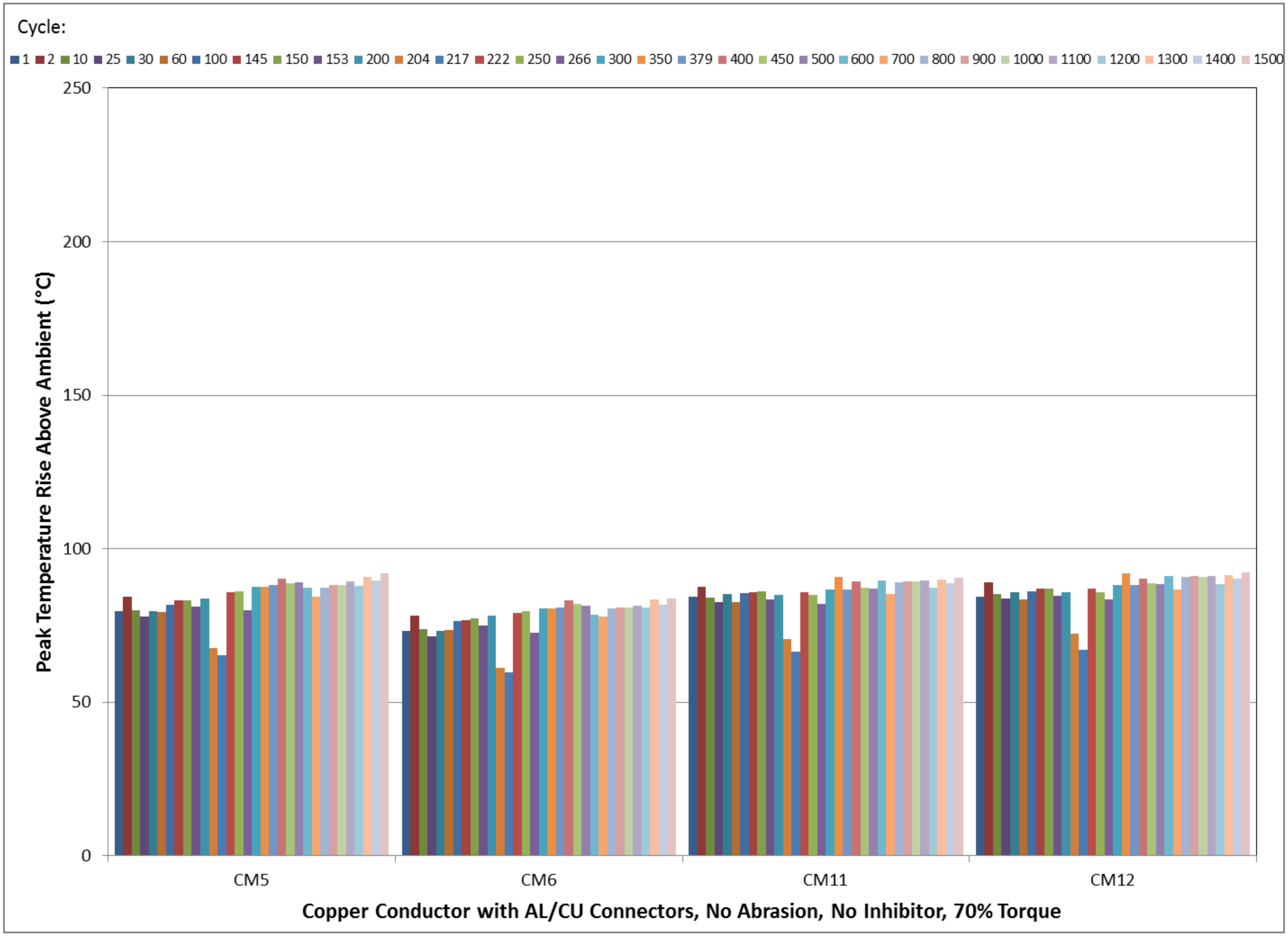

Figure 28. Peak temperature rise above ambient temperature of copper wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test.

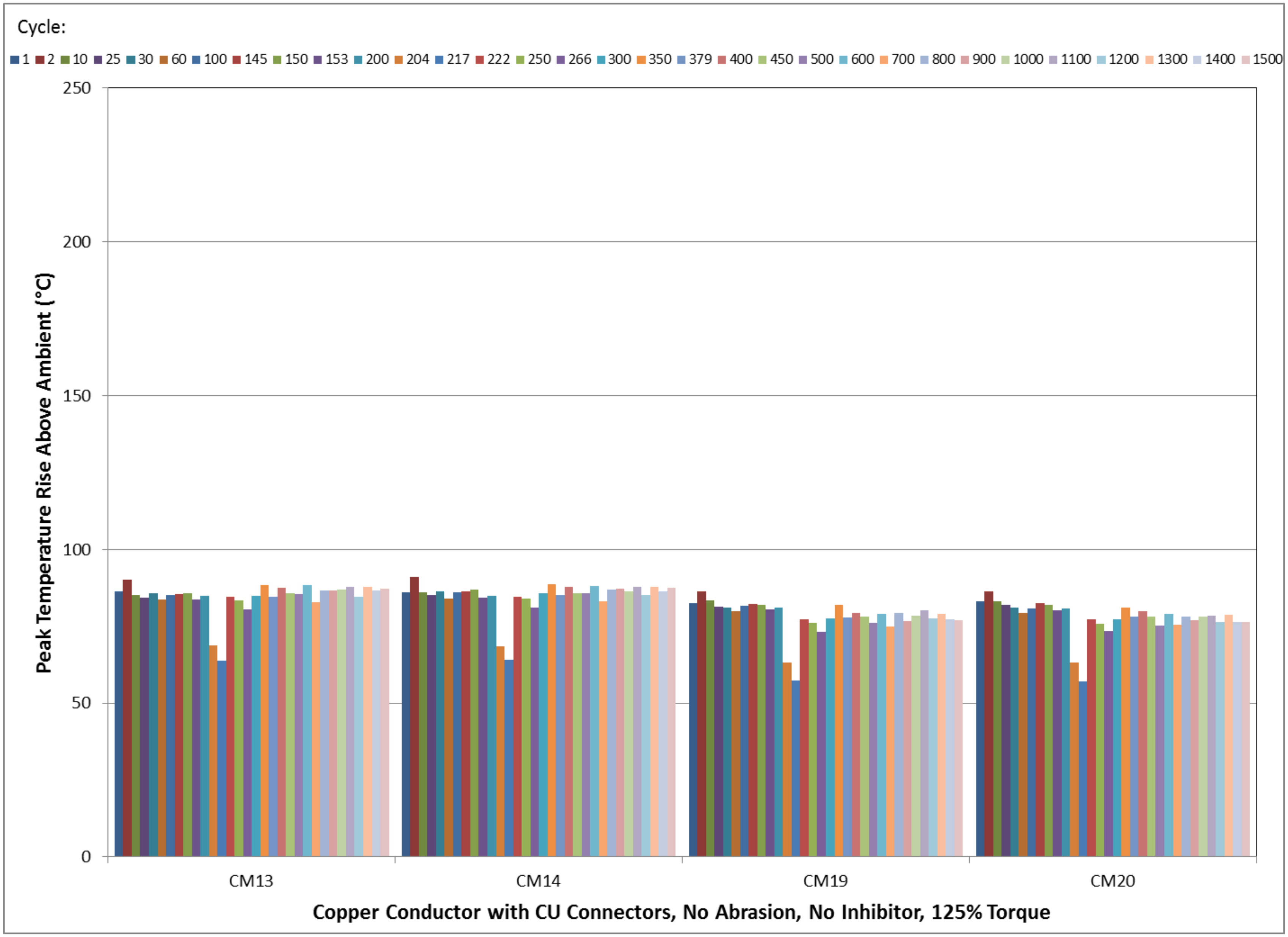

Figure 29. Peak temperature rise above ambient temperature of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test.

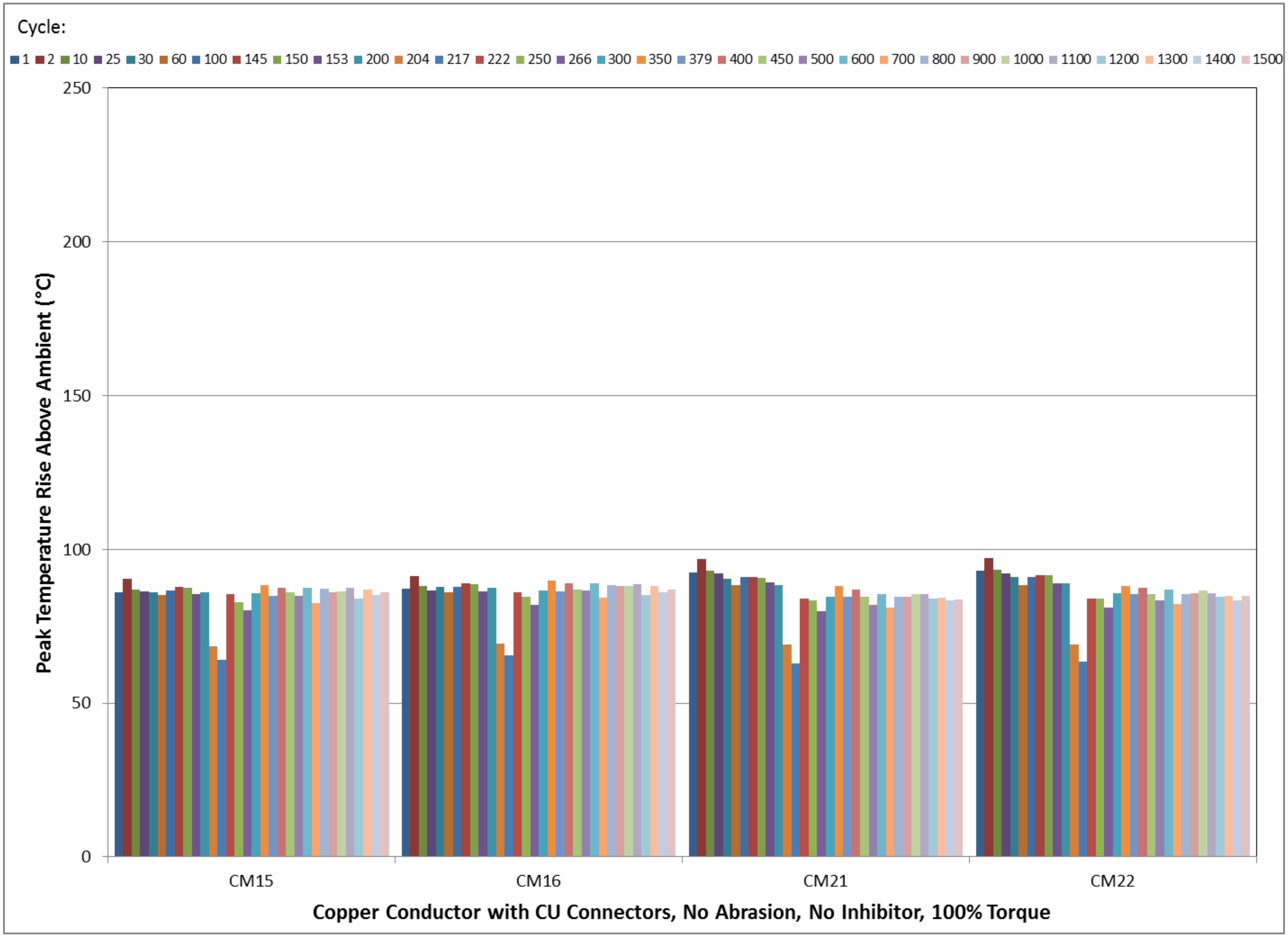

Figure 30. Peak temperature rise above ambient temperature of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test.

