

A COMPARISON OF ALUMINUM VS. COPPER AS USED IN ELECTRICAL EQUIPMENT

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ABSTRACT

The debate over the pros and cons of aluminum vs. copper conductors has been discussed for many years. Many of the concerns are based on old information and also misinformation. These concerns center on the very different properties of the two materials and their suitability for application within the Electrical Equipment Industry. Reliable performance from the conductors, the joints and terminations of the conductors is essential to the operation of the electrical system. With the recent increases in the cost of copper, customers are seeing these increases passed on to them by the equipment manufacturer. The variance in cost between equipment with copper versus aluminum conductors is now affecting the customer's buying decision.

This paper provides a comparison of the mechanical and electrical properties of copper (Cu) and aluminum (Al) and their relevance as applied to electrical distribution products. The offerings and impact of Cu and Al on various pieces of equipment is also discussed. The intended purpose is to provide the user with the information necessary to make an informed decision on the selection of copper or aluminum conductors within electrical equipment.

INTRODUCTION

Cu and Al are the two most commonly used materials for conductors and bus bars in electrical equipment. Each has positive and negative characteristics that affect their use in various applications. Both materials have been in continuous use in the electrical industry for many years. While aluminum is the most abundantly available of the two metals, the demand and scarcity of Cu have caused its cost to fluctuate widely. Silver is generally considered the best electrical conductor, however its high cost and low

strength limits its use to special applications such as joint plating and sliding contact surfaces.

For the purposes of this paper, the areas of discussion are:

- Current Carrying Capacity, Conductivity
- Physical Properties
 - a. Expansion
 - b. Weight
 - c. Tensile Strength
- Connections and Terminations
- Plating and Environmental Concerns
- Product Offerings
- Cost Comparison
- Impact on Various Pieces of Equipment

CURRENT CARRYING CAPACITY

The electrical and mechanical properties of a material are dependent on its alloy. For the comparison between copper and aluminum in this paper, the copper is cold-worked electrolytic tough pitch copper similar to ASTM B187, alloy UNC C11000. The copper used in electrical equipment is nominally pure 98% conductivity commercially hard based on the International Annealed Copper Standard (IACS). Pure Aluminum is not used as an electrical conductor in equipment since it is too soft for mechanical assemblies and is thus alloyed with other materials. The Al alloy 1350 used prior to 1975 was designated as EC (Electrical Conductor) grade aluminum with a 99.50% aluminum content. Even though it has 61% the conductivity of Cu it lacked in mechanical properties making it less than ideal as a conductor in the equipment. Al alloy 6101 is the predominant aluminum bus bar material being utilized and is stronger than 1350 Al because it has been hardened by heat treatment, but it only has 56% the conductivity of copper. The reduced conductivity of AL 6101 does not mean that the Al conductor will run hotter than the Cu

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conductor but does mean that the Al conductor for the same ampere rating must have a larger cross sectional area.

To analyze the current carrying capacity, two design criteria must be taken into consideration: The temperature rise of the conductor within the equipment above a maximum allowable ambient temperature and the current density in amperes per square inch of the cross sectional area.

Temperature rise is the established method for determining the current rating of the conductors within the electrical equipment. The heat generated in a bus bar is dissipated by convection, radiation or conduction or a combination of these methods. Industry standards such as UL and ANSI provide design requirements for various electrical equipment products. Switchboards and panelboards are designed to conform to UL standards, which permit a 55° C rise for switchboards and a 50° C rise for panelboards. Switchgear conforms to ANSI standard C37.20 which permits a temperature rise of 65° C above a maximum ambient of 40° C, provided that silver-plated (or acceptable alternative) bolted terminations are used. If not a temperature rise of 30° C over the same ambient is allowed. Regardless of which conductor material is used, aluminum, or copper, equipment manufactures must apply the proper conductor size to stay within the design requirements so that the equipment will operate under the same allowable temperature rise. To achieve this, an Al conductor must have its cross section area increased inversely as a function of the conductivity of the alloy used.

