WILSON POWER SOLUTIONS

Responsible Power Engineering

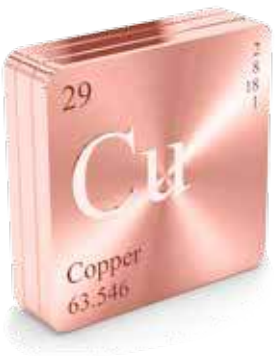
ALUMINIUM v COPPER

The electrical equipment industry is witnessing first-hand how a customer's purchase decision is being heavily influenced, by the finest of margins, when it comes to the two very similar performing metals of aluminium and copper.

Over the years, there has been plenty documented about the performance of these two metals, especially when it comes to their suitability, reliability and performance as conductors.

Now, as more factual information comes to the fore, (aligning the misconceptions from the past), there are lots of arguments to consider for both the manufacturers and consumers.

In turn, this paper aims to provide an informative comparison regarding the mechanical and electrical properties of aluminium (Al) compared to copper (Cu), and their abilities when applied to electrical distribution products. Hopefully, the information provided will give readers a greater insight to the argument, before having to make a decision of their own.



AREAS OF DISCUSSION /CONTENTS

A BRIEF HISTORY

Due to the fact that Al and Cu are the two most commonly used materials for conductors in transformers, (amongst other electrical equipment), there has always been comparisons made.

The competition between these two metals really began to heat up during World War II. Copper became scarce because it was being used for shells and bullet casing. This meant that, due to their similarities, several industries opted for aluminium as the nearest alternative.

Aluminium, at the time, was in good supply and mostly cheaper than copper. Therefore, it quickly became the preferred metal for high-power transmission power lines. Today, almost all major manufacturers' transmission lines are made with aluminium.

THE ARGUMENTS FOR COPPER OVER ALUMINIUM IN TRANSFORMER WINDINGS

Traditionally, Cu has been the preferred metal, when it comes to windings in distribution transformers. There are a lot of scientific and practical reasons for this, below.

Lower Levels of Creep

The standout factor supporting Cu over Al in power transformers is that Cu displays lower levels of creep. Creep (or cold flow) is the tendency of a solid material to move or deform under the influence of extreme loading or varying temperature conditions. Aluminium has near 25 times higher creep rates, in comparison to copper. Therefore, aluminium wound distribution transformers can be more susceptible to failures. However, alloys added to Al may reduce the incidence of failures.

Oxides

With regards to wire terminations and oxides, each metal has a different behavior. Aluminium oxide attaches itself firmly; it's hard to dislodge and difficult to work with. This is a problem when creating mechanical connections because soldering requires additional layers of tin or nickel for it to be compliant. Moreover, its electrically insulating, meaning all electrons are stuck in one place, unlike copper. Copper oxide is softer and breaks down easier, so it can be fixed or improved, making it less prone to failure.

Galvanic Action

Galvanic action occurs when electrochemically dissimilar metals are in contact with one another, creating a conductive path. Copper wires have no galvanic action because they are the same element as the connectors. This proves more problematic for aluminium, as it loses material through galvanic action and, consequently, loses contact. Additionally, copper is naturally harder, stronger and more ductile than aluminium. Cu also expands less and does not flow at terminations.

Size & Weight

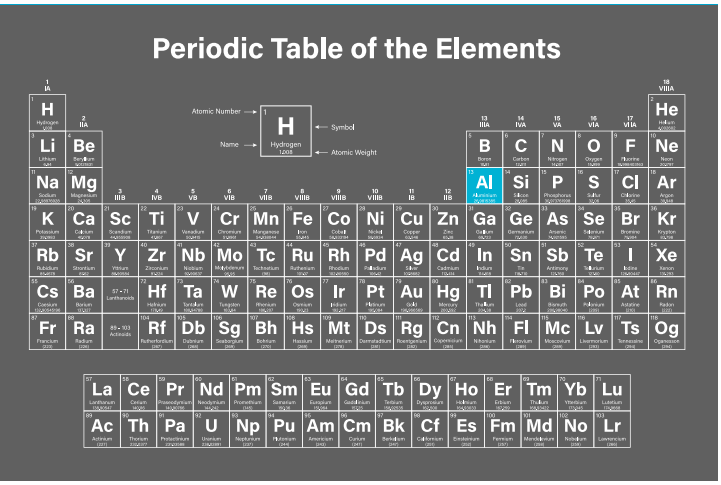
Despite aluminium being lighter than copper (of an equal volume), when it comes to wound distribution transformers, this fact is irrelevant. The reasons being that the resistivity of Cu is 0.6 times that of Al. This means that the cross-section of an Al conductor needs to be 1.8x the size of a Cu conductor of the same resistance. A larger core volume for the Al transformer results in a larger volume, enforcing a larger tank and more oil, making Cu distribution transformers smaller and lighter all round.