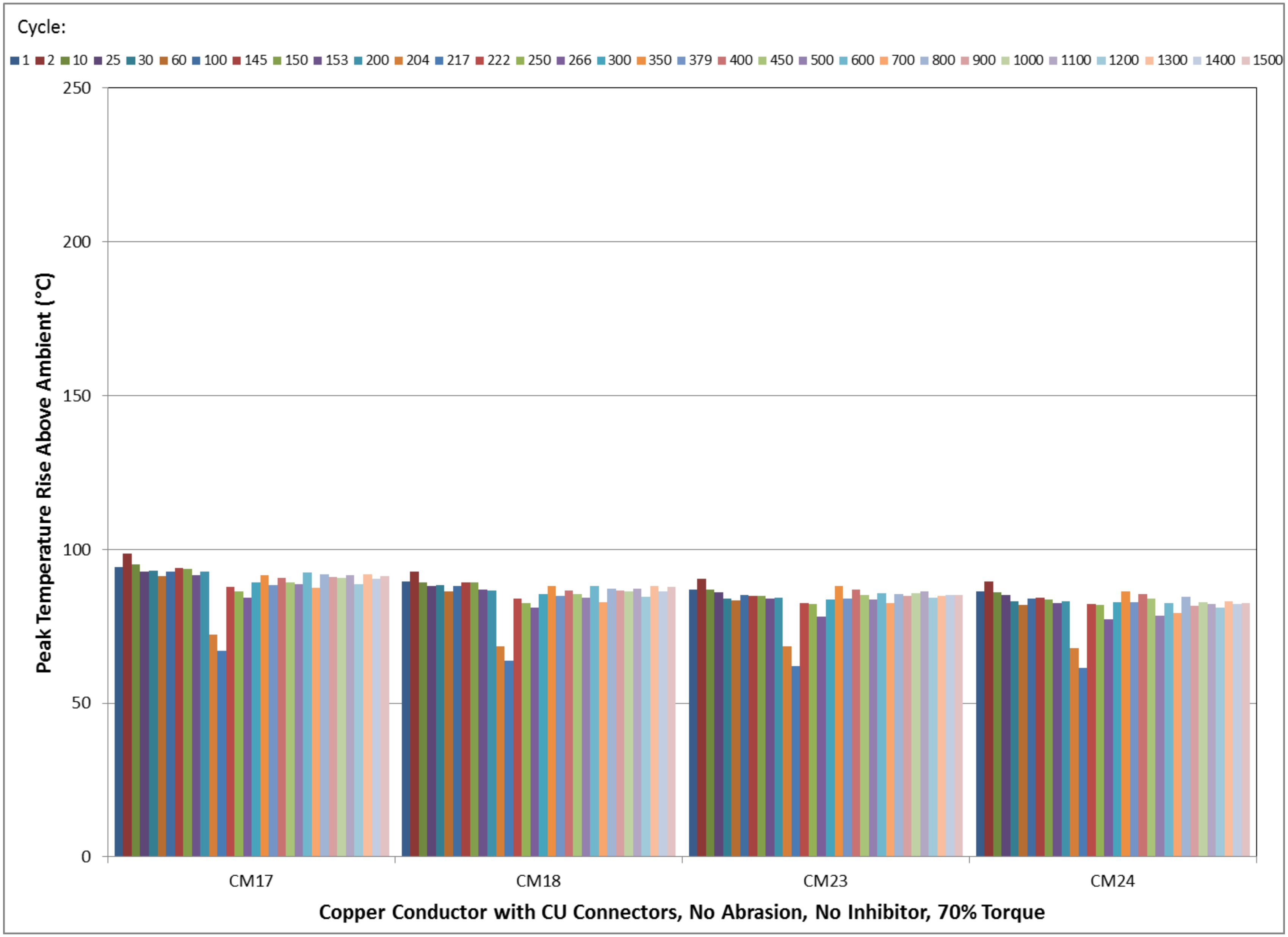

Figure 31. Peak temperature rise above ambient temperature of copper wire with CU connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test.

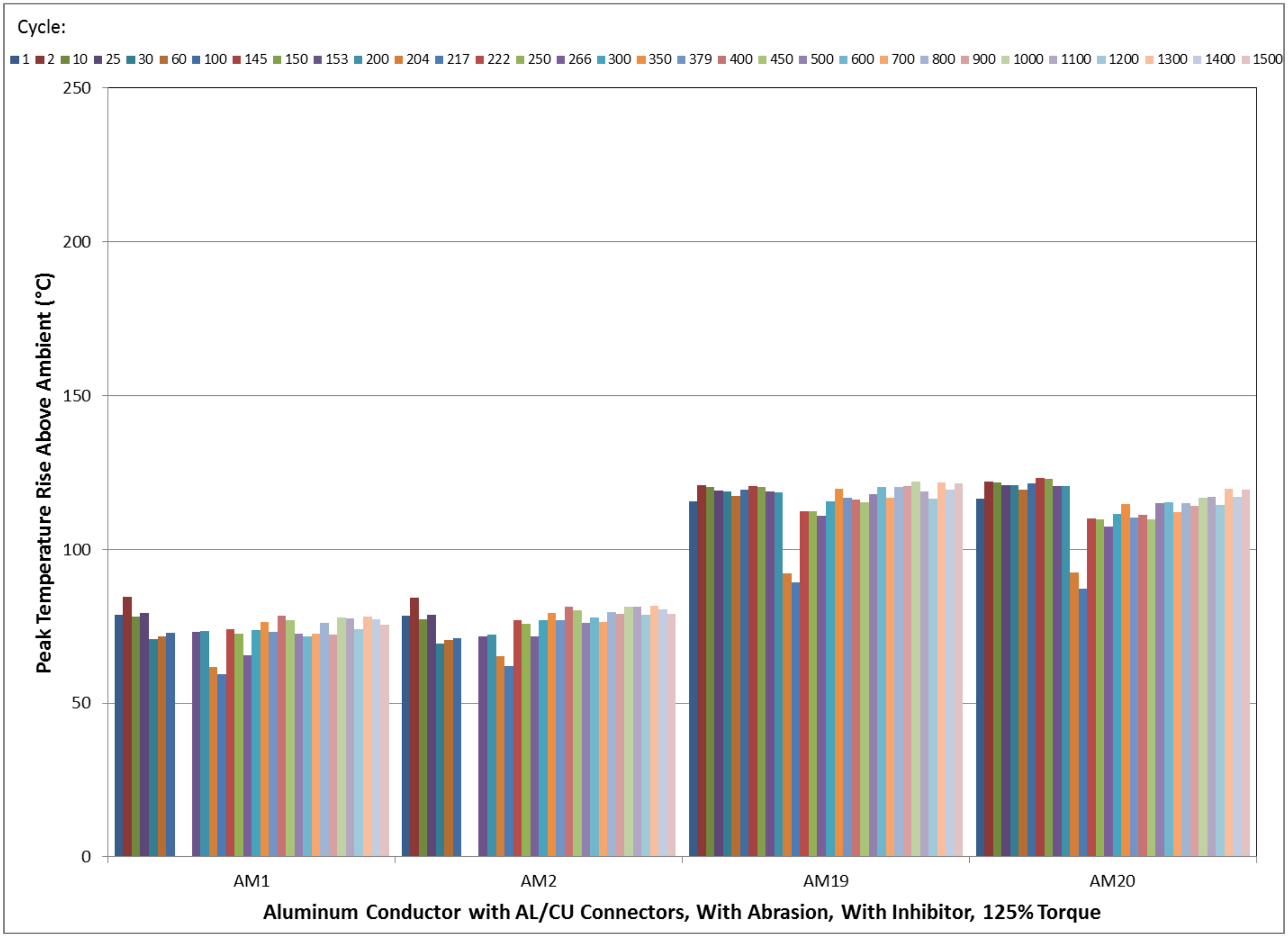

Figure 32. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 125% of rated torque at the start of the test.

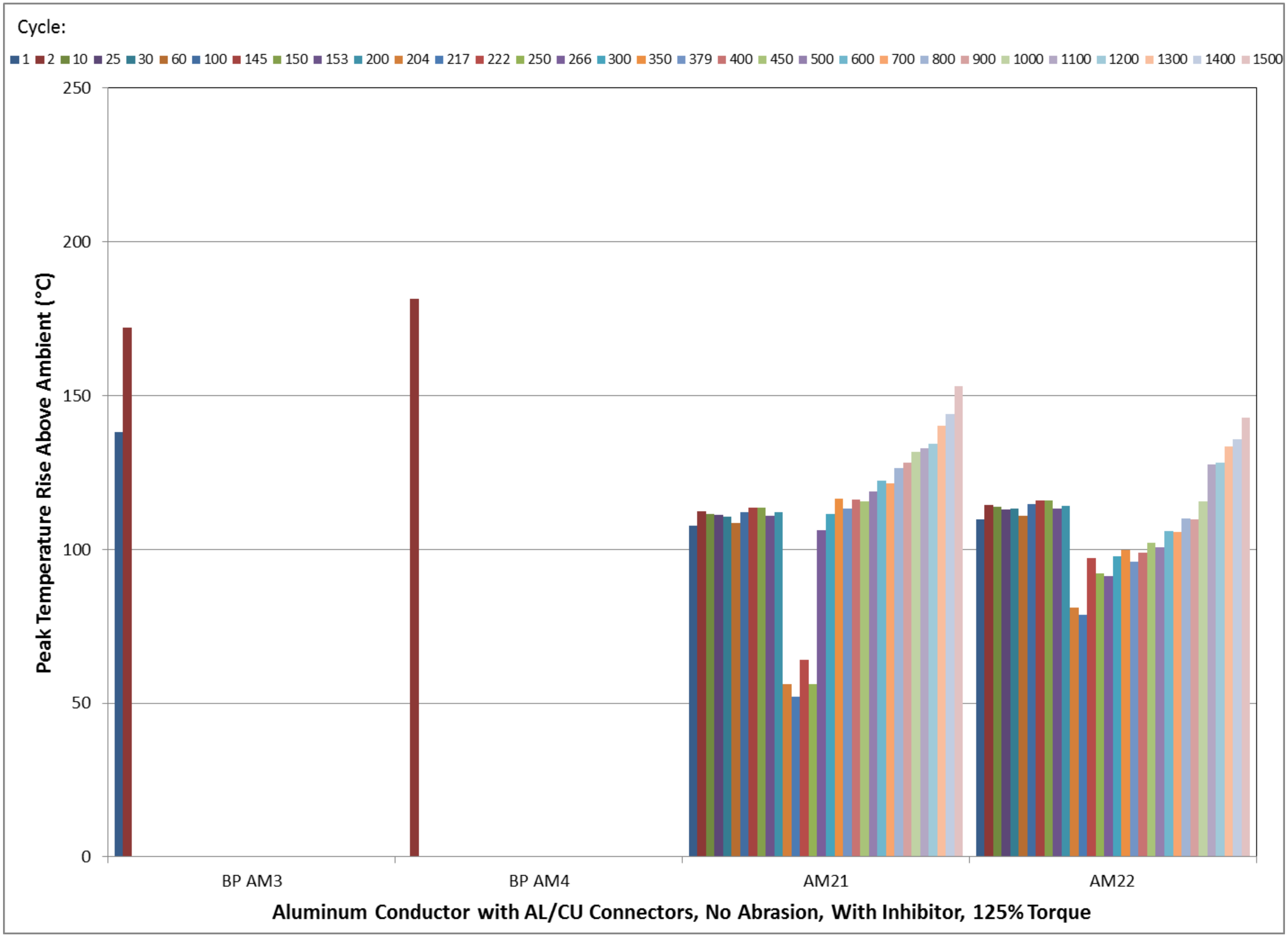

Figure 33. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 125% of rated torque at the start of the test.

