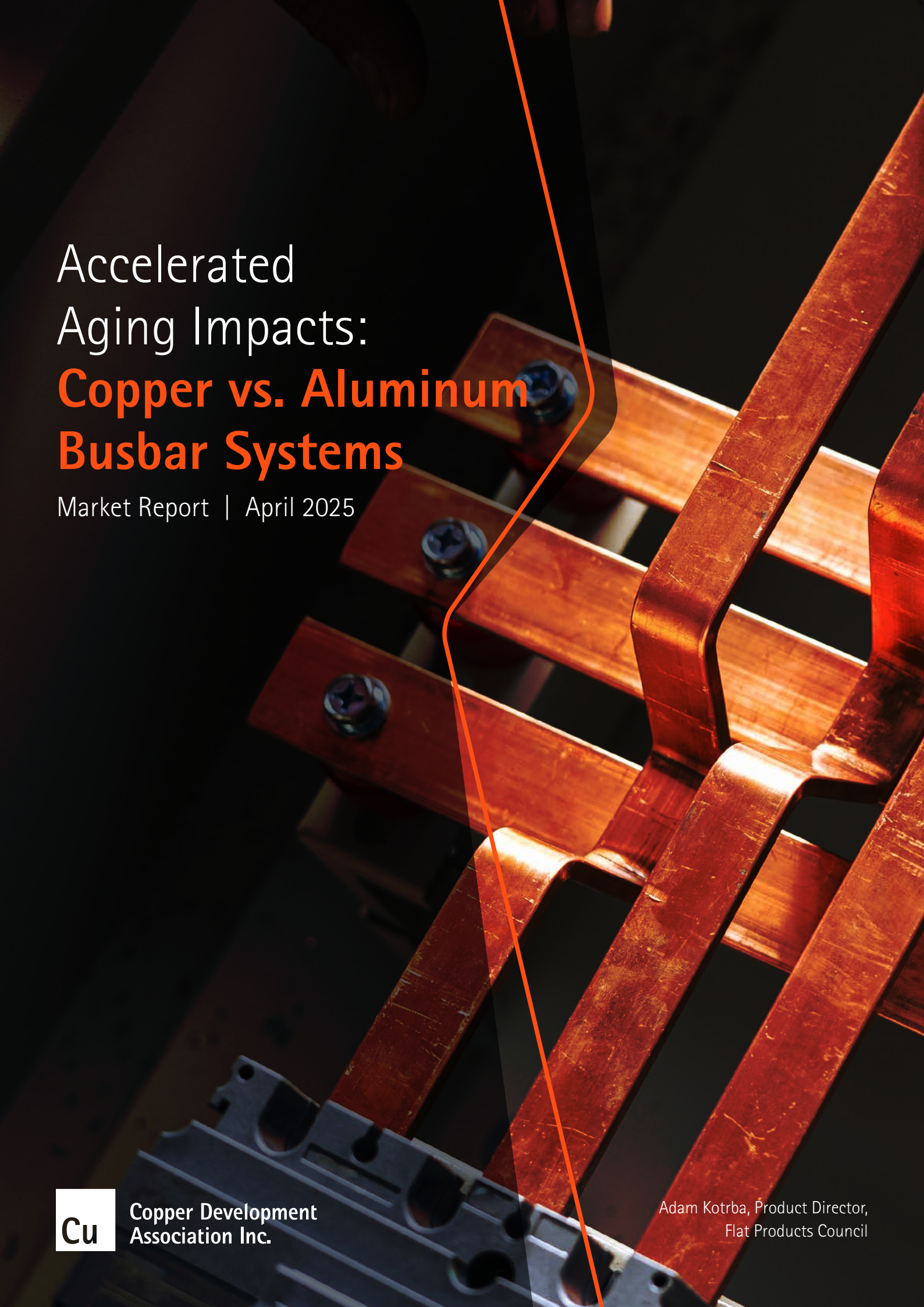


Accelerated Aging Impacts: Copper vs. Aluminum Busbar Systems

Market Report | April 2025

Copper Development Association Inc.

Adam Kotrba, Product Director,
Flat Products Council

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Executive **Summary**

Busbars are used in many electrical applications to easily and efficiently distribute electricity and often come in copper or aluminum materials. Busbars are used instead of wires and cables because multiple access points are required over short distances and a rigid, accessible bar is preferred. An accelerated aging test is performed across two copper and two aluminum designs to comparatively evaluate performance. The busbars were connected in series and cycled over time with high current (3500 amps) followed by no current and fan cooling for a couple of hours each, creating thermal cycles across the materials. Two fasteners are applied at each joint based on standard practice for busbar applications as specified per ANSI C119.0-2022, with 3/8" - 16 bolts, two flat washers, a split lock washer, and a nut, each of grade 5 zinc-coated steel and torqued to specification. All joints are monitored over time with temperatures and resistance measurements across each. Over time, the aluminum busbar joints started to slowly increase in resistance as well as temperature. After 304 cycles the test was paused due to excessive temperatures on the aluminum busbars, exceeding 250oC. All torques were recorded, acknowledging those of the aluminum busbars had significantly loosened. All fasteners were retorqued to specification and the test was continued with resistance and temperature measurements taken. Over time the aluminum joints again increased in temperature and resistance, causing the test to be stopped after an additional 78 cycles. Before stopping, infrared images were captured of each busbar to compare with those from the start, illustrating the temperature change over time and the excessive temperature at the joint of the aluminum busbars. Torques were measured, again acknowledging significant reductions in the aluminum busbar fasteners.

The increased temperature and resistance across the aluminum joints are a result of fastener fatigue due to the expansion and contraction cycling of the core material. As electricity conducts through a material, it heats up that material, losing some of the applied energy to the environment as heat, decreasing its efficiency. The amount of heat produced and lost to the environment depends on the material and its resistance, which is also function of its size, or cross-section. Most materials grow when heated, and their growth can be compared based on their thermal growth coefficients, which define material growth across temperature ranges. Copper grows much less than aluminum as it is heated, causing less flexing of the fasteners and creating a more robust system over time. As aluminum is heated and cooled, it stresses the fastener, causing fatigue in the lock washer, allowing the joint to loosen. This unfortunately becomes cyclic, as this loosening of the joint increases its resistance, which then increases its temperature, which again further expands the material and further stresses the fastener, resulting in further loosening. And these higher temperatures not only increase maintenance demands, but they can also lead to safety concerns. Furthermore, operational efficiencies decrease by not only losing some electricity to ambient heat, but also requiring more cooling to offset this additional heat, which also costs energy. Lower material costs are often the reason aluminum busbars are used instead of copper, however additional costs in fasteners as well as possibly a plating and/or insulative coating offset this advantage. It is recommended to use copper busbars to reduce fastener complexity and joint risks while keeping packaging small, improving operational efficiencies and maintenance costs and providing lower total ownership costs.



Introduction

Electrical conductors can efficiently transfer electrical energy, enabling downstream uses while minimizing energy losses along the way. Copper is one of the best conducting materials, second only to silver, while gold is third best, followed by aluminum. Low resistance in these materials enables high conductivity, and the reasonable costs of copper and aluminum make them more popular. For aluminum to equal the conductance (or resistance) of copper, it must grow in cross-sectional size. The resistance equivalence between them occurs when aluminum is 56% larger in cross-sectional area. Aluminum materials have an initial cost advantage, as the price for aluminum is less than half that of copper, but aluminum requires a larger package. The lowest mass of required material, however, remains with aluminum, since its density is less than one third that of copper. As conductors are sized equally based on resistance, aluminum still results in half the weight versus copper, even though it is over 50% larger.

Conductors are often in the form of cables or wires, however such products require joints with connectors to branch off and feed other uses, making them more complex and less efficient, as connectors are often sources of inefficiency. Busbars overcome these challenges, providing a bar sized appropriately that can easily be bolted to, providing simple branches to channel current where needed (see Figure 1). Busbars have been measured to provide an increase in efficiency versus cables, minimizing losses to allow more electricity to be available for downstream uses.



Figure 1: Copper busbars with connection branches

Much debate continues between practitioners and academia about which material is better for busbars, copper or aluminum. Initial cost and lower mass are the obvious advantages of aluminum, but copper offers smaller packaged solutions with less risk, as it's generally a more robust material, capable of sustaining higher temperatures and mechanical loads. Initial research did not reveal any studies demonstrating if either material offers long-term advantages, as there is not much published comparing aging effects, including risks and total ownership costs. Therefore, it was determined to establish and execute an accelerated aging test to evaluate comparable performance of both copper and aluminum after hundreds of extreme electrical cycles.

Test **Samples**

Busbars are sized according to their expected current load, not power, as voltage has no influence on conductor sizing. Power is the voltage multiplied by the current, described in Watts (volts x amps = watts). Another restriction on sizing is simply material availability, as often busbars come in established thicknesses and widths, while lengths are easily customized. To also study the effect of size on performance, two designs were chosen for each material with similar cross-sectional areas, but varying width and thickness.

It is of interest to test busbars sized for industrial electrical applications with relatively high current. Ampacity tables were used from UL requirements to ensure they were sized appropriately. Based on available standard material sizes, designs were chosen as noted in Table 1, targeting 1800 amps. Cross-sectional areas are compared, acknowledging one of the two copper designs is slightly smaller and the aluminum designs are at least 50% larger than the copper busbars. Weight is also included based on their two-foot length and density, noting the copper designs are at least twice the weight of aluminum. Figure 2 illustrates a drawing for one of the samples with the others being similar other than dimensional changes. Each component is labeled with its dimensions and material.