Costs

Transformers with copper windings are less expensive to manufacture. Simply, because they require less materials, thanks to the superior size and weight, compared to aluminium wound transformers. A finer balance of the copper wound transformers, its conductor, magnetic steel, tank and oil requirements concur less cost than aluminium equivalent.

Fatigue

The lifespan of distribution transformers with HV (High Voltage) windings made of copper are less susceptible to metal fatigue. Some studies suggest that aluminium HV winding conductors would fail earlier than copper ones, in similar stress conditions.



INTERESTING FACTS ABOUT ALUMINIUM

As aluminum is the most abundantly available of the two metals, (and because of its soft, lightweight, non-magnetic, corrosion resistant ductility), its uses go far beyond electrical equipment alone.

Did you know?

- Aluminium is the third most abundant element of the Earth's crust
- Rubies, emeralds and sapphires consist mainly of crystalline aluminium oxide.
- More than 60 tonnes of aluminium cans are used in Britain each year.
- Britain use over 1 tonne of aluminium foil each year.
- The energy saved from just one recycled aluminium can is enough to run your TV for three hours.
- Making cans from recycled aluminium causes 95% less air pollution than making cans from raw material.
- Recycled aluminium foil can be used to make vehicle parts.
- Recycled aluminium cans are back on the shelves as new cans in just 60 days.

Today, aluminium and aluminium alloys are used in a wide variety of products from kitchen utensils to rockets. They also prove popular in the electro-technical industry through transmission lines, cables and windings in power distribution transformers.

ALUMINIUM PRACTACALITY & RELIABILITY

Aluminium is both practical and reliable, in anabundance of situations and scenarios, mainly for the following reasons:

Strength

Aluminium has low density. This means that it is light-weight, but it does not impact its strength. Even at low temperatures, it does not become brittle, unlike some other metals. Although at higher temperatures (continuously above 100*degrees*), aluminium does falter, and must be taken into consideration.

Machining

In the modern era, it's important for a metal to be easily worked. Be it milling, punching, cutting or drilling, aluminium doesn't require much energy input to manipulate it. This makes it very adaptable which is quick and easy to work with.

Formability

Similar to the above, due to aluminium's superior malleability, it can be exploited into a variety of sizes and shapes. From strips to rolls, foils and sheets - the bending and forming of this metal is simply done, whether it's hot or cold.

Conductivity

Unsurprisingly, aluminium makes a fantastic conductor for both electricity and heat. Weighing around half as much as a copper conductor, yet having equal conductivity, it makes for an effective conductor in any electrical equipment.

Joining

Aluminium is a reliable metal and extremely easy to work with easy when joining it to other materials or metals. Popular for welding, bonding and taping, it's a facilitator of most mechanical engineering joints.

Reflectivity

Aluminium is a natural reflector of both visible light and radiated heat, making it a practical solution, or material, for many manufacturing processes and products.

Radiation Screening

Secured aluminium boxes have the ability to exclude electromagnetic radiation, largely due to aluminium's superior conductive ability. The more conductive a material, the better it performs, or acts, as a shield.

Anti-Corrosive

Because aluminium reacts with oxygen in the air, it forms its own protective layer of oxide. Despite it being one thousandth of a millimeter thick, it is dense and proves to be an ingenious method of protecting against corrosion.

Non-Magnetic

By being non-magnetic, aluminium avoids interference with any magnetic fields, which could prove problematic for some technologies, in some industries.

ALUMINIUM V COPPER ENVIRONMENTAL IMPACT

As with anything in the modern era, its impact upon our environment must be considered and taken seriously. Even the most minute of differences can potentially save energy, reduce emissions and prolong the future of our planet, so it's always important to identify potential issues.