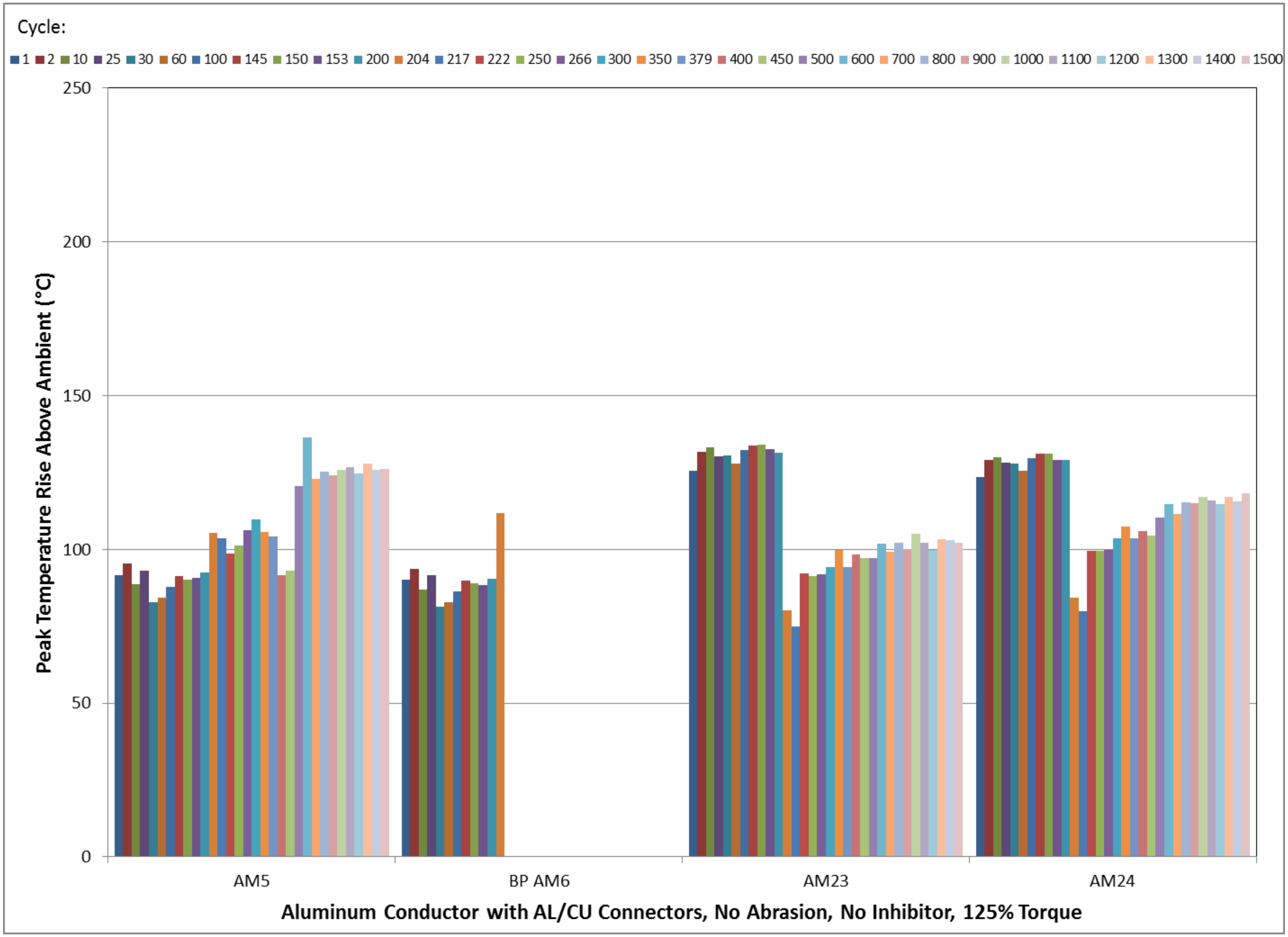

Figure 34. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 125% of rated torque at the start of the test.

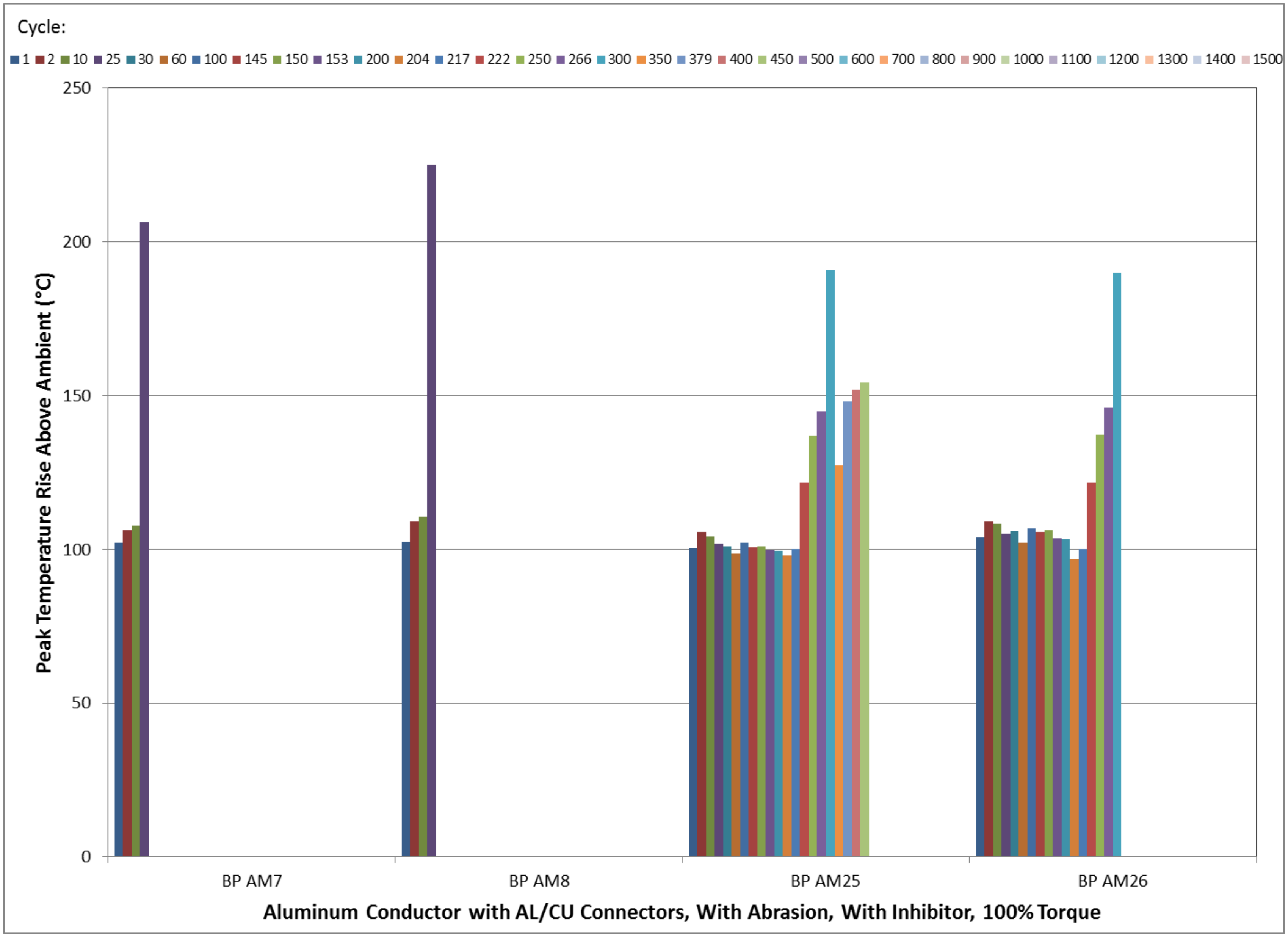

Figure 35. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 100% of rated torque at the start of the test.

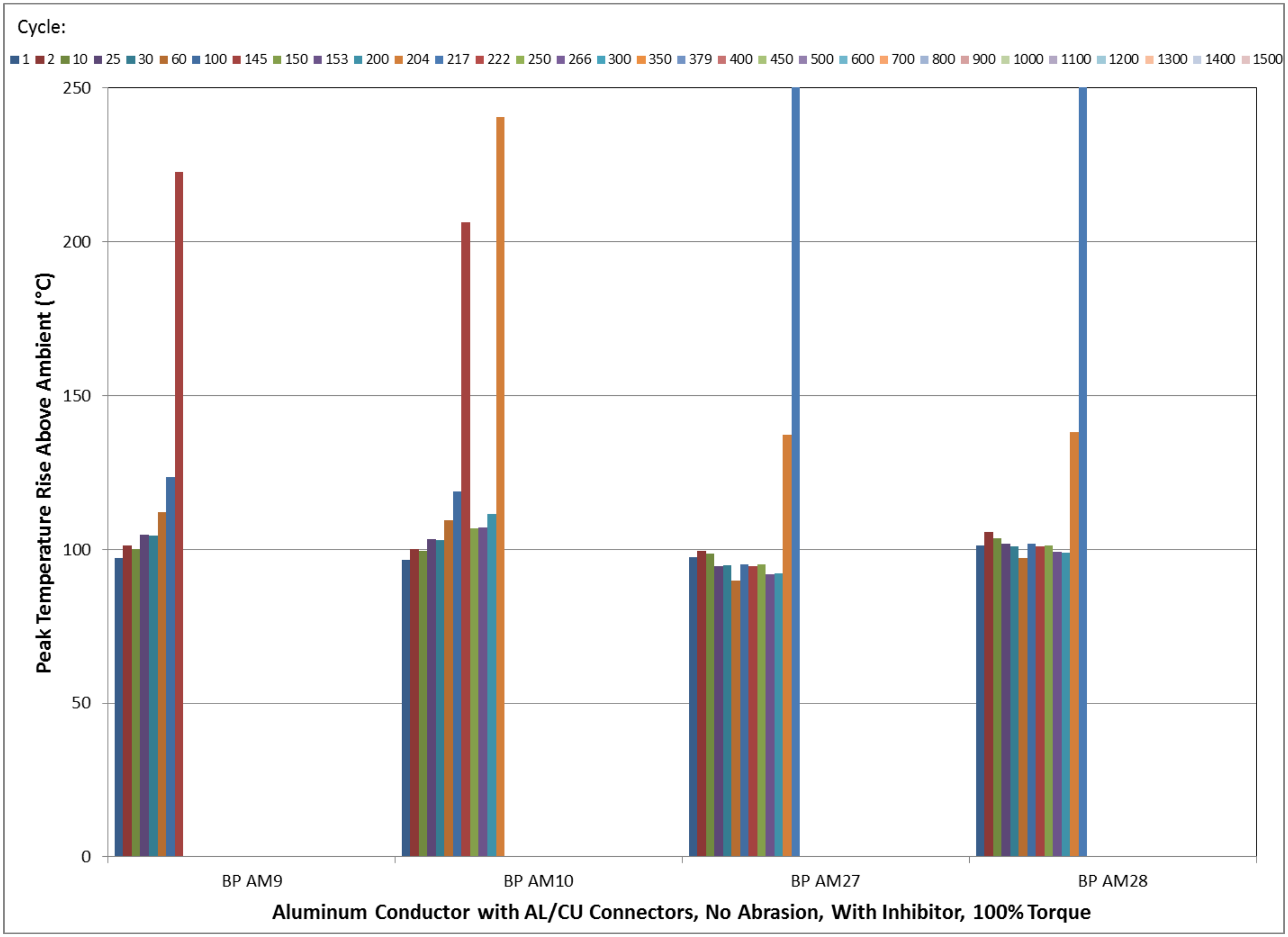

Figure 36. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 100% of rated torque at the start of the test.