Material	Thickness, in.	Width, in	Cross-sectional area, in^2	Volume at 24 in. lenght, in^3	Density, lb./in^3	Weight, lbs
copper	0.375	5	1.875	45	0.32	14.4
copper	0.5	4	2	48	0.32	15.36
aluminum	0.5	6	3	72	0.1	7.2
aluminum	0.75	4	3	72	0.1	7.2

Table 1: Test sample size and weight

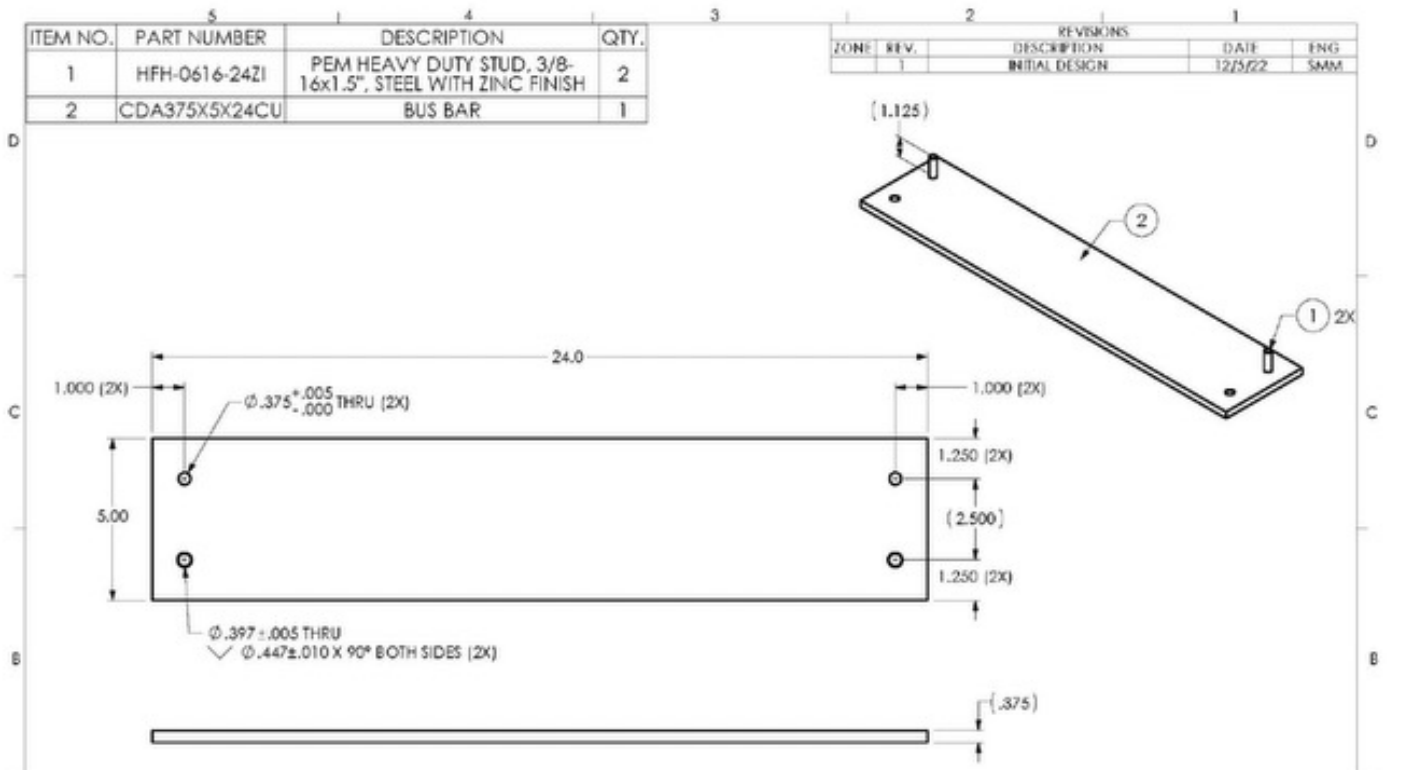


Figure 2: Drawing for the 0.375"x5" copper busbar

Test Conditions & **Setup**

Each of the three samples of the four designs (12 components altogether) are bolted in series as illustrated in Figures 3 and 4. The current is provided with an AC transformer and a variable transformer. The current starts down one leg which contains copper (0.375" x 5") followed by aluminum (0.5" x 6") samples and continues through an adapter plate down another leg, which is aluminum (0.75" x 4") followed by copper (0.5" x 4") samples. The samples have PEM studs installed during manufacturing, but in the 0.75" aluminum busbars they were replaced with 3/8"-16 bolts since they were too short. Fasteners applied are based on standard practice for busbar applications as specified ANSI C119.0-2022, consisting of two flat washers, a split lock washer, and a nut with each bolt, all of grade 5 zinc-coated steel. Each fastener was torqued to 23 ft-lbs., selected based on Fastenal's reference guide, the manufacturer of the fasteners, which is 15% higher than the minimum torque recommended by ANSI C119.0-2022, Table 3. No grease or inhibitor compounds were applied.

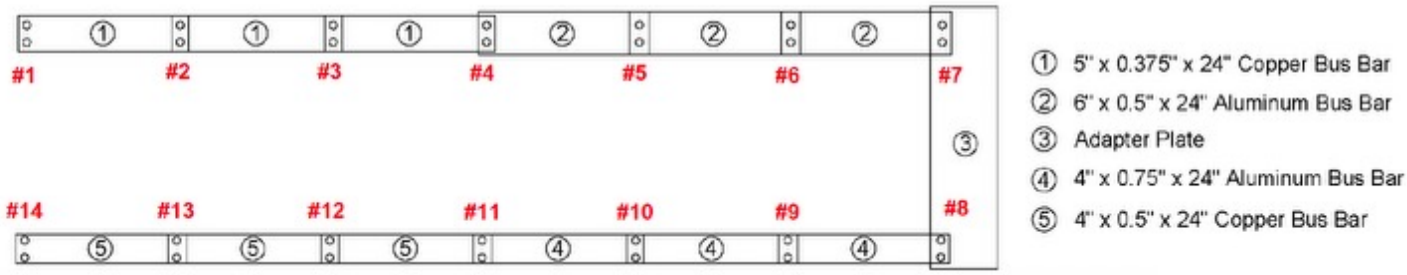


Figure 3: Drawing with layout for the busbars tested with joints labeled

Thermocouples are placed at three points along the width centerline of each busbar, including at its connecting ends and its center. Ambient air temperature is measured with two thermocouples installed on stands near the test loop, and their average is reported. DC Resistance measurements across each joint are taken every 25 cycles as the system has cooled to ambient temperature. Small indentations are made 1" from the edge of each bolted connection to ensure the same locations are consistently used throughout testing. And, at the beginning and end of testing, infrared (IR) images are captured of each busbar sample as they reach steady state temperatures with 2000 amps applied, providing visuals of the temperature change over time as well as the gradient across the bar, including the fastened ends.

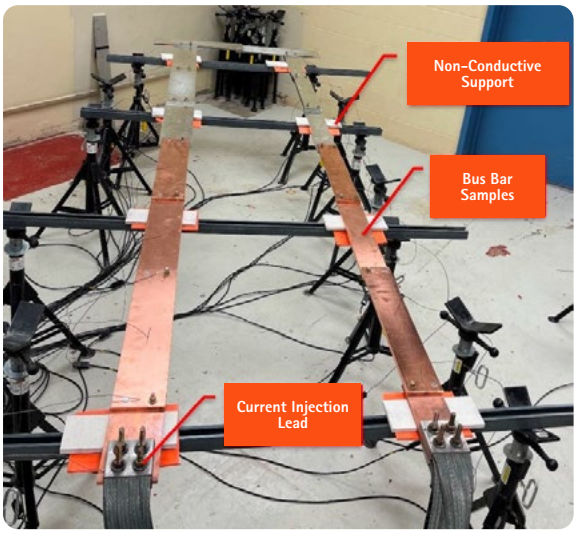
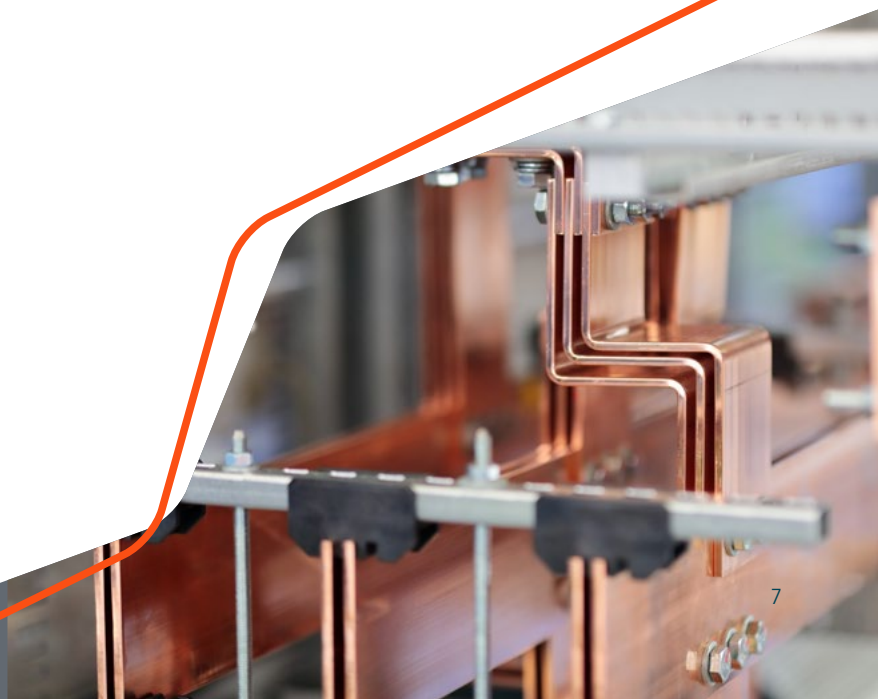