Expense

Copper represents one of the most expensive materials used in transformers. Copper is a finite resource, making its cost unstable. Yet, due to an increase in demand, it is becoming costlier.

In comparison, the cost of aluminium is lower than that of copper and it doesn't fluctuate as much either.

Reserves

Many of Earth's materials and products are under threat. The same can be said for the world copper reserves. They are limited and are expected to be depleted, at some point. This being the reason why prices are high and volatile. Its future is uncertain.

On the other hand, aluminium is in plentiful supply. There are copious amounts in the Earth's core and we now produce almost twice as much Al, compared to Cu, annually. Therefore, aluminium has a more stable platform, when it comes to supply and demand.
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Extraction

Both copper and aluminium require complex operations to mine and extract the metals from the earth. Huge mining operations are present in both camps. Each operation has been developed over the years to become more environmentally friendly. For instance, many of the byproducts are reclaimed. Sulfur dioxide, produced when extracting copper, is captured and turned into sulfuric acid which is then used in fertiliser. Aluminium requires a lot of electricity in its extraction process.

Reusability

Again, both copper and aluminium are highly recyclable. In fact, recycling these metals is a eco-friendlier method than mining them. Recycling scrap aluminium requires only 5% of the energy used to make new aluminium, for example. Moreover, due to the increasing value of copper, it has become more recyclable, and, in turn, more susceptible to theft.

Environmental Impact

To summarise, the environmental impact of each, comes down to the 'Eco-indicator' method which quantifies environmental impact in terms of 'points'. 1000 points roughly corresponds to the annual impact of an average European. Millipoints (mpt) are often the appropriate units for evaluating practical decisions in design work.

The values given for primary costs of Cu and Al are 1400 mpt/kg and 780 mpt/kg respectively. Al is clearly cheaper, but costs based on volume may be more helpful: per volume, the values can be expressed as 12.5 mpt/cm3 for Cu and 2.1 mpt/cm3 for Al.

Even when considering the 62% additional Al needed for equal resistivity, Al has much less environmental impact than Cu needed for the same winding by this measure.

ALUMINIUM V COPPER PROPERTIES & PERFORMANCE

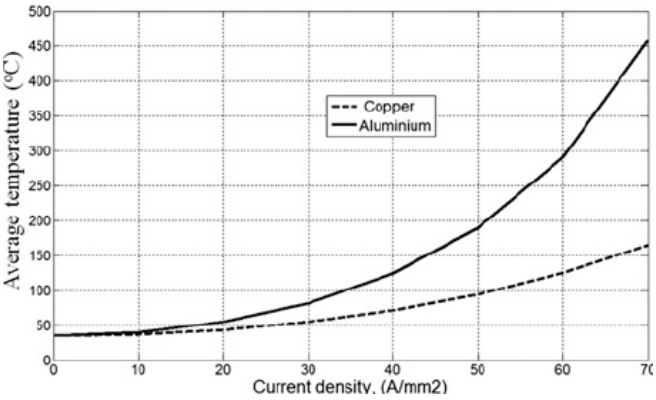
The informed choice of Al and Cu windings and conductors used in power and distribution transformers will be based on technical, commercial, economic and environmental reasons such as discussed above.

However, a more detailed look at some of the metals properties, and a closer assessment of their performance, may influence a decision further.

Current Density

To make comparisons between aluminium and copper, it is important to understand that each material's electrical and mechanical properties are dependent on its alloy. Pure aluminium cannot be used as an electrical conductor, as it is too soft for mechanical assemblies. As a result, Al is alloyed with other materials, forming new compounds. For example, the Al alloy 1350, used prior to 1975, was designated as an electrical conductor and was made up of 99.5% aluminium content. Despite it having 61% of the conductivity of Cu, it lacked mechanical properties, making it unreliable as a conductor. The alloy: Al 6101 is what is currently being used for busbars, and even though it's been hardened, it only has 56% of the conductivity of Cu. However, this doesn't mean that the Al conductor will run hotter than the Cu conductor. It just means the Al conductor must have a larger cross-sectional area.

To successfully measure the current carrying capacity, the temperature rise of the conductor within the equipment and the density of the cross sectional area must be analysed.