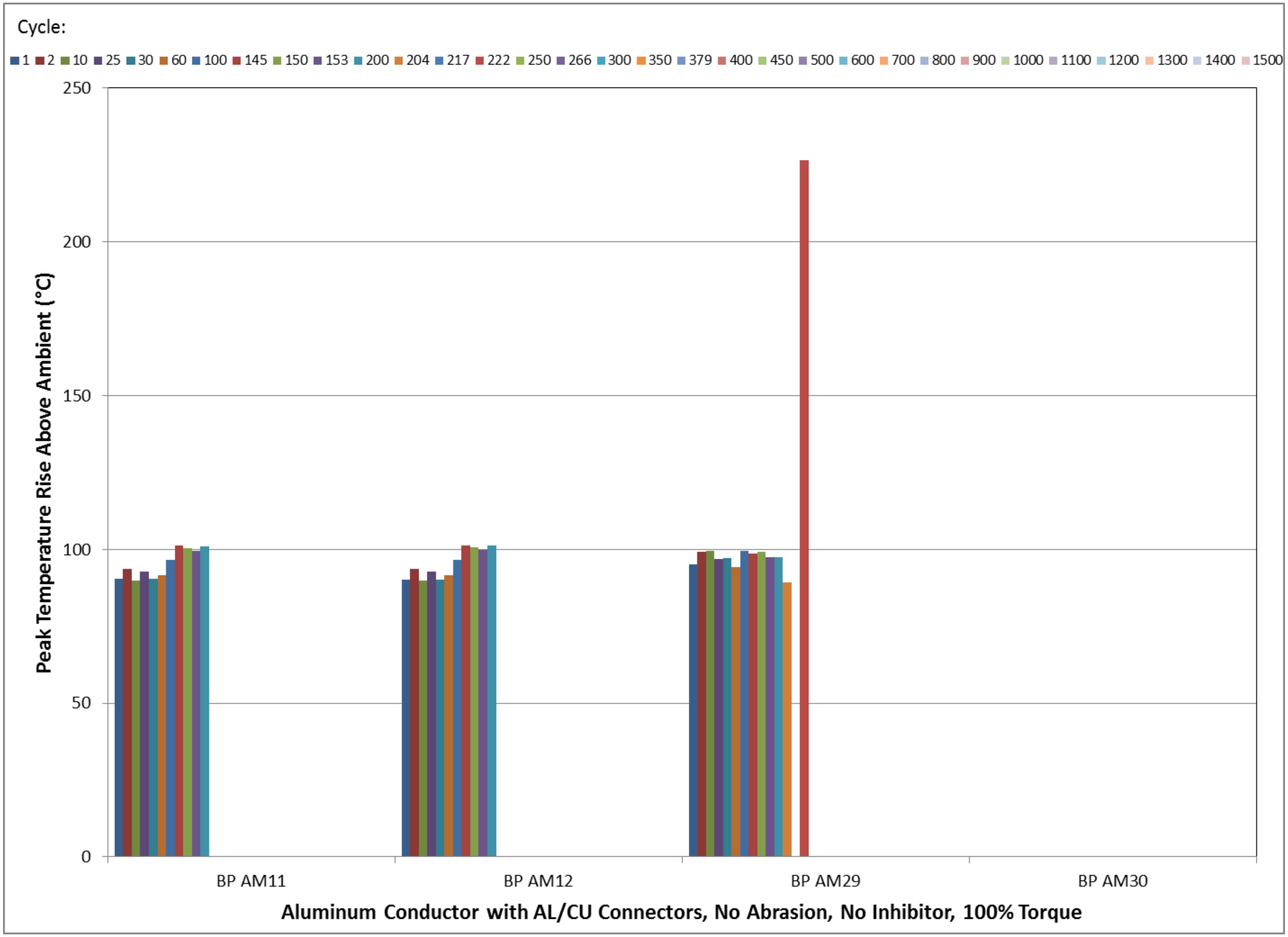

Figure 37. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 100% of rated torque at the start of the test.

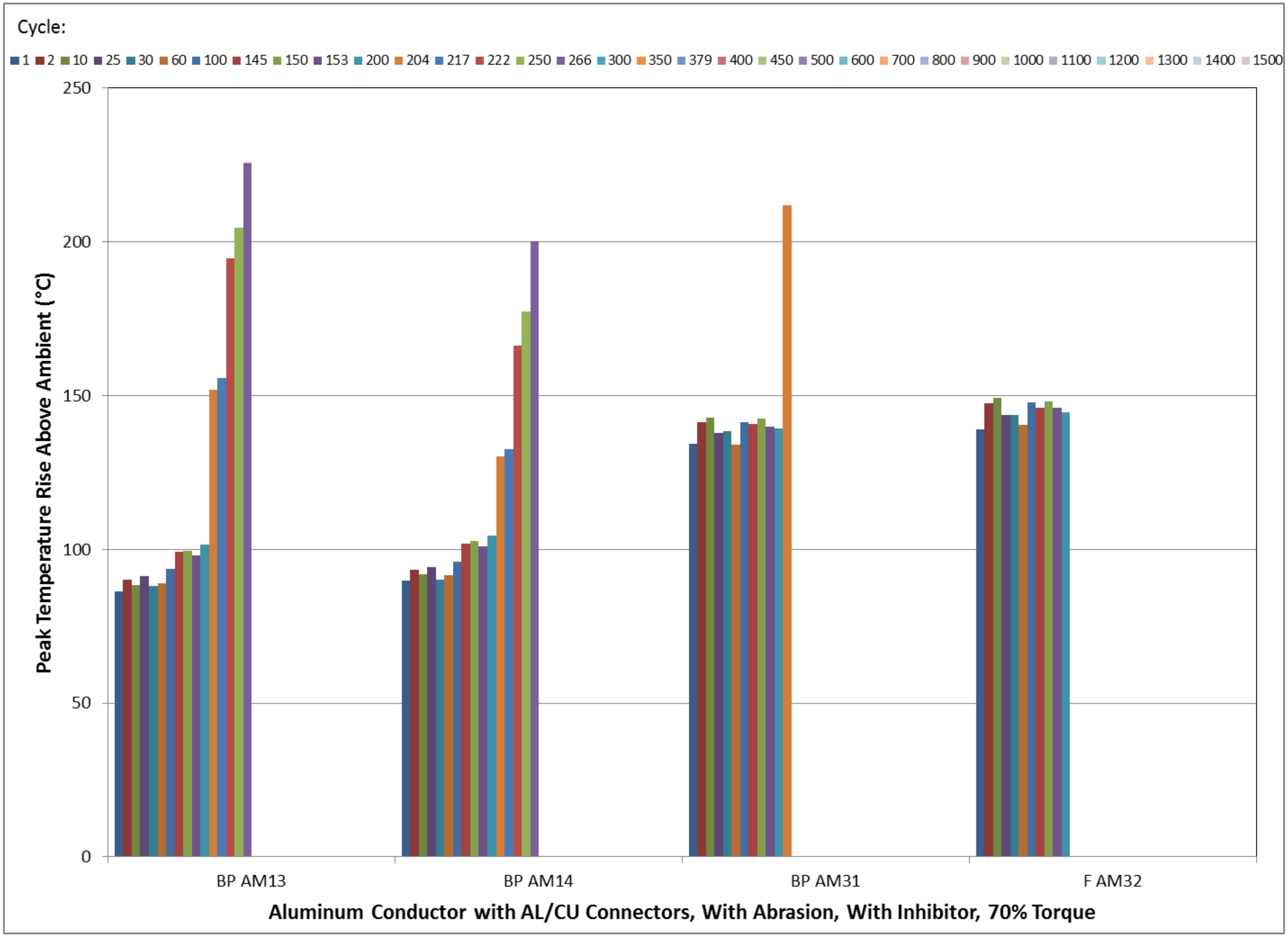

Figure 38. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, with wire abrasion, with oxide inhibitor applied, at 70% of rated torque at the start of the test.