Figure 4: Picture of actual layout of test setup prior to testing



Test Conditions & **Setup cont.**

A closed-loop system was used to maintain constant current with the motor-driven VARIAC variable transformer, such that if resistance in the test loop increases and current drops, current will be increased to keep it constant. A target of 3500 amps is demonstrated, which is nearly twice as high as the designed value to accelerate aging with a target of 500 cycles. The current cycling test was carried out with procedures and best practices from the American National Standard for Electric Connectors (ANSI C119.4-2016, ANSI C119.0-2015) and Electric Power Connections for Substations (ANSI/NEMA CC1-2018). Temperatures are observed during initial current cycling, and fans are turned on during cooling, but turned off during heating. Time cycles were determined based on steady state achievement for both the hot (current on, fans off) and cold (current off, fans on) cycles. Figure 5 illustrates the start of test thermal profiles (average temperature) from each of the designs, specifically the average temperature of the center component of each set. The hot cycle lasts for just over 2 hours while the cold cycle is about 1.5 hours. The aluminum busbars result in higher temperatures, particularly the thicker design, which has less surface area to dissipate heat. The copper busbars have lower temperatures, particularly the larger design, which has less resistance with its larger cross-section. The smaller copper busbar has a very similar thermal profile to that of the thinner aluminum busbar. These early thermal profiles are hints as to how performance will be affected over time, to be discussed further in the results.

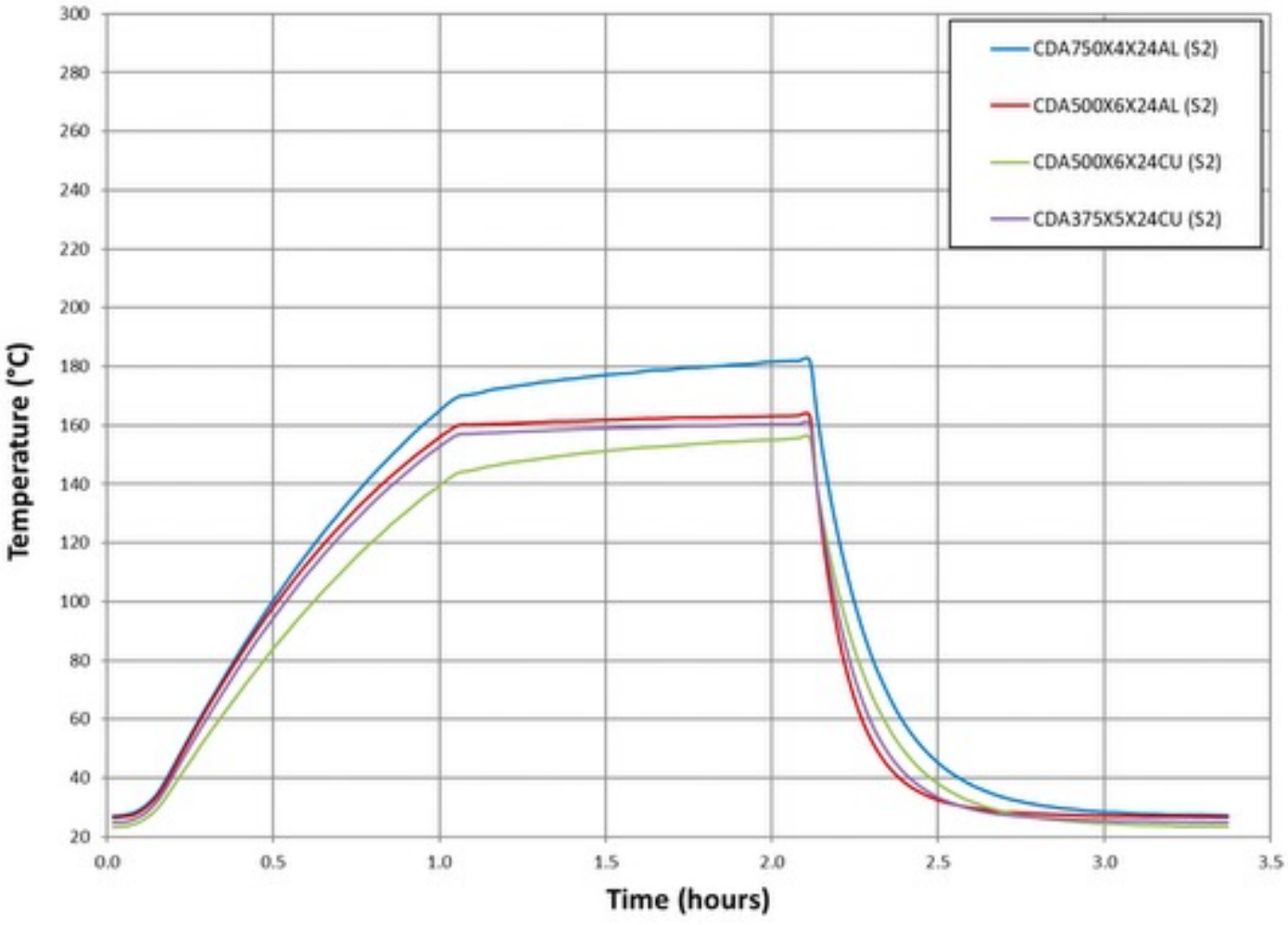


Figure 5: Start of test thermal profiles for each of the four busbar designs

Testing was started after completing initial measurements and establishing cycle times. It was observed after 100 cycles that temperatures and resistances began increasing across the aluminum busbars while the copper busbars remained constant. Testing continued until the temperatures of the aluminum busbar exceeded 250oC at cycle number 304, causing safety concerns, exemplifying a real-world issue, and the testing was paused. Torque measurements were made on all fasteners, acknowledging significant loss of torque for the fasteners of the aluminum busbars. It was determined to retorque all the fasteners, simulating a maintenance cycle, and testing was resumed.

After another 78 cycles, testing was stopped again due to temperature concerns of the aluminum busbars. Resistance values also were again increasing across the aluminum busbar joints and torques were again measured to have significantly dropped. Figure 6 charts the average temperatures across each sample over time, and Figure 7 plots the average DC resistance values across each sample's fastened joints throughout testing. Figure 8 provides the torque values measured over time across each fastener, associated with its connection identification point referenced with the key provided earlier in Figure 3. Figure 9 provides the end of test average thermal profiles across each sample and can be compared with the start of test profiles in Figure 5. And, finally, Figures 10 – 13 provide the IR images of each sample before and after test with 2000 amps applied.

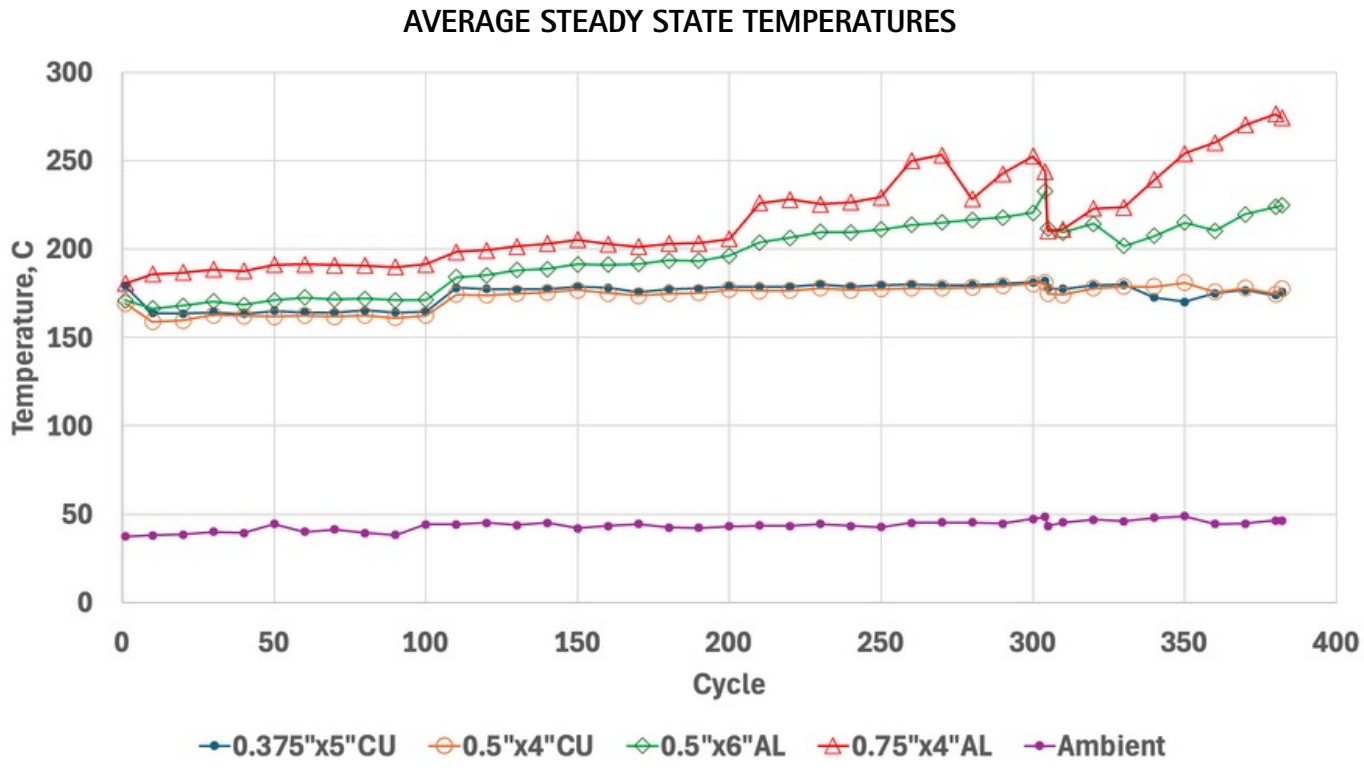


Figure 6: Average steady state temperatures across each sample during the hot cycle