When the density of Cu (559 lb/ft³) is compared to that of Al (169 lb/ft³) and taking into consideration the conductivity ratio of Al to Cu of 56%, the result shows that on a pound per pound basis, Al has an amperage capability that is approximately 1.85 times that of Cu. In other words, one pound of Al has the same electrical capability as 1.85 pounds of Cu. Cu has a greater conductivity on an equal volume, cross sectional area, basis.

NEC Article 310 lists the allowable ampacities of Al and Cu conductors. As a comparison, table 310.16 shows that where a 500 MCM, 75° C, Cu cable has a rating of 380 A, a 750 MCM, 75° C, Al cable would be required. This is a 50% increase in cross section for the same current carrying capacity. This will

result in an increase in conduit size for aluminum conductors versus the copper conductors for the same current carrying capacity.

For applications where weight is a concern, Al may be the better choice. Depending on the equipment type and it's application, and if space and size are a consideration, Cu may be the better choice. This comparison is examined later in this paper.

PHYSICAL PROPERTIES

A comparison of some of the properties of Cu and Al are given in the following table. Properties will vary depending on the alloy used.

CHARACTERISTICS	COPPER	ALUMINUM
Tensile strength (lb/in ²)	50,000	32,000
Tensile strength for same conductivity (lb.)	50,000	50,000
Weight for same conductivity (lb.)	100	54
Cross section for same conductivity	100	156
Specific resistance (ohms-cir/mil ft) (20°C ref)	10.6	18.52
Coefficient of expansion (per deg. C x 10 ⁻⁶)	16.6	23

Information in the above table was obtained from GE Properties and Material bulletins B11B4 for copper and B12H60 for aluminum.

The properties that need to be discussed are the tensile strength and thermal expansion of the conductors. Of particular concern is the ability of the conductor to withstand the forces resulting from short circuits and the effects of expansion from heat on joints and terminations.

Reviewing the information in the table above, you can see that the aluminum conductor will have a cross sectional area 56% larger than copper for the same current carrying capability. Even though aluminum does have a lower tensile strength than copper it can be seen that the Al has, essentially, the same tensile strength of Cu for the same ampacity (50,000 lb/in²). The main area where this would be of concern as stated previously would be strength to withstand the forces during short circuits.

Underwriters Laboratory (UL), the National Electrical Manufactures Association (NEMA), and the Institute of Electrical and Electronics

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Engineers (IEEE) publish the leading industry standards for the design and testing of electrical equipment.

Equipment manufactured under these standards whether the conductor is Al or Cu must meet the prescribed criteria for short circuit withstand testing. Additionally, Equipment certified by a third party, such as UL, are supervised by UL personnel to assure their compliance with manufacturer's certification documents. This insures that the customer is procuring equipment that is adequately braced for the designated withstand rating regardless of the conductor material.

The above table notes that the coefficient of thermal expansion for Al is 42% greater than that of Cu. This characteristic is of concern when we study the expansion and contraction of conductors in electrical connections during thermal cycling. One of the important factors in establishing and maintaining a low resistance bus bar joint is the use of proper and well-distributed force. To analyze this issue it is necessary to first understand the potential problem and then look at the methods and techniques manufacturers use to address this issue.

The surface of a piece of metal, no matter how smooth, consists of microscopic peaks and valleys. When increasing pressure is applied, the initial points are deformed and flattened, permitting contact at more points. Even under the maximum pressure that can be exerted, approaching the yield strength of the material, the actual contact area represents only a small percentage of the total area of the mating surfaces. When a bolted joint is made, the metal yields plastically under the increased pressure, which permits true metal-to-metal contact.

The type of hardware affects the distribution of pressure at the bolted joint. If a nut and bolt only are used, the contact area is concentrated heavily around the bolthole. The material in the vicinity may be highly stressed and subject to creep. Deformation or creep is not reversible.

Since the coefficient of thermal expansion for steel is only 50 % of that of aluminum, as temperature increases, during load cycling, the clamping force will also increase. This increased clamping force will tend to further deform the contact points that have already been deformed by the initial clamping force. Thus a permanent set in the joint can be produced. When the joint cools, this

permanent set results in a lower pressure on the joint, which causes an increase in joint resistance. On the next load cycle, the joint temperature will be increased causing more deformation resulting in more permanent set and loss of clamping force on cooling. Eventually joint failure may result.