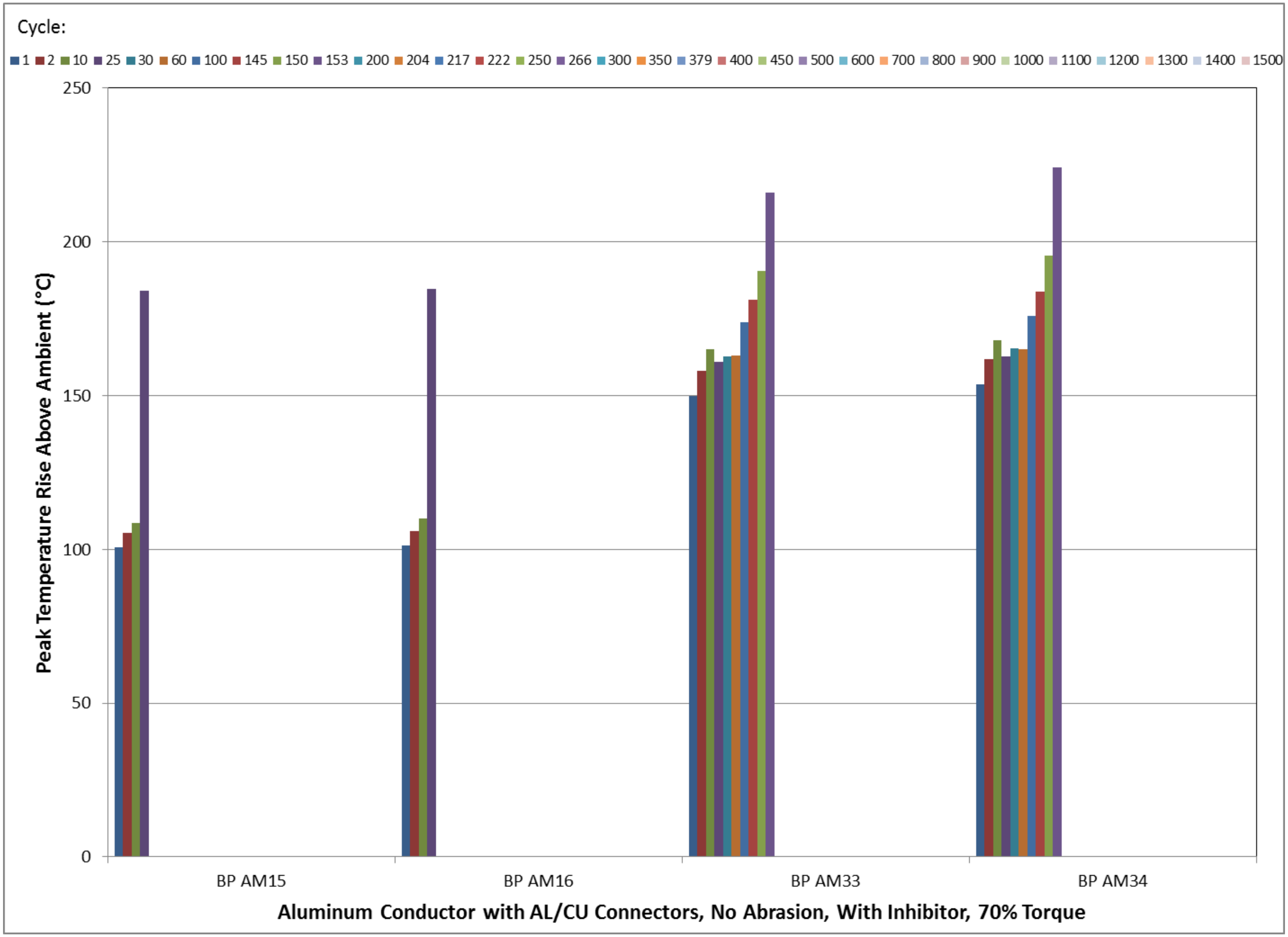

Figure 39. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, with oxide inhibitor applied, at 70% of rated torque at the start of the test.

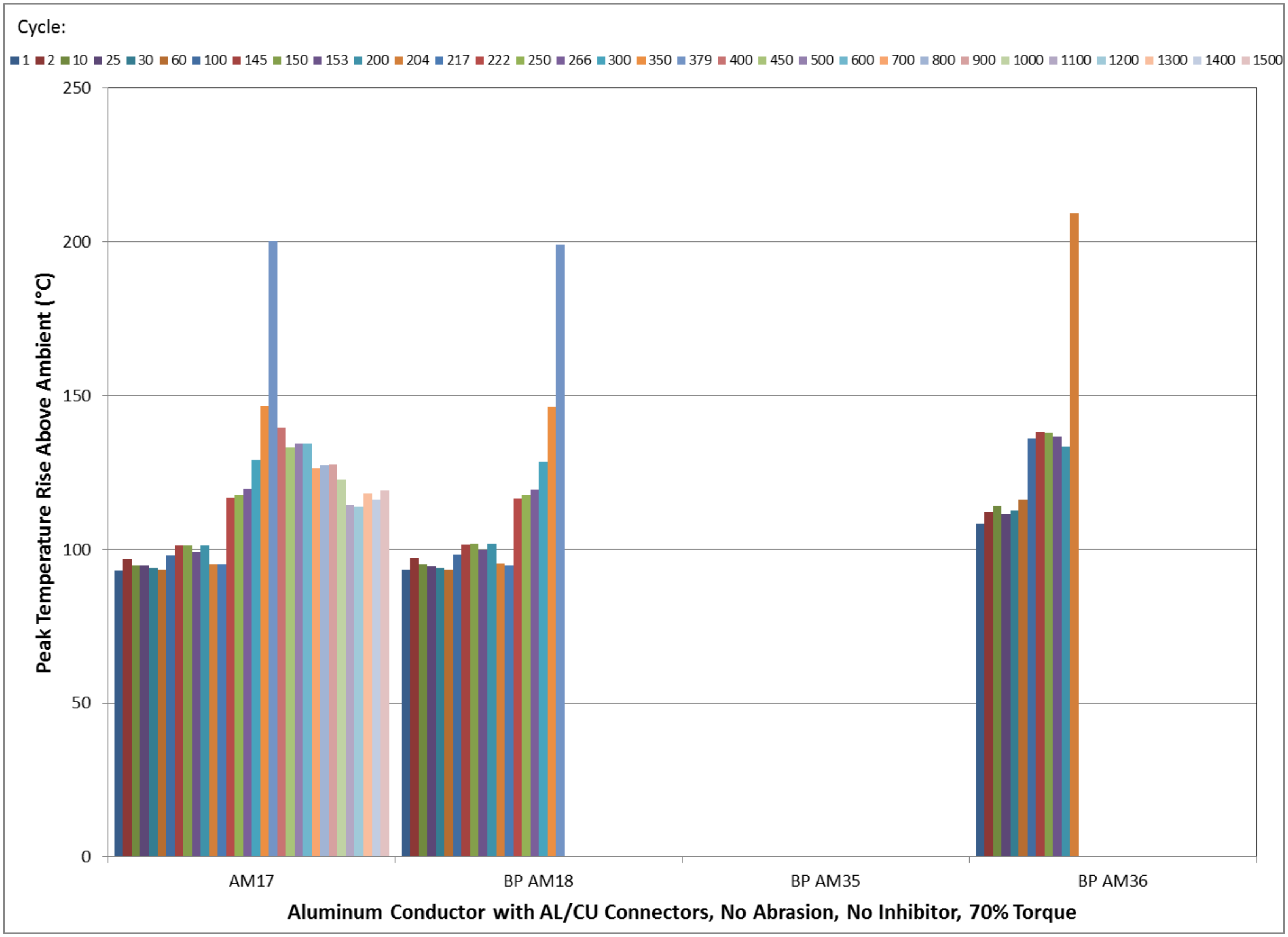

Figure 40. Peak temperature rise above ambient temperature of aluminum wire with AL/CU dual-rated connectors, no wire abrasion, no oxide inhibitor applied, at 70% of rated torque at the start of the test.

5.5 SAMPLES REMOVED DURING TESTING DUE TO 'FAILURE'

The list of samples that overheated or failed during testing are listed in Table 4, in order of the cycle in which they overheated or failed.

Table 4. Samples that were bypassed due to overheating or failure.

Failed at cycle	Sample No.	Abrasion	Inhibitor	Torque /Compression	Conductor	Type	Connector Rating
1	AM30	N	N	100%	2/0 Al	Mechanical	AL/CU
1	AM35	N	N	70%	2/0 Al	Mechanical	AL/CU
3	AM3	N	Y	125%	2/0 Al	Mechanical	AL/CU
3	AM4	N	Y	125%	2/0 Al	Mechanical	AL/CU
25	AM7	Y	Y	100%	2/0 Al	Mechanical	AL/CU
25	AM8	Y	Y	100%	2/0 Al	Mechanical	AL/CU
25	AM15	N	Y	70%	2/0 Al	Mechanical	AL/CU
25	AM16	N	Y	70%	2/0 Al	Mechanical	AL/CU
145	AM9	N	Y	100%	2/0 Al	Mechanical	AL/CU
153	AM33	N	Y	70%	2/0 Al	Mechanical	AL/CU
153	AM34	N	Y	70%	2/0 Al	Mechanical	AL/CU
200	AM32	Y	Y	70%	2/0 Al	Mechanical	AL/CU
201	AM11	N	N	100%	2/0 Al	Mechanical	AL/CU
201	AM12	N	N	100%	2/0 Al	Mechanical	AL/CU
204	AM6	N	N	125%	2/0 Al	Mechanical	AL/CU
204	AM10	N	Y	100%	2/0 Al	Mechanical	AL/CU
204	AM31	Y	Y	70%	2/0 Al	Mechanical	AL/CU
204	AM36	N	N	70%	2/0 Al	Mechanical	AL/CU
217	AM27	N	Y	100%	2/0 Al	Mechanical	AL/CU
217	AM28	N	Y	100%	2/0 Al	Mechanical	AL/CU
222	AM29	N	N	100%	2/0 Al	Mechanical	AL/CU
266	AM13	Y	Y	70%	2/0 Al	Mechanical	AL/CU
266	AM14	Y	Y	70%	2/0 Al	Mechanical	AL/CU
303	AM26	Y	Y	100%	2/0 Al	Mechanical	AL/CU
379	AM18	N	N	70%	2/0 Al	Mechanical	AL/CU
487	AM25	Y	Y	100%	2/0 Al	Mechanical	AL/CU
523	CM4	N	N	100%	#1 Cu	Mechanical	AL/CU
941	CM1	N	N	125%	#1 Cu	Mechanical	AL/CU

5.6 ANALYSIS OF THE RESULTS

The results were analyzed by comparing the change in corrected resistances and peak temperature rises above ambient for each type of connector sample at the end of the test. The change in resistance was determined as the percent difference between the values after 1500 cycles compared to the values after 25 cycles. A plot of the change in resistance for each connector after 1500 current cycles is shown in Figure 41. The peak temperature rise was determined as the difference between the peak connector temperature and the peak control conductor temperature at the end of the test. A plot of the temperature rise difference between each connector and the control conductors at 1500 current cycles is shown in Figure 42.

Table 5 gives a summary of the results for the connector samples by change in resistance and temperature, grouped by the type and preparation of the samples.

Table 5. Summary of sample performance by type and preparation.