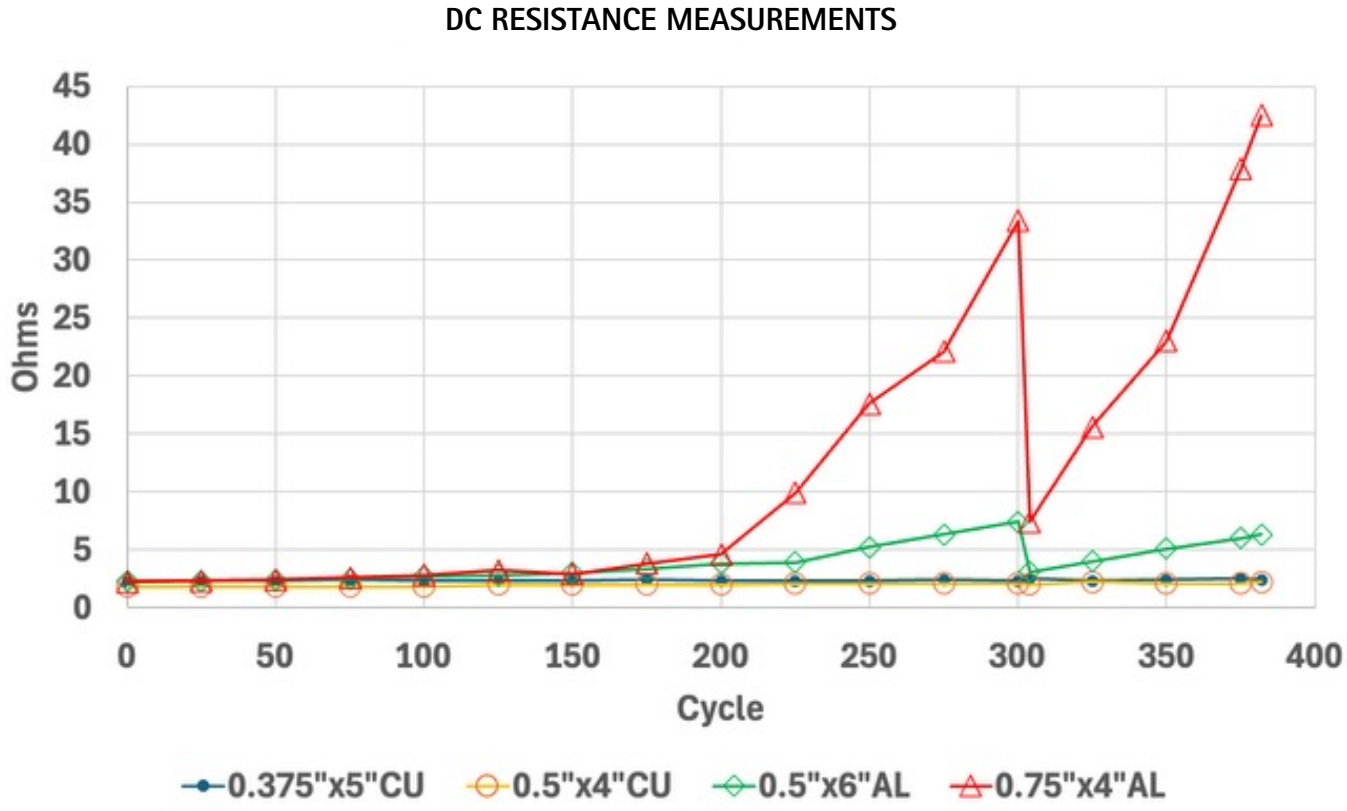


Figure 7: DC resistance history across each sample

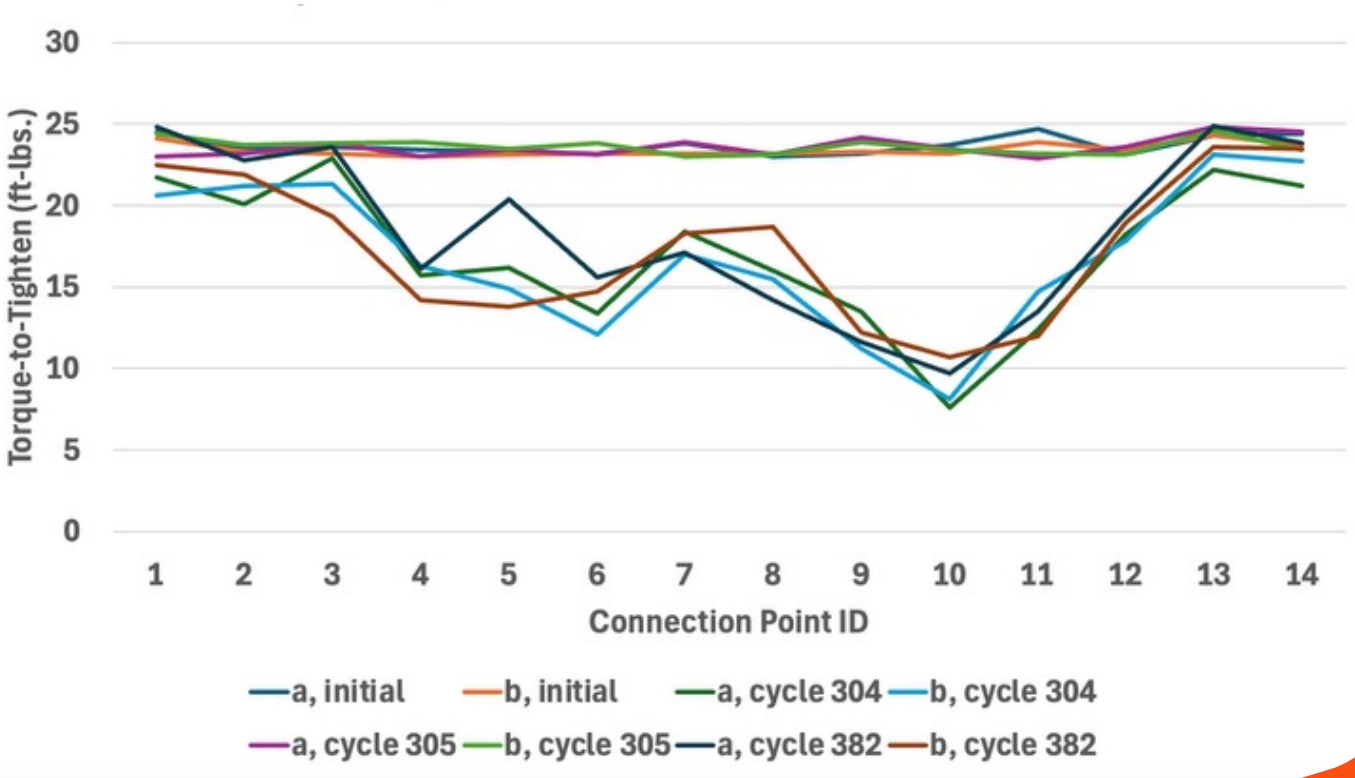


Figure 8: Torque data across the applied fasteners

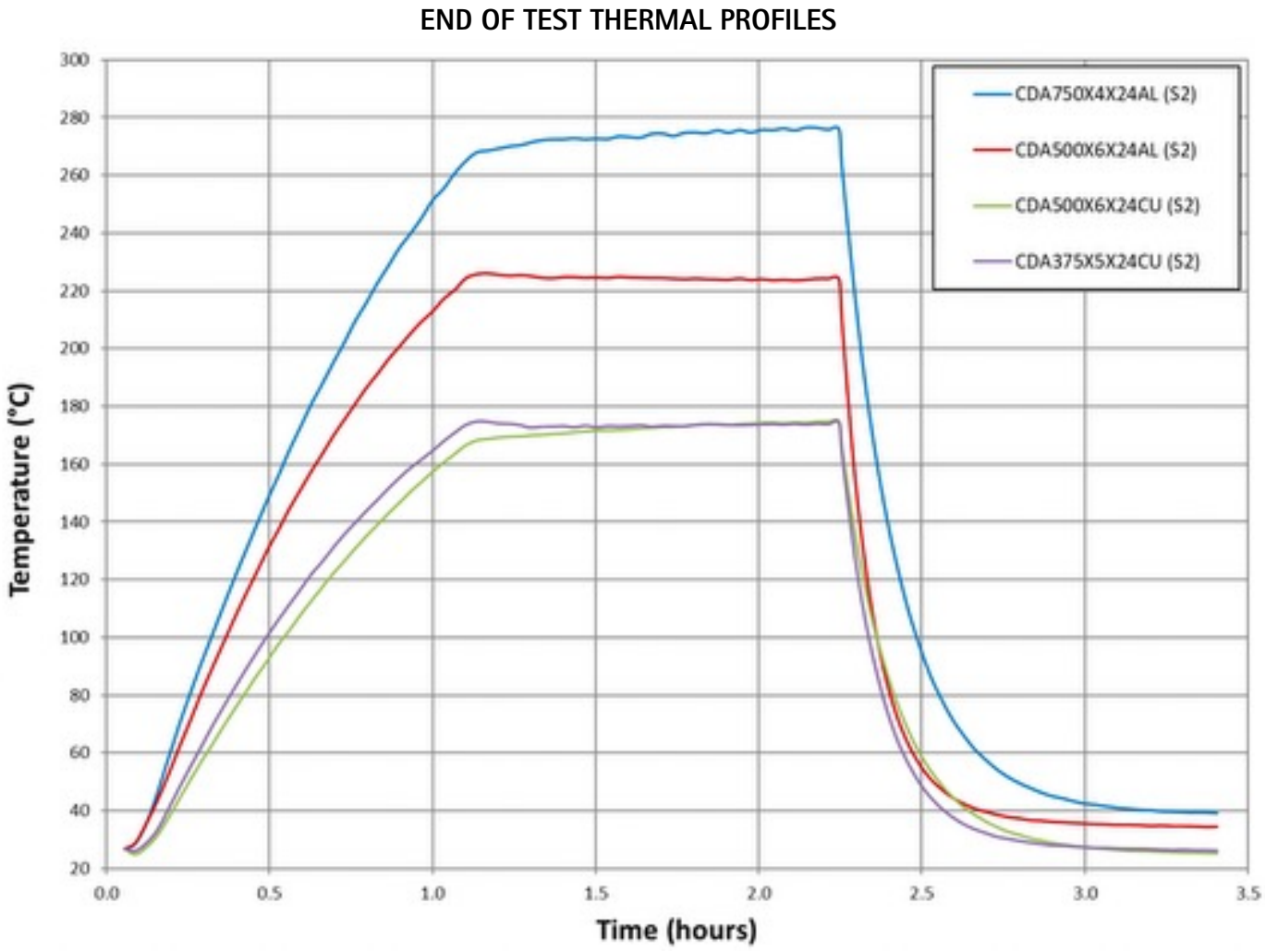


Figure 9: End of test thermal profiles of each sample

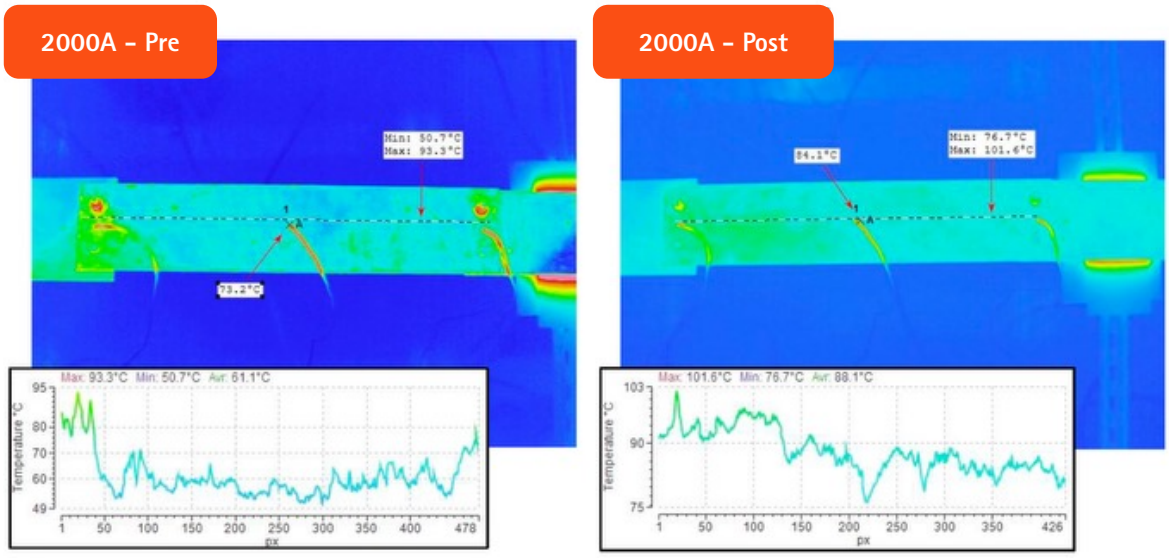


Figure 10: IR image for 0.375"x5"CU

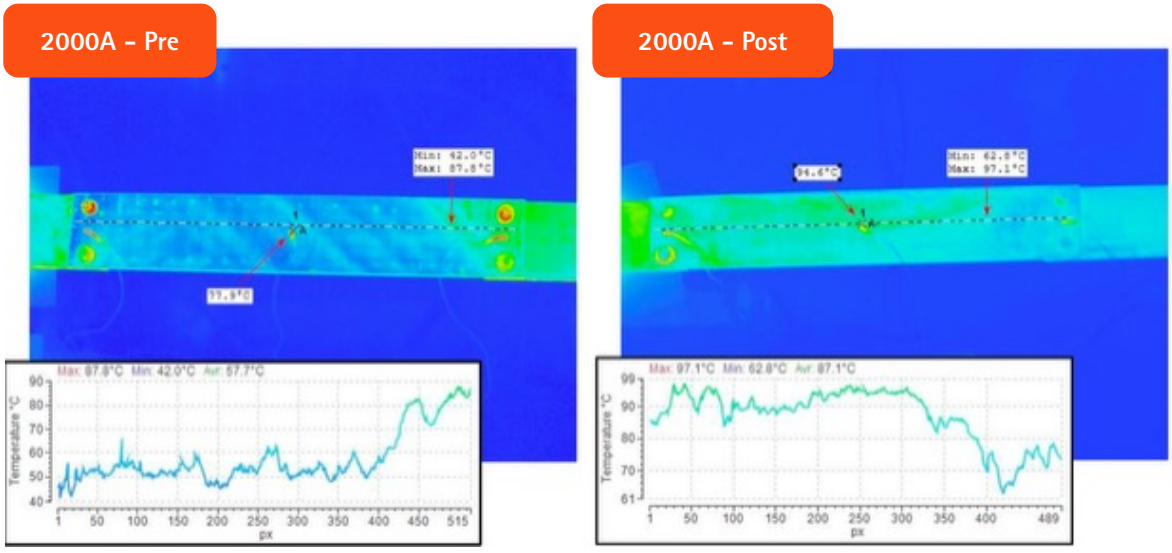


Figure 10: IR image for 0.375"x5"CU

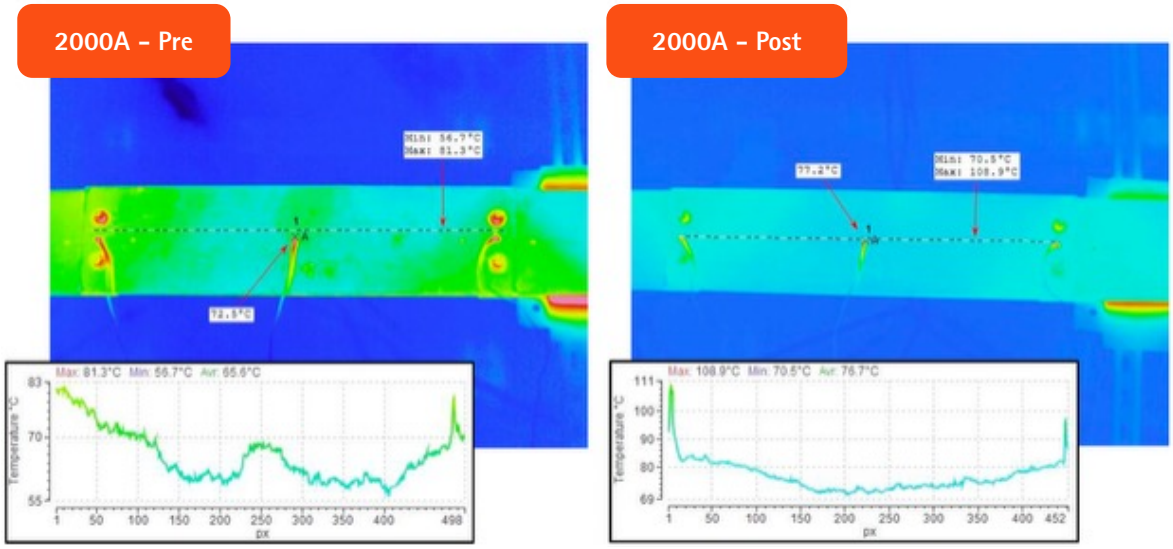


Figure 12: IR image for 0.5"x6"AL

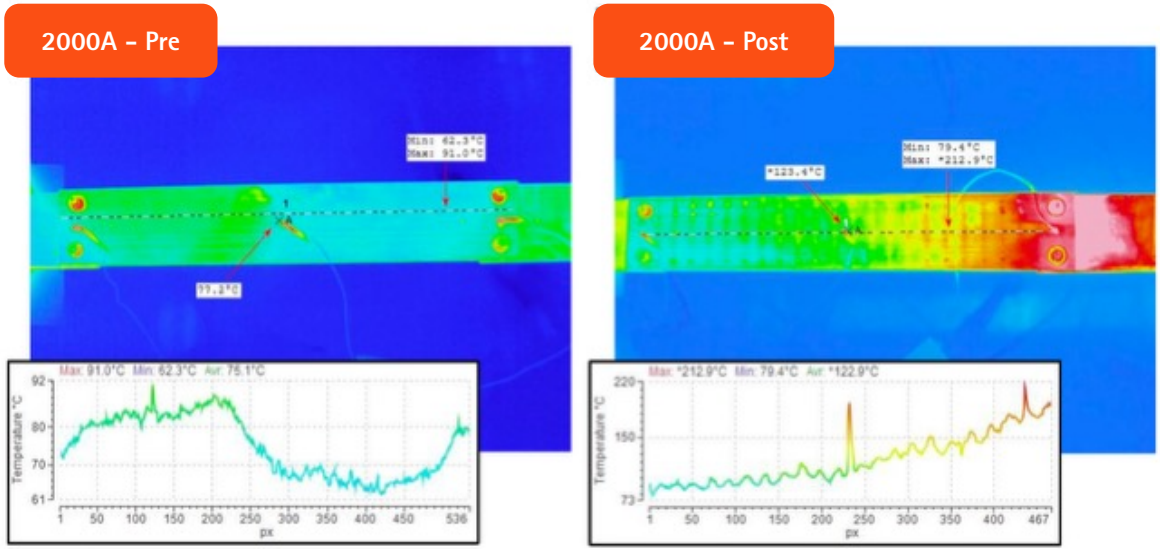


Figure 13: IR image for 0.75"x5"AL

Analysis & **Discussion**

Test data provides clear evidence demonstrating long term aging concerns of performance degradation of aluminum busbar systems. This study highlights a critical issue with fastener joint integrity of aluminum busbars. Figure 14 illustrates this concern with aluminum busbar joint integrity by isolating the torque data at both ends of each middle component in each sample leg, quantifying the torque loss for each busbar design uninfluenced by the other samples. Both phases are included, with the initial phase being the first 304 cycles and the second phase being the additional 78 cycles after retorquing fasteners. Copper busbar fastener torque losses are 9-15% in phase 1 and 8-10% in phase 2, while aluminum losses are 38-56% in phase 1 and 31-53% in phase 2, clearly demonstrating advantages with copper as its torque losses are minimal.

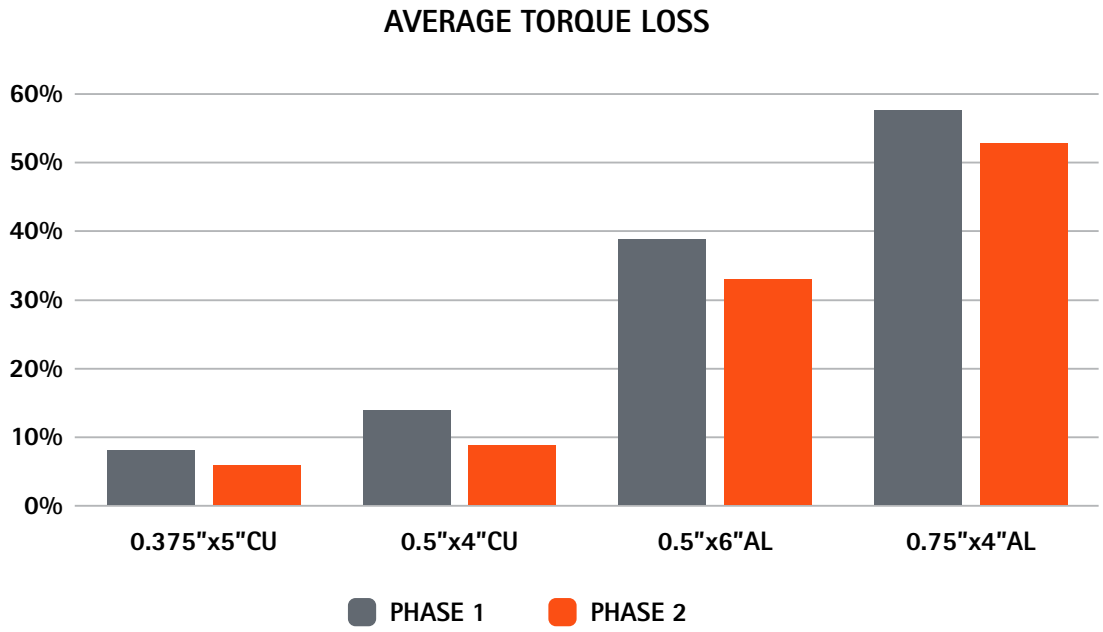


Figure 14: Average torque loss across each sample