The above scenario can occur with materials having low tensile strength such as "EC" aluminum if joint hardware is not properly applied. Joint connection components such as split lock washers and Belleville washers can be applied to alleviate the effects of thermal expansion with conductor materials. This potential joint breakdown will not normally happen to higher strength materials such as copper or higher strength aluminum alloys. Aluminum alloy 6101, as mentioned earlier, is commonly used for bus bars and has a tensile strength approaching copper. Alloy 6101T63 has a tensile strength of 27,000 psi and will operate as satisfactorily as copper. Some UL standards such as busway standard UL 857 take into account the tensile strength at the joint and does not require a Belleville spring for Al joints if the tensile strength is at least 20,000 psi. Depending on the conductor material and the application, a Belleville spring or split washer will be utilized to insure that a stable joint is provided.

CONNECTIONS AND TERMINATIONS

The constructions of aluminum wire and terminals have both been revised from past years. At one time the conductor was nearly pure aluminum, now they are all much stronger 8000 series alloys, with physical characteristics similar to copper. The wire terminations also have much more severe UL test requirements, resulting in reliable long-term connections when installed in accordance with instructions. There is a common misconception that only compression (crimp) lugs should be used with aluminum cables, but this is not true. In the past with the use of the softer aluminum conductors, only compression connectors were suitable. However with the aluminum conductors used today and modern design and plating of mechanical pressure connectors, compression connectors are no longer required. The terminals on molded case circuit breakers are typically plated aluminum alloy with mechanical setscrews, listed for use with either aluminum or copper conductors. These lugs rated ALCU alleviate the

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need for more expensive compression connectors and the more laborious installations for these connectors.

The substitution of aluminum wire for copper always involves size and can also impact quantity. The size increase is usually one or two wire sizes. It is more common to have compact stranding of aluminum wire than copper, which can reduce the conduit upsizing required. Even though physically larger the aluminum wire is lighter and easier to handle than the equivalent copper conductor. In most cases the same lug can accommodate either aluminum or copper and has adequate wire range. Any lug marked ALCU is suitable for use with either conductor.

Another factor with the use of aluminum wiring for the supply or load from a piece of the electrical equipment is the size of the conduits. As mentioned previously, the use of aluminum conductors will result in either larger conductor size or more quantity of conductors. Either way, more or larger conduits will be utilized. A design trend is always toward equipment with smaller footprints. Cost of the space in the structures housing the equipment is constantly increasing. However in many cases there might not be physical space in the equipment for the termination of the conduits using aluminum conductors while there is adequate space for the quantity and size of the conduits for the copper conductors.

PLATING AND ENVIRONMENTAL CONCERNS

Both Al and Cu will oxidize when exposed to the atmosphere. Oxides, chlorides, or sulfides of the base metal are much more conductive for copper than aluminum. For a low resistance aluminum joint, the aluminum bar conductors must be plated to minimize oxidation. Concern over the Al oxidation away from the joint is not an issue and will act to protect the conductor from further corrosion in most environments. Aluminum bus conductors depend upon the plating for the integrity of the electrical connection. Aluminum and copper conductors are typically plated with silver or tin. In general, bolted connection of unplated aluminum to copper bus bars is discouraged. The majority of Al to Cu connections are made by applying silver or tin plating to the joint areas of either or both of the conductors.

The presence of hydrogen sulfide (H₂S) in the atmosphere is of main concern for base metal Cu

and silver plating. Both corrode heavily in a relatively low concentration of H₂S and most intensely in locations usually having an elevated temperature while the equipment is energized. Two processes are active at the same time, general corrosion of the silver and creep corrosion of Cu. Silver plating is widely used on contacts and other conductive parts in electrical equipment due to its superior conductivity, abrasion resistance and longevity. Hydrogen sulfide is usually present at chemical plants, oil refineries, steel mills, pulp and paper mills, and wastewater treatment facilities.