Type	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Total No. Units	No. Showing >10% increase in resistance	No. with Connector Temp. > Control Temp.	No. Failed
Mechanical	#1 Cu	AL/CU	N	N	125%	4	2	1	1
Mechanical	#1 Cu	AL/CU	N	N	100%	4	1	1	1
Mechanical	#1 Cu	AL/CU	N	N	70%	4	1	1	0
Mechanical	#1 Cu	CU	N	N	125%	4	0	0	0
Mechanical	#1 Cu	CU	N	N	100%	4	0	0	0
Mechanical	#1 Cu	CU	N	N	70%	4	0	0	0
Mechanical	2/0 Al	AL/CU	Y	Y	125%	4	1	2	0
Mechanical	2/0 Al	AL/CU	N	Y	125%	4	4	4	2
Mechanical	2/0 Al	AL/CU	N	N	125%	4	2	4	1
Mechanical	2/0 Al	AL/CU	Y	Y	100%	4	4	4	4
Mechanical	2/0 Al	AL/CU	N	Y	100%	4	4	4	4
Mechanical	2/0 Al	AL/CU	N	N	100%	4	4	4	4
Mechanical	2/0 Al	AL/CU	Y	Y	70%	4	4	4	4
Mechanical	2/0 Al	AL/CU	N	Y	70%	4	4	4	4
Mechanical	2/0 Al	AL/CU	N	N	70%	4	4	4	3

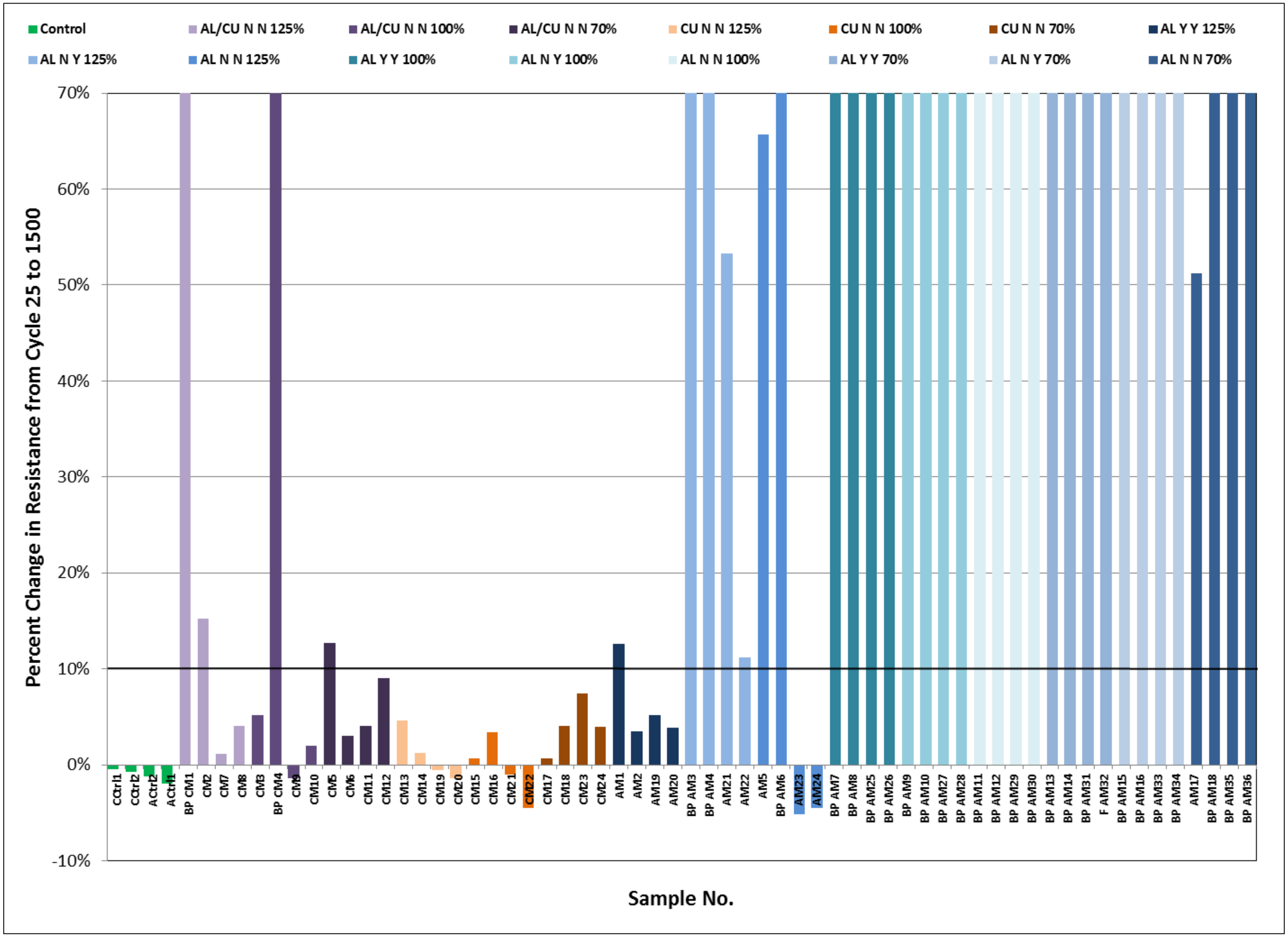

Figure 41. Change in corrected resistance from cycle 25 to cycle 1500 for each sample. Samples are grouped by type and preparation. Solid bars indicate samples that failed and were removed from the test.

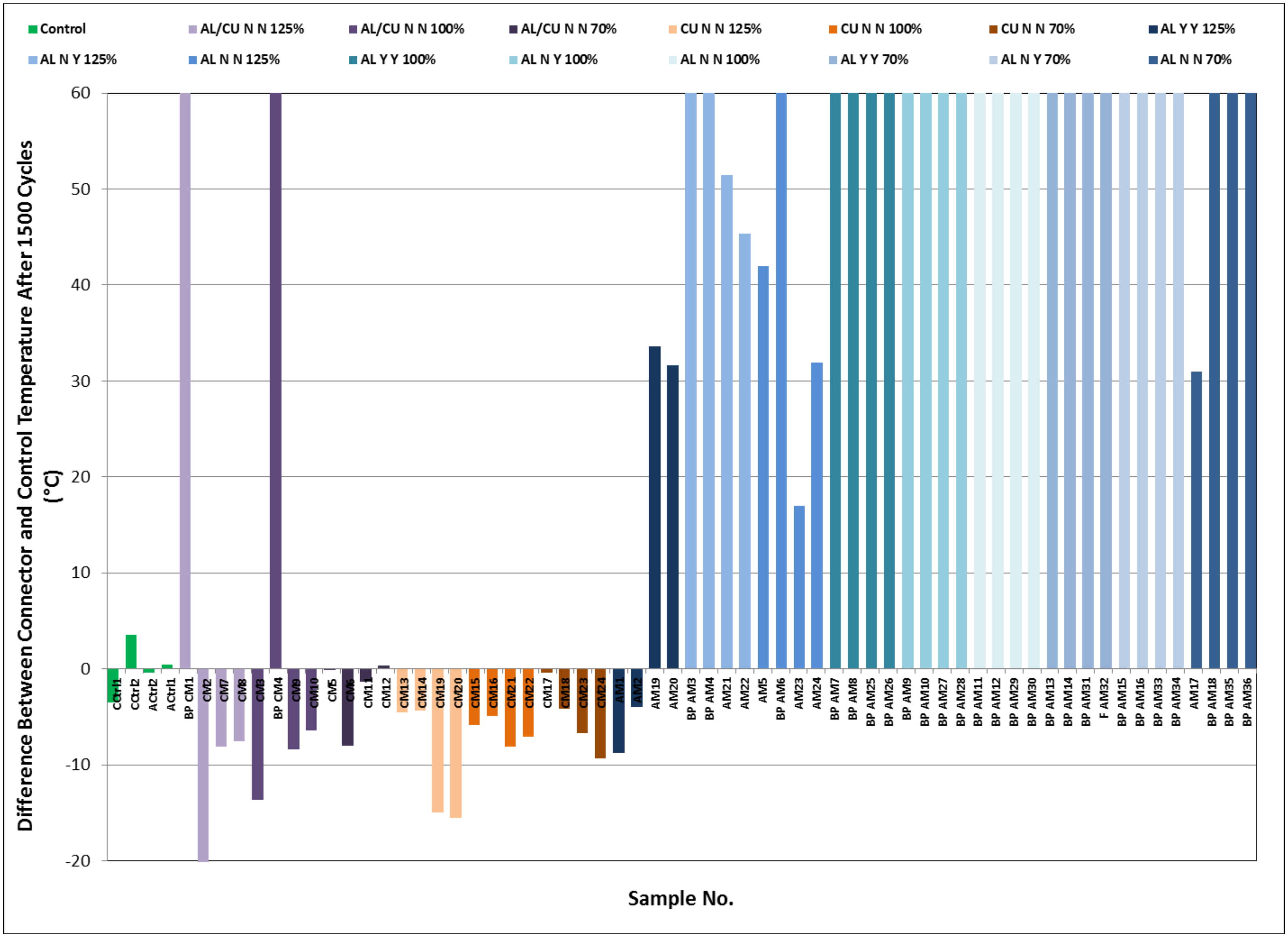

Figure 42. Difference between connector temperature rise and control conductor temperature rise after cycle 1500 for each sample. Samples are grouped by type and preparation. Solid bars indicate samples that failed and were removed from the test.

6. ANALYSIS BY IEC 61238-1 METHODOLOGY

The standard IEC 61238-1 (2003-05), "Compression and mechanical connectors for power cables for rated voltages up to 30 kV (Um = 36 kV)", was used as a guide for evaluating samples. The standard uses the following criteria to evaluate the performance:

- Initial scatter of resistance values for all connectors of the same type at the start of the test.
- Mean scatter of resistance values for all connectors of the same type throughout the test.
- Change in resistance factor[2] of each connector throughout the test.
- Resistance factor ratio of each connector, comparing the resistance factor at the end of the test to the start of the test.
- Maximum temperature difference between each connector compared to the control (reference) conductor temperature.
- Evaluation of the values up to cycle 1000.

Of these values, the initial scatter and mean scatter are not applicable since there are not enough samples of each type and preparation to make these values meaningful. Due to variations in the test procedure compared to the IEC standard procedure, the change in resistance factor was not evaluated.

The maximum values required by IEC 61238-1 are:

- Resistance factor ratio ≤ 2.0
- Maximum connector temperature $\leq \theta_{ref}$ (θ_{ref} = max. temperature of the control conductor)

A summary of the IEC analysis is shown in Table 6. The resistance ratio values and maximum connector temperature for each type of connector are summarized in Table 7 and Table 8 respectively, and are shown in Figure 43 and Figure 44.

[2] The resistance factor is a dimensionless value that is defined as the ratio of the resistance per unit length of the connector to that for the control conductor.

Table 6. Summary of IEC Analysis.

Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Results of IEC Analysis (see Note (1) below)			
					Resistance Factor Ratio		Maximum Temperature Difference (sample-control)	
					No. Pass	No. Fail	No. Pass	No. Fail
#1 Cu	AL/CU	N	N	125%	1	3	2	2
#1 Cu	AL/CU	N	N	100%	2	2	2	2
#1 Cu	AL/CU	N	N	70%	2	2	4	0
#1 Cu	CU	N	N	125%	4	0	4	0
#1 Cu	CU	N	N	100%	4	0	2	2(2)
#1 Cu	CU	N	N	70%	4	0	3	1(2)
2/0 Al	AL/CU	Y	Y	125%	2	2	2	2
2/0 Al	AL/CU	N	Y	125%	1	3	0	4
2/0 Al	AL/CU	N	N	125%	1	3	0	4
2/0 Al	AL/CU	Y	Y	100%	0	4	0	4
2/0 Al	AL/CU	N	Y	100%	0	4	0	4
2/0 Al	AL/CU	N	N	100%	0	4	0	4
2/0 Al	AL/CU	Y	Y	70%	0	4	0	4
2/0 Al	AL/CU	N	Y	70%	0	4	0	4
2/0 Al	AL/CU	N	N	70%	0	4	0	4

Note (1):

- Any resistance factor ratio > 2.0 or maximum connector temperature that exceeds the control conductor temperature at any time during the test is considered a 'failure' by IEC. There is no method to differentiate connectors that exceeded the limit by a small amount and those that exceeded the limit by a large amount. There is also no allowance for connectors that briefly exceed the limit in the middle of the test, but then drop below the limit by the end of the test.

Note (2):

- The copper connectors on copper wire, with 100% and 70% torque applied, exceeded the control conductor temperature by a small amount in the middle of the test, but dropped below the control conductor temperature by the end of the test.

Table 7. Results of evaluation of resistance factor ratio for IEC.