As with the torque data, average DC resistance data across each component's joints is plotted similarly in Figure 15, including both phases (initial 304 cycles, followed by 78 cycles after retorquing). DC resistance indicates the electrical integrity of the joint, particularly its efficiency of transferring electricity; larger resistances reduce current flow and increase temperatures. Clearly the change of resistance in copper busbar joints are much less than aluminum's, with its increase in phase 1 at 11-14% and 0-4% in phase 2. Aluminum's increase in resistance was more drastic for the thicker design, increasing 236% and 172% in phase 1 and 2, respectively, while the thinner design increased 35% and 58%. Nevertheless, copper's increase in DC resistance is significantly less, demonstrating a more robust and efficient joint over time.

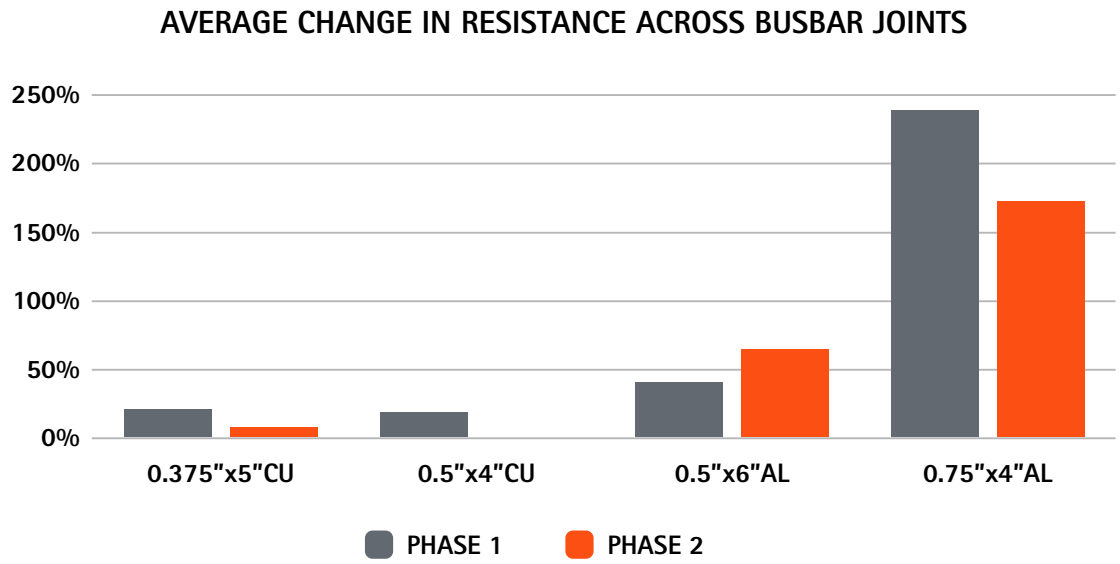


Figure 15: Average torque loss across each sample

Average steady state temperatures in Figure 6 capture how busbar temperatures vary based on applied current, even from the start of testing. Notice that both aluminum busbars have higher temperatures than both copper busbars, even in the early cycles. Busbar temperatures are a result of the applied material and its size or geometry as well as its position. For instance, busbars with more exposed surface area (thinner and wider) will be less hot, as they more easily dissipate the generated heat. This is evident in the aluminum busbars, which are equal in cross-sectional area but not in surface area, as the thicker and less wide design is always hotter. This is not the case with the copper busbars, but this is because they are not of equal cross-sectional area; the thinner and wider copper busbar is actually hotter, but this is because it is slightly smaller (6% less cross-sectional area). Position also affects busbar temperatures; busbars held vertically