Temperature

The resistance of pure metals, like copper and aluminium, increases as the temperature increases. Heat, generated by the busbar, is dispersed in all directions through radiation, convection and conduction. So, in order to determine the reliability and performance of a conductor, temperature rise is the preferred measuring tool. The resistances of both Cu and Al, to make a comparison, must be measured at the same temperature. Therefore, industry standards impose regulations on manufacturers, no matter which material is used as the conductor. The conductors must stay within the size allowance and other design requirements, so that the equipment will perform in situations where the temperature may rise of fluctuate.

For instance, electrical equipment (such as switch boards and panel boards) must conform to industry standards. These standards permit a 55°C temperature rise for switchboards and a 50°C rise for panel boards. To achieve this, Al conductors require the cross-section area to be increased inversely. Meaning, to accommodate the rise in temperature, additional Al is required.

Despite this, when comparing the density of Cu (559 lb/ft^3) to Al (169 lb/ft^3), alongside the conductivity ratio of Al to Cu at 56%, Al, on a pound for pound basis, has an amperage capability some 1.85 times that of Cu. To summarise, one pound of Al has the same electrical capability as 1.85 pounds of Cu. But Cu has a greater conductivity, based on an equal volume, cross sectional area.

Material properties of pure Copper and Aluminum

MATERIAL PROPERTY	DIMENSION	COPPER	ALUMINIUM
Density (@20°C)	$g \cdot cm^{-3}$	8.94	2.70
Electrical resistivity (@20°C)	nΩ·m	16.78	28.2
Thermal expansion (@25°C)	$\mu m \cdot m^{-1} \cdot K^{-1}$	16.5	23.1
Ultimate tensile strength	MPa	380	200

This table gives some of the material properties for both Aluminium and Copper.
Please note that the material properties in this table refer to the pure elements and can differ per alloy.

Conductors

Good conductors consist of materials which conduct electric current or allow the flow of electrons; these are often non-magnetic like Al and Cu.

Copper Conductors

Copper has a rich history. Used by experimental inventors, it eventually became the conductor for inventions like the telegraph and telephone.

Cu is the most common conductive metal, and over time, it became the international standard. Commercially pure annealed Cu has a conductivity of 100%.

Aluminium Conductors

Although Cu has been the material of choice for conducting electricity, for many years, Al has its advantages, making it an attractive alternative.

Carrying 61% of the conductivity of Cu at 30% the weight, Al weighs half as much but has the same electrical resistance. Nowadays, Al is often made up of different alloys to recreate similar levels of creep and elongation properties, similar to Cu.

Connections

The type of connections can vary from Al to Al, Al to Cu and CU to CU. Be aware that when it comes to connections, if standard nut and bolt connection materials are used, the thermal expansion between the metals can lead to problems.

One solution is using a plated Al. Plating the Al conductors guarantees there is no direct, physical contact between the two metals, especially if Cu is used for the bus bar.

To prevent maintenance, whether or not the bus bar is Al or Cu based, the use of disk spring washers (Belleville washers) for all combination of connections, is recommended. When installing, the bolted connections are set a specific amount of torque to compress the washer. When it's compressed, the washer acts a s a spring, compensating expansion and contraction whilst maintaining the correct contact pressure. Additionally, by using spring washers it eliminates any temperature expansion effects. Therefore, thermal cycling will not occur. This form of fatigue only occurs when plastics deforms, as a result of the ratio of thermal expansion of the conductor material and the connector material.

Construction

Like most technologies and inventions, the construction of them is constantly monitored and revised, to improve its performance and success.

It's no different for the construction of Al and Cu wire and terminals. At one point, the conductor was pretty much pure aluminium, whereas now, they're much stronger alloys with similar characteristics to that of copper.