Sample No.	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Resistance factor ratio	Pass/Fail
BP CM1	#1 Cu	AL/CU	N	N	125%	did not finish	fail
CM2	#1 Cu	AL/CU	N	N	125%	3.17	fail
CM7	#1 Cu	AL/CU	N	N	125%	2.07	fail
CM8	#1 Cu	AL/CU	N	N	125%	1.72	pass
CM3	#1 Cu	AL/CU	N	N	100%	9.16	fail
BP CM4	#1 Cu	AL/CU	N	N	100%	did not finish	fail
CM9	#1 Cu	AL/CU	N	N	100%	1.84	pass
CM10	#1 Cu	AL/CU	N	N	100%	1.89	pass
CM5	#1 Cu	AL/CU	N	N	70%	2.81	fail
CM6	#1 Cu	AL/CU	N	N	70%	2.28	fail
CM11	#1 Cu	AL/CU	N	N	70%	1.93	pass
CM12	#1 Cu	AL/CU	N	N	70%	1.76	pass
CM13	#1 Cu	CU	N	N	125%	1.33	pass
CM14	#1 Cu	CU	N	N	125%	1.35	pass
CM19	#1 Cu	CU	N	N	125%	1.18	pass
CM20	#1 Cu	CU	N	N	125%	1.48	pass
CM15	#1 Cu	CU	N	N	100%	1.40	pass
CM16	#1 Cu	CU	N	N	100%	1.28	pass
CM21	#1 Cu	CU	N	N	100%	1.17	pass
CM22	#1 Cu	CU	N	N	100%	1.00	pass
CM17	#1 Cu	CU	N	N	70%	1.14	pass
CM18	#1 Cu	CU	N	N	70%	1.25	pass
CM23	#1 Cu	CU	N	N	70%	1.41	pass
CM24	#1 Cu	CU	N	N	70%	1.43	pass
AM1	2/0 Al	AL/CU	Y	Y	125%	1.94	pass
AM2	2/0 Al	AL/CU	Y	Y	125%	1.49	pass
AM19	2/0 Al	AL/CU	Y	Y	125%	3.25	fail
AM20	2/0 Al	AL/CU	Y	Y	125%	2.26	fail
BP AM3	2/0 Al	AL/CU	N	Y	125%	did not finish	fail
BP AM4	2/0 Al	AL/CU	N	Y	125%	did not finish	fail
AM21	2/0 Al	AL/CU	N	Y	125%	3.51	fail
AM22	2/0 Al	AL/CU	N	Y	125%	1.95	pass
AM5	2/0 Al	AL/CU	N	N	125%	5.42	fail
BP AM6	2/0 Al	AL/CU	N	N	125%	did not finish	fail
AM23	2/0 Al	AL/CU	N	N	125%	2.77	fail
AM24	2/0 Al	AL/CU	N	N	125%	1.58	pass

Table 8. Results of evaluation of resistance factor ratio for IEC – cont'd.

Sample No.	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Difference Between Connector and Control Temperature	Pass/Fail
BP AM7	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM8	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM25	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM26	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM9	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM10	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM27	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM28	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM11	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM12	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM29	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM30	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM13	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM14	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM31	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
F AM32	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM15	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM16	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM33	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM34	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
AM17	2/0 Al	AL/CU	N	N	70%	5.27	fail
BP AM18	2/0 Al	AL/CU	N	N	70%	did not finish	fail
BP AM35	2/0 Al	AL/CU	N	N	70%	did not finish	fail
BP AM36	2/0 Al	AL/CU	N	N	70%	did not finish	fail

Table 9. Results of evaluation of maximum connector temperature for IEC.

Sample No.	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Difference Between Connector and Control Temperature	Pass/Fail
BP CM1	#1 Cu	AL/CU	N	N	125%	did not finish	fail
CM2	#1 Cu	AL/CU	N	N	125%	28.95	fail
CM7	#1 Cu	AL/CU	N	N	125%	-8.55	pass
CM8	#1 Cu	AL/CU	N	N	125%	-7.95	pass
CM3	#1 Cu	AL/CU	N	N	100%	54.45	fail
BP CM4	#1 Cu	AL/CU	N	N	100%	did not finish	fail
CM9	#1 Cu	AL/CU	N	N	100%	-7.4	pass
CM10	#1 Cu	AL/CU	N	N	100%	-5.8	pass
CM5	#1 Cu	AL/CU	N	N	70%	-0.65	pass
CM6	#1 Cu	AL/CU	N	N	70%	-8.15	pass
CM11	#1 Cu	AL/CU	N	N	70%	-2.15	pass
CM12	#1 Cu	AL/CU	N	N	70%	-0.35	pass
CM13	#1 Cu	CU	N	N	125%	-3.35	pass
CM14	#1 Cu	CU	N	N	125%	-2.55	pass
CM19	#1 Cu	CU	N	N	125%	-8.05	pass
CM20	#1 Cu	CU	N	N	125%	-8.05	pass
CM15	#1 Cu	CU	N	N	100%	-3.05	pass
CM16	#1 Cu	CU	N	N	100%	-1.25	pass
CM21	#1 Cu	CU	N	N	100%	1.35	fail
CM22	#1 Cu	CU	N	N	100%	2.05	fail
CM17	#1 Cu	CU	N	N	70%	3.95	fail
CM18	#1 Cu	CU	N	N	70%	-0.55	pass
CM23	#1 Cu	CU	N	N	70%	-4.95	pass
CM24	#1 Cu	CU	N	N	70%	-5.95	pass
AM1	2/0 Al	AL/CU	Y	Y	125%	-7.5	pass
AM2	2/0 Al	AL/CU	Y	Y	125%	-3.7	pass
AM19	2/0 Al	AL/CU	Y	Y	125%	37.9	fail
AM20	2/0 Al	AL/CU	Y	Y	125%	39.05	fail
BP AM3	2/0 Al	AL/CU	N	Y	125%	did not finish	fail
BP AM4	2/0 Al	AL/CU	N	Y	125%	did not finish	fail
AM21	2/0 Al	AL/CU	N	Y	125%	45.95	fail
AM22	2/0 Al	AL/CU	N	Y	125%	32.15	fail
AM5	2/0 Al	AL/CU	N	N	125%	52.5	fail
BP AM6	2/0 Al	AL/CU	N	N	125%	did not finish	fail
AM23	2/0 Al	AL/CU	N	N	125%	50.15	fail
AM24	2/0 Al	AL/CU	N	N	125%	47.35	fail

Table 10. Results of evaluation of maximum connector temperature for IEC – cont'd.

Sample No.	Conductor	Connector Rating	Abrasion	Inhibitor	Torque	Difference Between Connector and Control Temperature	Pass/Fail
BP AM7	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM8	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM25	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM26	2/0 Al	AL/CU	Y	Y	100%	did not finish	fail
BP AM9	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM10	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM27	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM28	2/0 Al	AL/CU	N	Y	100%	did not finish	fail
BP AM11	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM12	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM29	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM30	2/0 Al	AL/CU	N	N	100%	did not finish	fail
BP AM13	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM14	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM31	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
F AM32	2/0 Al	AL/CU	Y	Y	70%	did not finish	fail
BP AM15	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM16	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM33	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
BP AM34	2/0 Al	AL/CU	N	Y	70%	did not finish	fail
AM17	2/0 Al	AL/CU	N	N	70%	116.6	fail
BP AM18	2/0 Al	AL/CU	N	N	70%	did not finish	fail
BP AM35	2/0 Al	AL/CU	N	N	70%	did not finish	fail
BP AM36	2/0 Al	AL/CU	N	N	70%	did not finish	fail

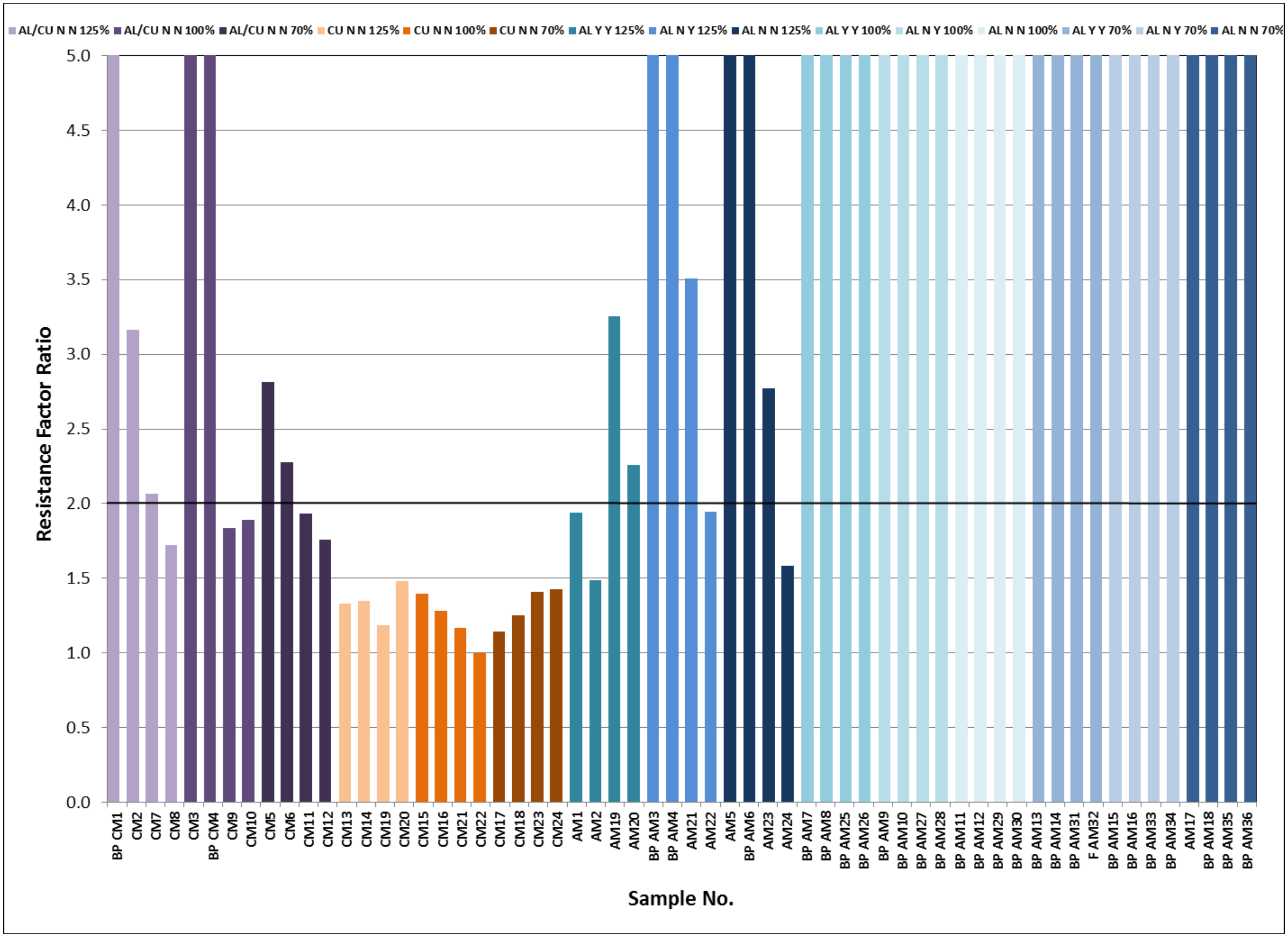

Figure 43. IEC resistance factor ratio for each sample, with the maximum IEC limit indicated by a line at 2.0. Samples are grouped by type and preparation. Solid bars indicate samples that failed and were removed from the test.