as opposed to horizontally as tested will be cooler, as there is more natural convection benefit. And the material properties also influence resulting temperatures, including its thermal mass and thermal conductivity, both of which are larger for copper, providing benefits in keeping it cooler than aluminum.

It is easy to see in Figure 6 that temperatures of both aluminum busbars rise throughout testing while the temperatures of both copper busbars remain steady. It is also apparent that after retorquing (cycle 305), the temperatures of the aluminum busbars did not return to their original temperatures. This is a result of increased resistance at the joint possibly due to reduced clamping forces, although the torques were the same, but more likely some damage to the joint's mating surfaces, either from heat or corrosion. The copper busbar temperatures dropped much closer to their original temperatures.

It is demonstrated that joint integrity of copper busbars is more robust than aluminum, with evidence generated throughout testing via DC resistance, temperature, and torque measurements. Clearly the trends are repeated across two designs of each material. But it is still not acknowledged why this occurs, and why it is worse for some designs. What is it about copper and aluminum materials and their shapes that causes some fasteners to fatigue more than others? Looking more closely at some of the data helps better understand the meaning some of these trends, which ultimately must help explain why aluminum busbar fasteners loosen more quickly than copper busbar fasteners. The answer lies in the thermal growth characteristics of each material, acknowledging that growth for aluminum is much more than that of copper.