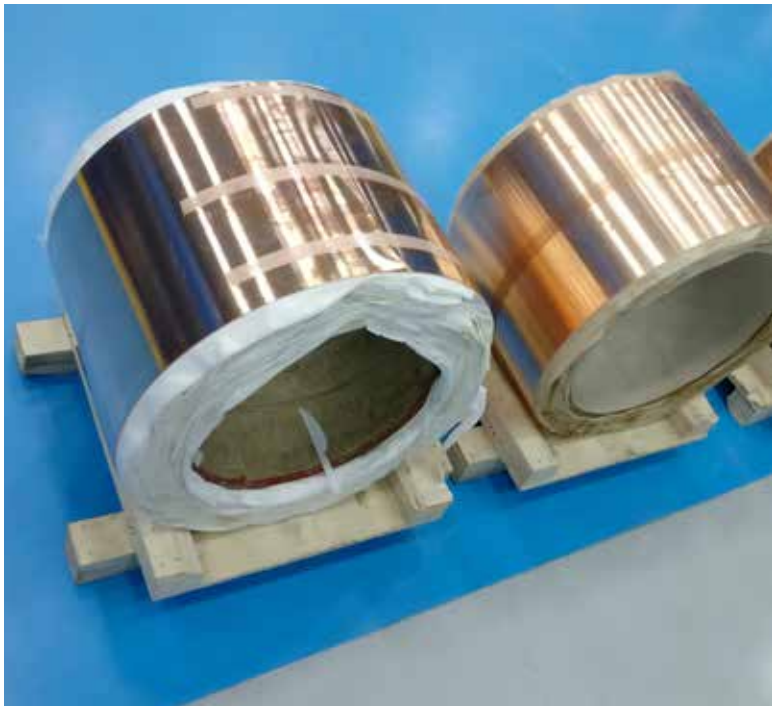
The testing of wire terminations is also a lot more severe, nowadays. This is to ensure the reliability of connections lasting long-term.

A common misconception is that, due to the softer aluminium conductors of old, only compression connectors are suitable. However, modern designs benefit from using plated mechanical pressure connectors, resulting in compression connectors becoming surplus to requirements.

Another way to alleviate the need for more expensive compression connectors and eradicate the laborious installations in doing so, is to to ensure the terminals on moulded case circuit breakers are plated aluminium alloy with mechanical set screws, which are listed for use with either Al or Cu conductors. Any lugs marked ALCU are adaptable for both metals.

Substituting aluminium wire for copper wire will impact on size and quantity. The overall size increase is by one or two wire sizes. Despite being physically larger, the aluminium wire is somewhat lighter and easier to maneuver than an equivalent copper conductor. However, the use of aluminium conductors will result in either a larger conductor size or more conductors. This directly impacts on the size and space needed for the structures housing the components; causing implications towards design trends staying in line with having smaller footprints.

Naturally, the increased size and space needed impacts upon the costs and manufacturing process. Although aluminium transformers may require additional space compared to copper, the actual costs of the metals can play a crucial factor in the final decision for the size of the conduits and terminals.



ALUMINIUM V COPPER COSTS

Like most commodities, it has come to light that the deciphering factor when a customer is choosing their products and equipment is cost.

The costs of copper and aluminium does fluctuate, in the commodities market. Therefore, a truly accurate representation is not always feasible. Regardless of that, the references made in this report are based on the components used surrounding distribution transformers and electrical equipment.

As previously mentioned, the percentage of each metal used in the construction and containment of distribution transformers will have a direct impact upon the costs. For instance, a 1200A distribution panel with zero breakers installed would be some 25-50% less than one loaded with breakers, so an instant saving could be made here. However, the percentage of the price of the bus bars is somewhat lower than the overall price of the panels. Add to that the cost difference between Al and Cu bussed panels and even greater savings of around 7-8% can be seen.

In contrast to this, if the conductor is a large percentage of the overall assembly with a busway, the greater the amperage of the busway, the larger the base conductor is to the percentage of the overall equipment.

Again, referring to components which possess the metals in the overall build like panelboards, can see huge variations in costs. The same can be said for switchboards which can often see a 25-30% premium added for Cu over Al.

It's within the transformers themselves where we see the greatest variations. To have a copper version of a dry type transformer, you can expect to pay an additional 45-100% more than for an aluminium version.

Liquid filled transformers again show price differences of around 10-15% for Cu-Cu v AL-AL. However, this percentage drops again when comparing a Cu-Cu to a Cu-Al wound transformer.

As is stands, all electrical equipment with aluminium conductors (designed and tested to perform to the same level of copper), prove to be a more cost-effective option to the end user.