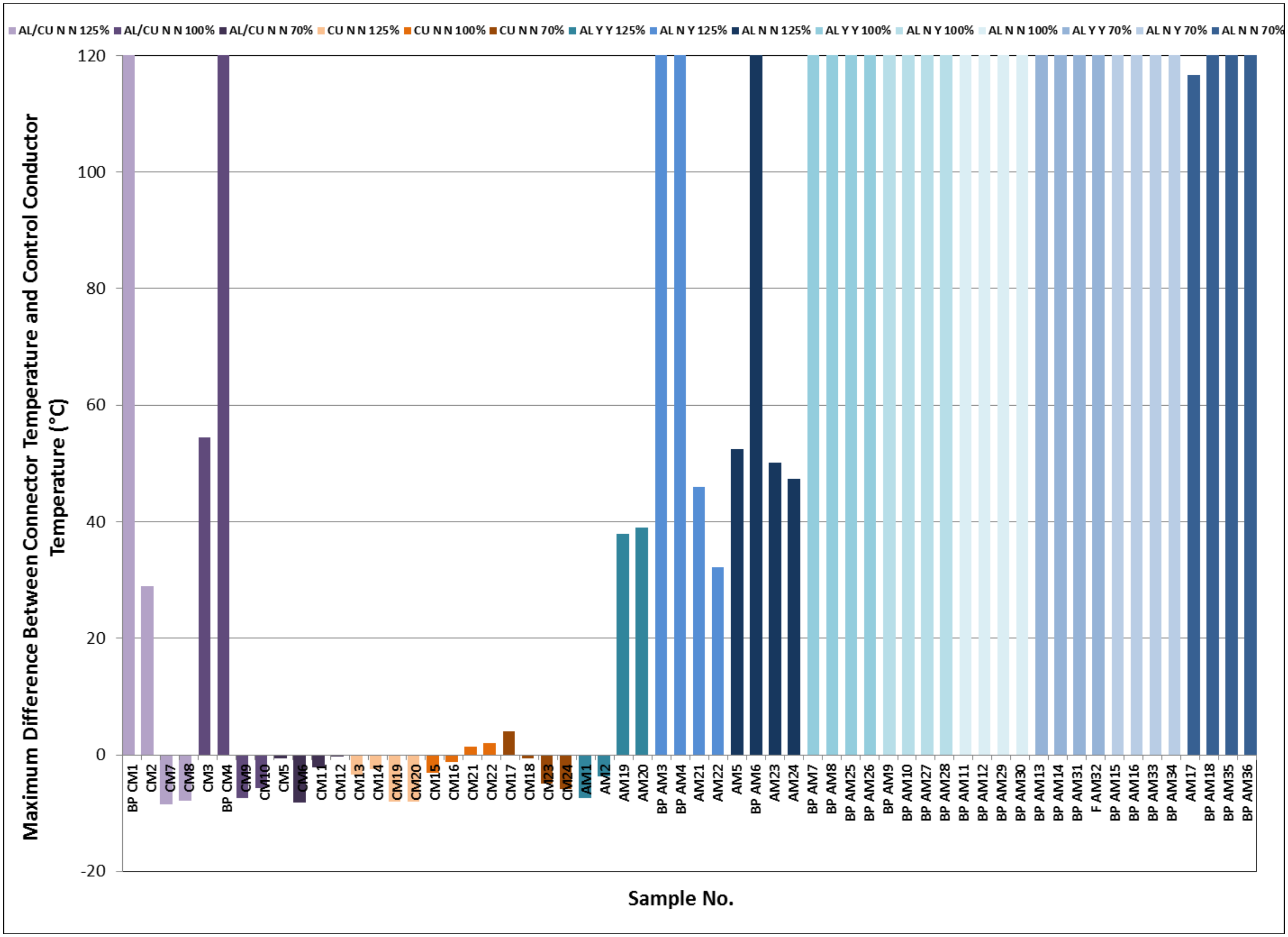

Figure 44. IEC maximum difference between connector temperature and control conductor for each sample. Samples are grouped by type and preparation. Solid bars indicate samples that failed and were removed from the test.

7. CONCLUSIONS

7.1 IEC ANALYSIS

The IEC analysis provides a quantified, standardized method of evaluating connectors. However, because this analysis normalizes and averages the results over the full duration of the test, it does not necessarily give a complete picture of the trends throughout the test. IEC also considers failure of any sample in any of the evaluation criteria at any point in the test to be failure of the test. In this test, no sample sets were able to achieve an overall 'pass' rating according to IEC, so this evaluation criteria alone is not sufficient to compare the performance of the different types of connectors. Overall, a good performing connector should exhibit a trend of stability of resistance and temperature readings throughout the test, particularly during the latter half of the test.

The general results of the IEC analysis were as follows:

1. **Mechanical dual-rated (AL/CU) connectors on #1 AWG copper wire**:
   Resistance factor ratio: fail
   Maximum connector temperature: fail

2. **Mechanical copper (CU) connectors on #1 AWG copper wire**:
   Resistance factor ratio: pass
   Maximum connector temperature: fail*

   * Although the rating is a 'fail' by the strict interpretation of IEC analysis, the connector temperatures exceeded the control conductor temperature only a small amount and for a few cycles in the middle of the test.

3. **Mechanical dual-rated (AL/CU) connectors on #2/0 AWG aluminum wire**:
   Resistance factor ratio: fail
   Maximum connector temperature: fail

7.2 OVERALL CONCLUSIONS

The general conclusions from the testing to 1500 cycles are:

1. **Mechanical dual-rated (AL/CU) connectors on #1 AWG copper wire**: 33% of the samples failed or showed a trend of significantly increasing resistance and temperature by the end of the test. There was no definite correlation between performance and the torque level applied to the connectors at the start of the test.
2. **Mechanical copper (CU) connectors on #1 AWG copper wire**: All samples had a relatively stable resistance and temperature over the course of the test. No samples failed, and none showed a trend of significantly increasing resistance and temperature by the end of the test.

3. **Mechanical dual-rated (AL/CU) connectors on #2/0 AWG aluminum wire**: 94% of the samples failed or showed a trend of significantly increasing resistance and temperature by the end of the test. The best performance was achieved by the samples that had been prepared with the conductor wire brushed (abraded), oxide inhibitor applied, and a torque level of 125% of the rated torque.

A summary plot of the connector performance in the testing is shown in Figure 45.

The overall conclusions from the testing to 1500 current cycles are as follows:

1. The **copper mechanical connectors on copper wire** had the most stable resistance and temperature readings, and performed the best during the test.

2. The **aluminum (dual rated) mechanical connectors on copper wire** performed relatively poorly during the test, with 1/3 of the samples failing or showing elevated resistance and temperature levels by the end of the test.

3. The **aluminum (dual rated) mechanical connectors on aluminum wire** performed very poorly during the test, and had a very high failure rate even before the mid-point of the test. Over 90% of the samples had either failed or showed elevated resistance and temperature levels by the end of the test. There was no clear correlation between conductor preparation method, torque level, and failure, except that the connectors that had been torqued to 125% of the rated torque level seemed to perform slightly better than the others.

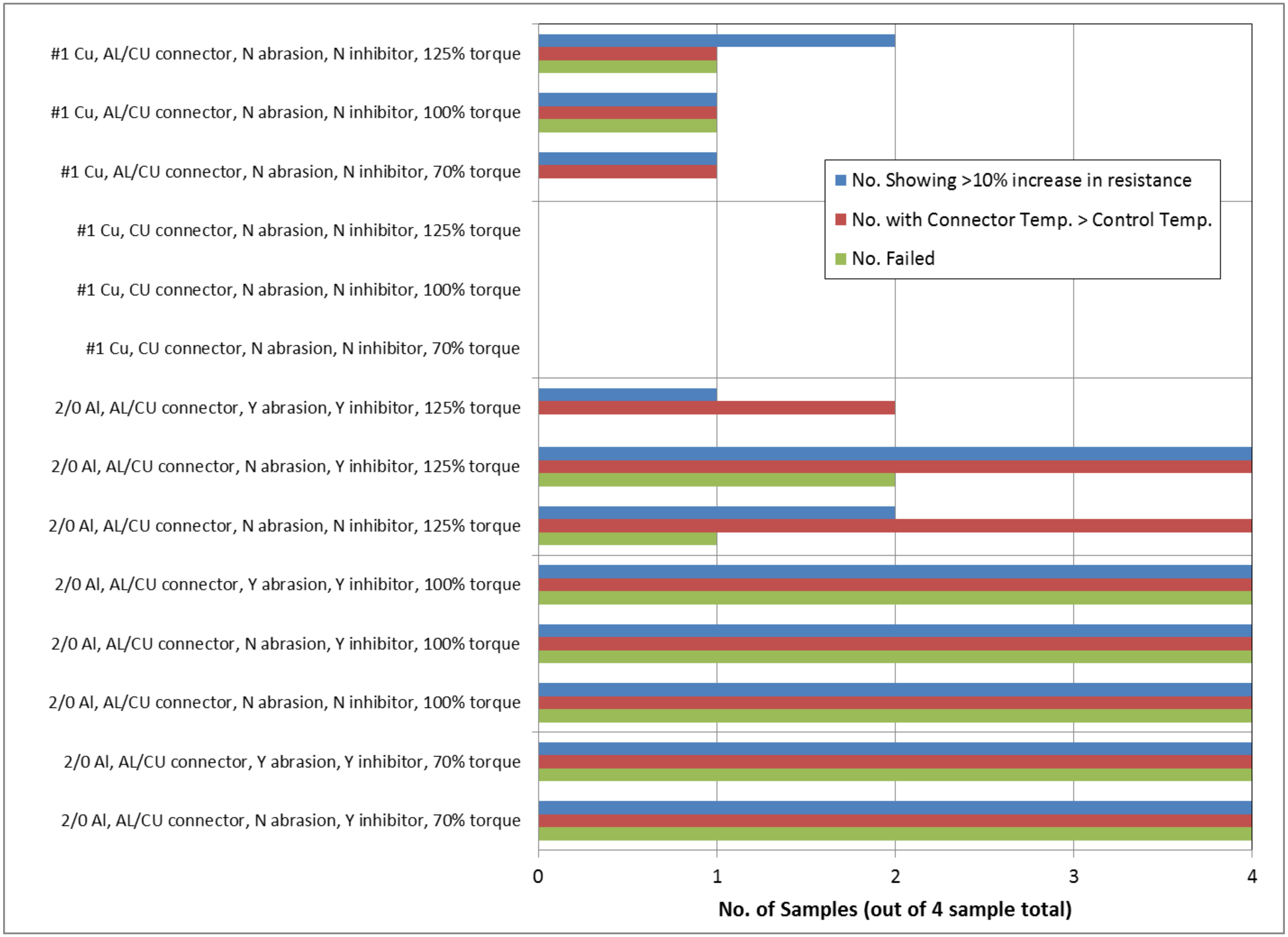

Figure 45. Overall summary of the results.