Most materials grow as they are heated, but they vary on how much they grow. Thermal expansion coefficients are determined experimentally for each material across a range of temperatures, characterizing growth based on temperature. Aluminum has a 35% larger thermal expansion coefficient than copper, meaning the aluminum components grow 35% more than copper under equal temperature rises, putting additional stress on the fasteners as they are cycled over time. Furthermore, the aluminum busbar fasteners are further stressed since they are also experiencing higher temperatures, meaning the aluminum busbars are growing even further compared with copper. And the larger the material, the more it will grow, suggesting thicker busbars will grow more under the same temperature than thinner busbars. Figure 16 plots calculation results comparing the growth of copper and aluminum at two different thicknesses (10 and 20mm) and two different temperature changes (150oC and 250oC), which are similar to the thicknesses of the applied busbars and their resulting temperatures. Trends are as expected, such that twice the thickness grows twice as much, and aluminum grows 35% more than copper under same temperatures. But, as mentioned earlier, aluminum temperatures are higher than copper's, particularly at the joints over time. A "hot" aluminum busbar compared to a "cool" copper busbar could yield growth over twice as much. And when comparing a "hot" thick aluminum busbar to a "cool" thin copper busbar, the aluminum's growth is nearly four times that of copper.

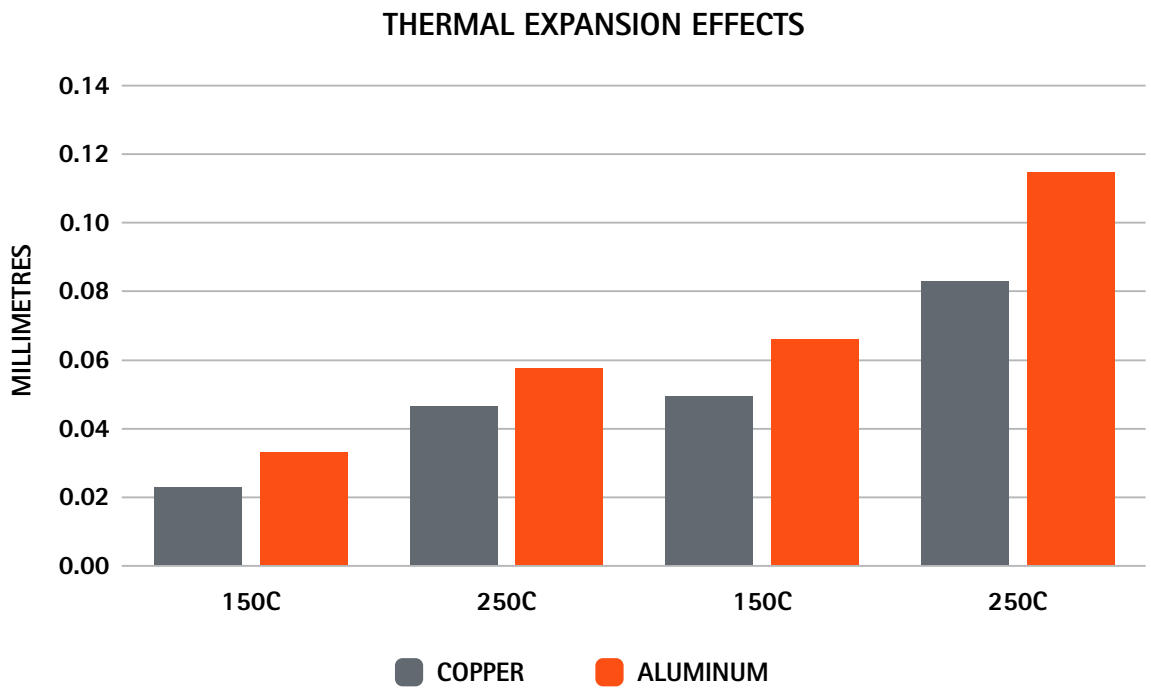


Figure 16: Thermal expansion effects of material, temperature, and size

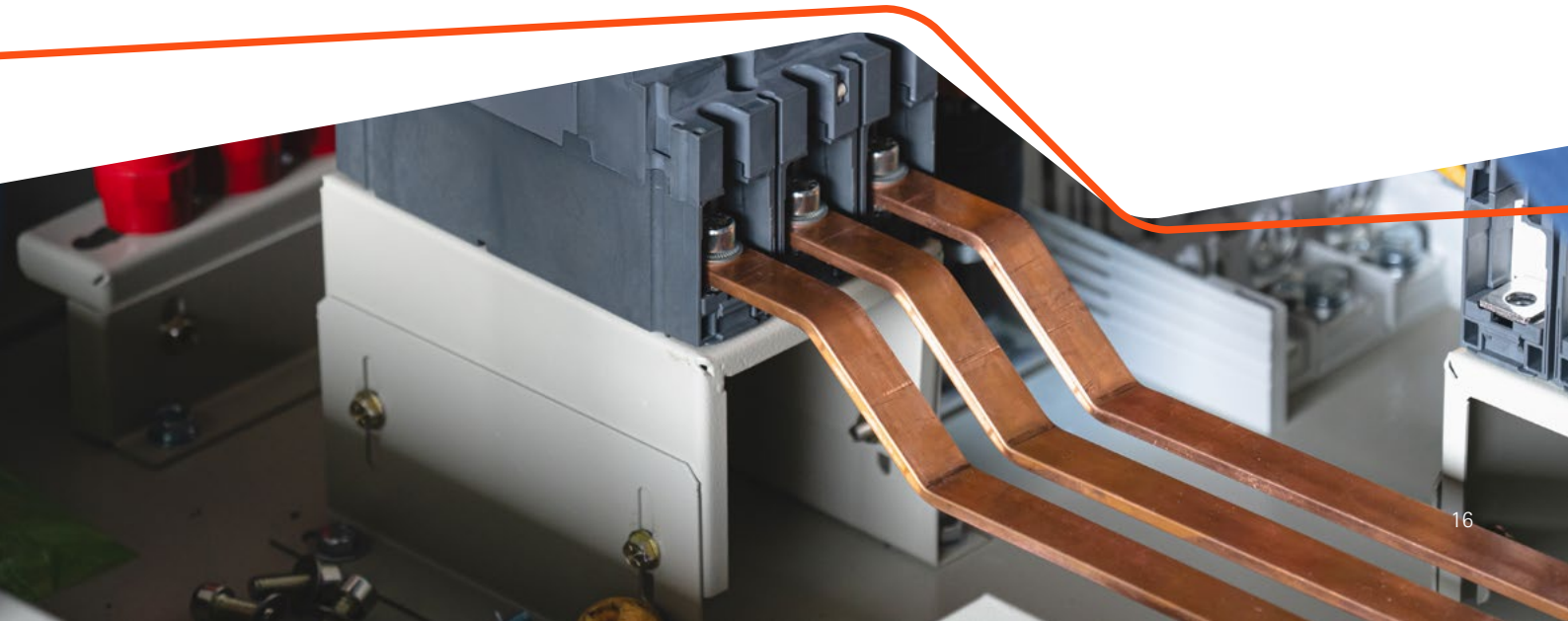
As the joint grows with temperature, it flexes the fastener and slightly loosens, causing its resistance to increase because more air is introduced between the connections, weakening the conduction path between the metal surfaces. As this resistance increases, the joint efficiency drops, and its temperature increases as the energy is lost in the form of heat. This further exacerbates the problem, creating a cyclic series of events that will continue to weaken the joint over time. As the joint loosens, it heats up more, further expanding the fastener, which in turn further loosens the joint. And, after a certain point, the fastener is weakened such that it cannot simply be retorqued but must be replaced if done early enough to not damage the busbar, including its mating surface. This was observed after the testing continued beyond cycle 304, since at this point all the fasteners were retorqued as testing continued. But only an additional 78 cycles were able to be completed before the fasteners loosened again on the aluminum busbars, which is only 25% of the initial cycles after retorquing.

Analysis & **Discussion cont.**

This accelerated torque loss is a result of spring fatigue of the lock washer as a result of its mechanical cycling induced from thermal cycling. Thermal growth cycling response on fastener retention from extreme loading must be considered when sizing and selecting materials for busbars, as it will influence aging robustness, as demonstrated.