ADVANTAGES & DISADVANTAGES OF ALUMINIUM & COPPER

There are plenty of positives about the usefulness of aluminium and copper, but here are a few when it comes to our industry, when considering the components as windings:

Advantages of Al Windings

- Aluminium costs a lot less than copper and thus brings commercial advantages.
- Aluminium has a very thin layer of oxides on the surface, which stops air and water getting to the metal, resisting corrosion.
- Although the conductivity of copper is stronger, pound for pound aluminium proves to be almost double as effective a conductor.
- Aluminium is more flexible than copper making it easier to wind in production processes.
- he higher resistivity of aluminium gives inherently lower eddy losses in the windings. This mitigates the risk for hot spots.

Disadvantages of Al Windings

- Aluminium connections can be susceptible to fire. Connections must pierce the aluminium oxide layer so that it remains gas tight[LG2] [j3] .
- Aluminium wound coils are larger than an equivalent copper coil, meaning it requires approximately 1.8 times as much cross section as copper to carry an equivalent amount of current.

Advantages of Cu Windings

- Copper is stronger than aluminium. It expands less and requires less inspection and maintenance.
- Copper can carry almost twice the current capacity of aluminium
- Transformers with copper windings can be less expensive to manufacture because they're smaller.
- They reduce the cost of the magnetic steel, tank and oil needed to achieve the specified energy performance.

Disadvantages of Cu Windings

- Copper is significantly more expensive than aluminium.
- Copper is more difficult to wind into a core than the more flexible aluminium.

WILSON POWER SOLUTIONS EXPERIENCE

After over 70 years' experience in the industry, Wilson Power Solutions have seen a lot of advancements and changes. This is what has spearheaded the company's product innovation, engineering excellence and dedicated customer service today.

The transitions have embedded a strong sense of social and environmental responsibility within the business, and perhaps have made the company a valued and trusted power solutions partner for some of the UK's biggest companies.

DISTRIBUTION TRANSFORMER WINDINGS

When considering distribution transformer windings in particular, historically speaking, most were made from copper, for commercial reasons, as copper prices were low, and the conductivity of the material made it a logical choice.

However, around 10 years ago, copper prices rose significantly on the back of China buying most of the world's copper supply for their own internal consumption, meaning that transformer manufacturers were forced to look at alternatives for winding materials.

From the mid 1970's manufacturers had experimented with aluminium as a winding material, but, at that time, there wasn't a significant price difference between that and copper. Additionally, in this era, welding technology made it difficult to weld a busbar onto the end of the winding for the LV connection. Since that time, there have been significant advances in welding technology, such that with robot welding the performance is much more consistent and therefore the connection between the busbar and the winding itself is as robust as with a copper winding.

Now that the technological issues with welding have been resolved, the decision on which winding material to use is a purely commercial one as the performance and reliability of the two options are equivalent.

As such we have decided to change the specification of our standard distribution transformers from copper to aluminium.

CONCLUSION

Having analysed many aspects surrounding the Al v Cu debate, the final thoughts have to be surrounding personal experience, preference and understanding. Whilst the majority of people grasp the concept of costs, and are heavily influenced by it, there are other aspects to consider.

Tradition is often hard to interrupt. In certain parts of the UK, manufacturers may not have had the experience of working with aluminium before, and therefore stick to what they know. Hesitancy to change habits of a lifetime could be a reason as to why copper remains a popular choice, despite the similar advantages of aluminium.

On the other hand, the equipment manufacturers will make what they customer requests. If said customer has limited knowledge of the benefits of aluminium versus copper, they too will side with what they're used to. Perhaps this is because many consultant, and end user, specifications state the use of copper only conductors throughout their projects. The chances are that these specifications have not been updated for decades, so people are not being educated or informed about other possibilities and solutions.

As we've seen there are lots of similarities between aluminium and copper, and when the equipment is designed to new industry standards, the performance is near identical. This is a key reason as to why a designer should be aware of both metals and their performance capabilities. Having the knowledge that aluminium components will weigh less than copper, for the same levels of performance, may be a crucial factor in the overall design process, for instance. On top of that, they should also be aware that, if choosing aluminium, there will be a physical size difference.

Asides form design and costs decisions, the prominent factor has to be environmental. Each metal is sourced, recycled and dependent on numerous factors. Selecting the right one, at the right time, for the right product can be crucial to the impact upon our environment.

All of the points in this paper need to be considered by all parties, when making a decision between the use of Al or Cu in distribution transformer windings. Both materials will meet customer expectations, if designed to industry standards and installed correctly.