In a H₂S environment metal filaments (whiskers) start to grow as soon as a thick enough layer of silver sulfide has been formed. This silver corrosion results in a high resistance producing more heat, which further stimulates tarnishing and growth of whiskers. This process if allowed to continue leads to failure due to over heating or short circuit. Tin plating displays good environmental protection and is a practical solution to the H₂S corrosion problem of copper and silver-plated copper

OFFERINGS

GE currently offers aluminum conductors in a variety of products, but not in all products. Products lines such as Motor Control Centers and Switchgear have historically offered aluminum bus, but currently only offer copper bus. There are numerous reasons for the copper only offering, but primarily customer demand and in turn manufacturing efficiencies drove the decision. In the past Aluminum bus was prevalent in switchgear, but issues at the time with joint connections forced welding of the bus. This in turn limited flexibility of the equipment in the field and resulted in customer dissatisfaction. Also in the past copper bus was not offered with tin plating so aluminum bus with tin plating was the standard for certain environments such as H₂S where the silver plating would react and turn black. When copper bus became available with tin plating and even though past issues with aluminum bus had been resolved, 99% of the customers requested copper bus. From a manufacturing perspective, it was not economical to support aluminum bus for this equipment.

The current offering from GE for both switchgear and motor control centers is either tin or silver

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plated copper bus. In the Spectra line of switchboards silver plated copper or tin plated aluminum is offered. In lighting panelboards, both aluminum and copper bus is offered with the copper available in either tin or silver plating. One unique item with lighting panels is that even though aluminum bus is furnished for the vertical bus, the breaker mounting straps are still furnished in copper. There is no issue with this mix since the aluminum is tin-plated and the copper is silver-plated. Copper and aluminum bus are also offered in the Spectra distribution panels.

Spectra busway is offered with either copper or aluminum conductors. The aluminum bus is provided with a multi-layer plating of tin, copper, bronze and silver to maximize conductivity, provide resistance to galling at plug-in locations and prevent any fretting corrosion at stab locations.

Dry type transformers are offered with either copper or aluminum conductors. Many specifications are still written not allowing aluminum foil conductors. However for over 45 years, GE has utilized thermally stable insulated aluminum magnet wire terminated by solder or weld to lug pads for customer connections. At this time all general purpose transformers must meet the same NEMA TP-1 efficiency standards whether copper or aluminum wound.

Oil filled padmount or substation transformers are offered by GE with aluminum primary and secondary windings, copper primary and copper secondary winding or a combination with copper primary and aluminum secondary. The variety of offerings is provided to meet the customer's electrical and budgetary needs.

COST COMPARISON

The cost difference between copper and aluminum varies with the fluctuating cost of the base metals on the commodities market. However this cost difference is many times the deciding factor when a customer is considering aluminum conductors in their equipment. All of the references on the cost differences are based on the effect that the current commodities market has on the components into electrical equipment.

The percentage difference in the cost between aluminum and copper also varies as the percentage that the conductor is a component of the overall equipment. For example a 1200A

distribution panel with no breakers installed would show a cost difference of 25-50% but when the panel is loaded with breakers, the percentage of the price of the bus bars is much less than the overall price of the panel. The cost difference between and aluminum and copper bussed panel drops to approx 7-8%. A contrasting example of the conductor being a large percentage of the overall assembly is with busway. The larger the amperage of the busway, the greater the base conductor is to the percentage of the overall equipment. An example would be comparing 3 phase, 4 wire busway at 1000A to the same busway at 4000A. At 1000A, the adder to go from aluminum to copper would be approximately 50%, but at 4000A, the adder for copper over aluminum is almost 100%.

Panelboards both distribution and lighting class can have a copper to aluminum price differential anywhere between 10-50%. This varies as explained above with the overall price of the breakers and other components installed in the panelboards. Switchboards on average will have a 25-30% premium for copper bus over aluminum bus.