One may argue that the aluminum busbars in these tests were undersized compared to copper, and rather than being only 50% larger in cross-sectional area, they should be 60-70% larger. In review of various standards (UL 891 for example for switchboards < 1000V), the ratio of aluminum cross-sectional area to copper to achieve busbar ampacity equivalence varies from 1.33 – 2.0, depending on shape, temperature rise allowed, and applied loads. Most of the upsize ratios are 1.5 or less, however if 1.7 is preferred, this would further increase the thickness and/or width of the aluminum busbars. For instance, the 0.75"x4" profile would need to grow to 0.875"x4" or 0.75"x4.5". If space constraints allow thicker busbars instead of wider ones, the thermal growth impact could remain a concern since thicker materials grow more. Although, the larger cross-sectional area would reduce its resistance, resulting in lower temperatures during the high electrical loads, reducing thermal growth impacts. How these varying inputs ultimately affect fastener fatigue in aluminum busbars would need further study.
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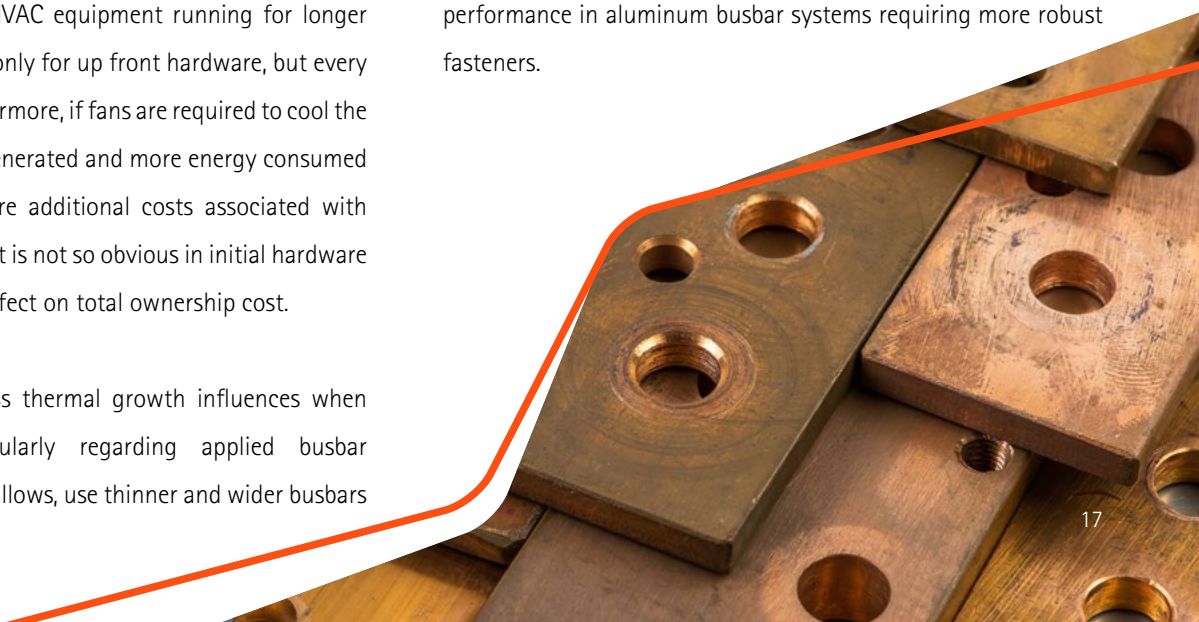
Conclusions & **Recommendations**

In conclusion, repeated current cycling induced thermal cycles in applied busbars, which fatigued the fasteners over time for aluminum busbars while copper busbar fasteners remained secure. Thermal growth difference between aluminum and copper is the main reason for these trends, although influence from shape factors was also evident. Copper materials are capable of higher current loads per cross-sectional area, enabling them to remain thinner than aluminum, resulting in less fastener stress over lifetime cycles. For both the copper and aluminum designs, the thicker busbars had more torque loss in both phases. Additionally, DC resistance was much higher across the aluminum busbar joints than those of copper, and the thicker aluminum joints had much higher DC resistance over time than the copper joints. An increase in resistance signals a weaker conductive connection, a result of fastener fatigue, further evidenced with torque loss. It became apparent that the fasteners were fatigued for the aluminum busbars, as they were not able to retain torque in the second phase of testing after being retorqued, returning more quickly (78 vs. 304 cycles) to the high temperatures and resistances from the first phase. Aluminum busbars require more specialized fasteners to handle their expected growth under heavy electrical loads or require periodic replacement, offsetting initial cost benefits.

Trends uncovered in these results not only indicate a longevity concern with aluminum busbar fasteners, but operational efficiency concerns as well. Additional heat into a facility comes at a cost, requiring larger HVAC equipment running for longer periods of time, costing not only for up front hardware, but every month in utility costs. Furthermore, if fans are required to cool the busbars, more heat will be generated and more energy consumed in fan operations. These are additional costs associated with busbar material selection that is not so obvious in initial hardware costs but has a significant effect on total ownership cost.

It is recommended to assess thermal growth influences when specifying busbars, particularly regarding applied busbar fasteners. When packaging allows, use thinner and wider busbars to reduce risk of fastener fatigue, as thinner ones will grow less, inducing less stress on the fasteners. It is also recommended to consider total ownership costs when choosing the busbar material, including maintenance and repair as well as operational costs. Under extreme loading conditions, particularly with tight packaging, copper is the preferred material, as it can be two thirds the size of aluminum and will stress the fasteners least with lower temperatures and smaller growth. Finally, if it is of interest to determine what size of aluminum busbar would minimize the concern of fastener fatigue, it is recommended to repeat this testing with larger aluminum busbars, extending their cross-section greater than 60% compared with copper.

Follow-up engagements were had with a fastener manufacturer to understand the options for improvements, acknowledging the insufficiencies of split lock washers with aluminum busbars. Belleville washers are an option for consideration with improved fatigue performance, however initial internet research reveals engineering chats with feedback regarding poor performance of both lock (split ring) and Belleville washers in dynamic systems. "A split ring does nothing except damage surface finish. A Belleville does nothing except for change the curvature of your preload loss curve." It is recommended to further investigate fastener options if aluminum busbars are applied, leveraging the known thermal growth cycle dimensions to determine torque loss over cycle time capability. It is further recommended to investigate updating the referenced ANSI standards to acknowledge the insufficiency of performance in aluminum busbar systems requiring more robust fasteners.



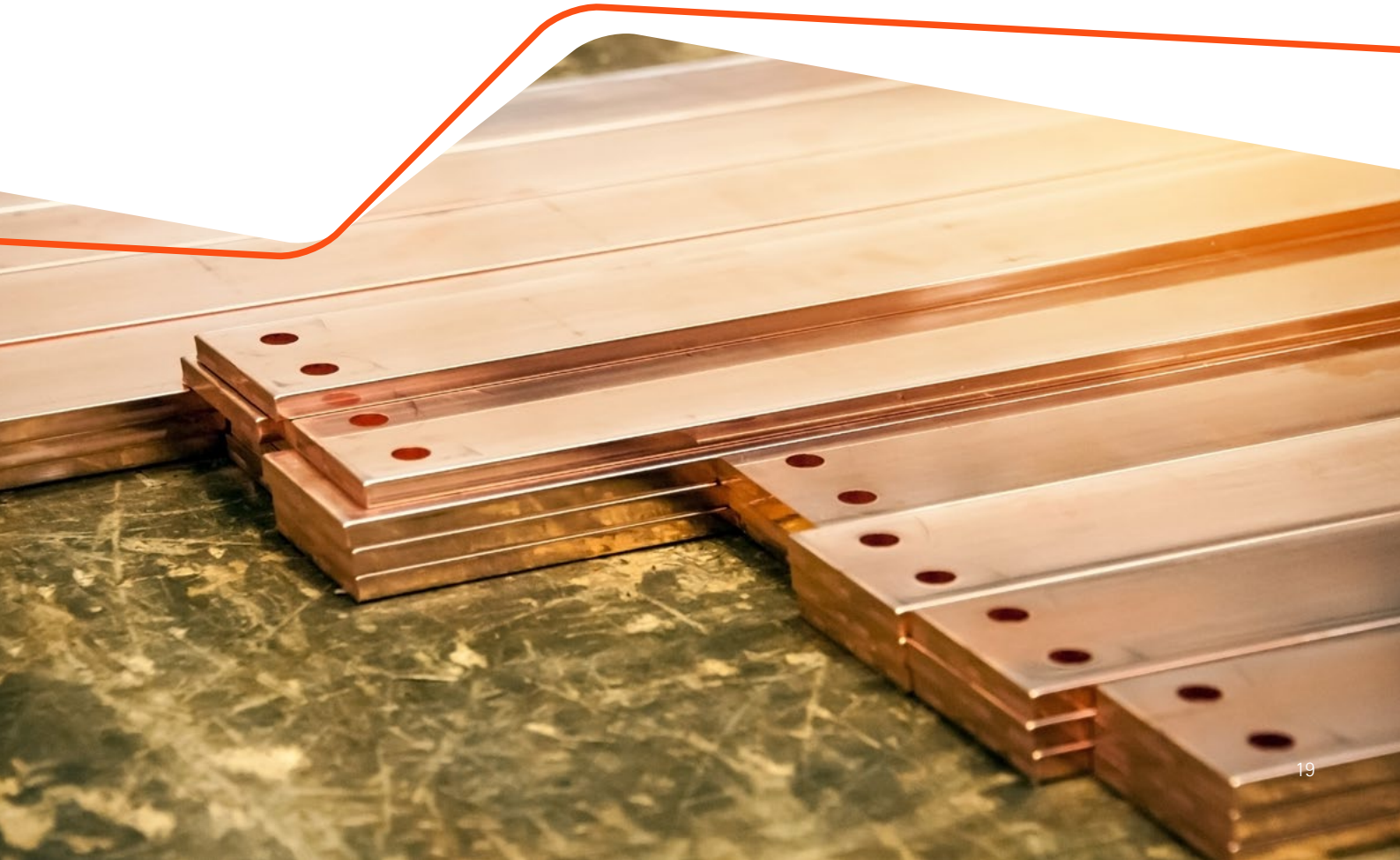
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Compiled by:
Adam Kotrba, Product Director,
Flat Products Council

Copper Development Association Inc.