With respect to percentage of conductor content within the equipment, transformers have a higher percentage of the conductor than a panelboard, but much less than busway. Typical dry type transformers used on commercial projects will vary anywhere from 45% to as much as 100% premium for the copper over the aluminum windings. Liquid filled transformers such as padmounts or SSTs, currently show a price differential of 12-15% for Cu-Cu vs. AL-AL, but this percentage drops to about 6-8% when a Cu-Cu is compared to a Cu-Al wound transformer.

Currently electrical equipment with aluminum conductors designed to perform identical to the same equipment with copper conductors will provide a dollars savings to the end user.

IMPACT OF VARIOUS PIECES OF EQUIPMENT

It is a common misconception that electrical equipment built using aluminum conductors will always be larger than the same equipment using copper conductors. While the actual conductor within the equipment will be larger with aluminum, many times the enclosure for the

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equipment is the same size whether copper or aluminum conductors are used. This is true for switchboards, panelboards and most dry type transformers. Oil filled transformers will generally range from 2-5% larger when constructed with aluminum instead of copper windings.

The biggest size impact for electrical equipment when copper and aluminum conductors are considered is for busway. Since the actual conductor is the primary component within the busway, the size difference will be more apparent. All of GE Spectra busway is 4.5" thick, but the width will vary. For 1000A busway, the aluminum bus will be approximately 22% larger than copper bus and for 4000A busway, the size difference increases to almost 27% larger for the aluminum.

Even though the size for the aluminum bus is larger than for the copper bus, the weight difference is more dramatic and favors the aluminum bus. Using the same examples used for size and assuming 3 phase, 4 wire busway, the 1000A copper is 50% heavier than the aluminum and for the 4000A busway, this value increases where copper is 73% heavier than the aluminum. This weight differential can be a huge factor for both the designer and the installer. For example a 4000A, 10 foot section of copper bus is approximately 520 pounds, while the same busway with aluminum conductors is only 300 pounds. Installation by the contractor and mechanical support design by the engineer are considerations when the difference between the two products is considered.

The weight difference between equipment items with aluminum or copper conductors is present with all of the equipment types. For switchboards, the actual percentage will vary significantly with the amount of breakers installed in a section; and with a higher count of breakers, the percentage of weight contributed by the busbars diminishes. However, if you just consider the weight of the steel enclosure and the busbars, copper bussed switchboard sections will be heavier than aluminum bussed switchboard sections, varying between 20% for 1000A sections to 29% for 4000A sections.

Dry type transformers like switchboards do not typically have a physical size difference between copper and aluminum units, but they like switchboards, have significant weight differences. These differences will vary from 18% for a 45kVA

unit to 22% for a 75kVA unit. This translates to a copper wound 75kVA transformer weighing 130 pounds more than the corresponding aluminum wound transformer.

When considering the differences between copper and aluminum conductors in electrical equipment, size must be acknowledged, but for most equipment types the size is not a delineating feature. The weight of the equipment is generally not apparent, but can be big difference in terms of labor and material for the installation and support of the equipment.

CONCLUSION

A common question to manufacturers is what percentage of equipment is furnished with aluminum versus copper conductors. Many people understand the cost difference between the two, but they do not have personal experience with equipment with aluminum conductors and are hesitant to change. This percentage varies widely within equipment lines and locations throughout the country. The equipment manufacturers only make what the customer requests. Many consultant specifications and end user specifications require copper only conductors throughout their projects. Some of these specifications could be relics from the time when aluminum conductors in equipment was not the best choice or the people producing the specifications are not informed of the actual differences and similarities between aluminum and copper conductors. When the equipment is designed to the applicable industry standards, the performance of a piece of equipment should be identical whether the internal conductors are copper or aluminum. Most importantly, the designer should be aware that equipment available with aluminum conductors will definitely weigh less than the same equipment with copper and at the current commodity pricing will cost less. At the same time the designer should be aware that there might be a physical size difference. The environment in which the equipment is installed may also dictate the conductor material and plating requirements. All of these factors should be taken into account when the decision is made between copper and aluminum conductor material. Either material will meet customer expectations when designed to industry standards and installed correctly.

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