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A COMPARATIVE EVALUATION OF COPPER AND ALUMINIUM WIRES AND CABLES IN BUILDING INSTALLATIONS

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SUMMARY

This paper carries out a comparative evaluation of wires and cables used within building installations with copper and aluminium conductors respectively. Arguments relating to the physical properties of copper and aluminium are examined and comparisons between the two types of wires and cables made for ampacity, thermal capacity, weight, size, strength, ease and reliability of installation, reliability of connections and terminations, corrosion aspects and relative costs.

Based on these arguments, the paper concludes that in each respect, copper conductors out-perform aluminium conductors for all wire and cable types used within buildings.

INTRODUCTION

All metals conduct electricity and heat as seen in Table 1 (below), but excluding precious metals due to their scarcity and cost, only copper and aluminium come into consideration for use in electrical wires and cables within buildings due to their relatively high electrical and thermal conductivities.

Material	Electrical Conductivity (S/m) at 20°C	Thermal Conductivity (W-cm/cm^2 °C) at 20°C
Silver	6.3×10^7	4.30
Copper 99.95%	5.80×10^7	3.94
Gold	4.1×10^7	3.20
Aluminium (1XXX)	3.5×10^7	2.50
Iron	1.0×10^7	0.80
Bronze	7.5×10^6	-
Lead	4.55×10^6	0.35
Stainless Steel	1.45×10^6	0.16

Table 1 – Key electrical and thermal characteristics of copper and aluminium (1)

Historically, of the two metals, copper has long been the preferred conductor material for wires and cables used within building installations and the use of aluminium conductors has been comparatively restricted by National and International Standards[#] due to several reasons, which are explored in detail in this paper.

CONDUCTIVITY, CURRENT CARRYING CAPACITY AND VOLUMETRIC HEAT CAPACITY

Between the two metals, a cable manufactured from copper exhibits a greater current carrying capacity or ampacity than that made from aluminium for the same conductor cross sectional area (CSA), due to its higher electrical conductivity.

This may be demonstrated by a comparison of the ampacities of constructionally similar cables with copper and aluminium conductors respectively, defined by the installation method and the constraint on temperature rise placed by the thermal withstand limits of the insulation. Table 2 below shows the relative ampacities of 35mm^2 4 core XLPE insulated, Steel Wire Armoured, PVC sheathed cables typically used within buildings with copper and aluminium conductors respectively.

Cable Type	Installation Method	Ampacity (A)
35mm^2 4C XLPE/SWA/PVC – Copper Conductors	perforated cable tray in free air	162 Amperes
35mm^2 4C XLPE/SWA/PVC – Aluminium Conductors		120 Amperes

Table 2 – Ampacities of constructionally similar cables with copper and aluminium conductors (2)

In practical terms , the use of cables with copper conductors leads to reduced cable sizes as compared with those using aluminium conductors – more amperage delivered at a given conductor cross-sectional area (CSA), or smaller cables used for the same amperage.

A further examination of table 1 shows that the thermal conductivity of copper is approximately 60% greater than that of aluminium. This accelerates heat diffusion and reduces the hot-spot temperature rise at terminations and busbar sections.

In sum, the better electrical conductivity, and hence current carrying capacity, and higher thermal conductivity makes copper the superior choice on account of these properties.

 # [The minimum cross sectional area of conductors for use in building power systems is restricted by National and International Standards. For example, IEC 60364-5-52 restricts the use of aluminium conductors to cables sizes exceeding 2.5 mm2 CSA (5). National Codes go further – for example, within the UK, BS 7671 requires the minimum conductor cross sectional area to be 1.0 mm2 copper and 16 mm2 for aluminium (6). This effectively prevents the use of aluminium for a number of low current services such as lighting due to the impracticalities of installation within space constrained conduit and trunking systems and of termination at wiring outlets, luminaires etc. Historically speaking, it should be noted that the minimum size of aluminium was set following the poor experience with the installation and termination of aluminium conductors used for building wiring in the post war years.]

PHYSICAL PROPERTIES

Table 3 highlights some important physical characteristics of the two materials, which are relevant to their use in wires and cables for building installations.

Characteristic	Copper	Aluminium
Weight for same conductivity (Comparative)	100	54
Cross section for same conductivity (Comparative)	100	156
Tensile Strength Annealed (N/mm^2)	200	50 - 60
0.2% Proof Stress Annealed (N/mm^2)	≤ 120	20 – 30
Tensile Strength Half Hard (N/mm^2)	250	85 – 100
0.2% Proof Stress Half Hard(N/mm^2)	≤ 180	60 - 65
Tensile strength for same conductivity (Comparative)	100	72
Mass density g/cm^3	8.91	2.70
Thermal expansion rate/K	17×10^{-6}	23×10^{-6}
Temperature for creep of 0.022 %/1000h under typical termination stress	150 °C	20 °C
Cold Flow/Hardness (Elastic Modulus) – kN/mm^2	130	70

Table 3 – Physical Properties of Copper and Aluminium (3)

The practical implications of these material characteristics for use in cables are investigated below:

Taking an example of a 300 Ampere 3phase and Neutral (TP&N) electrical load being supplied by a copper or aluminium conductor XLPE insulated, Steel Wire armoured PVC sheathed cable the required cable sizes would be 4 core x 95mm^2 XLPE/SWA PVC in copper and 4 core x 150mm^2 XLPE/SWA/PVC in aluminium respectively. The relative cable characteristics are shown in Table 4 below:

Characteristic	4 core x 95mm^2 XLPE/SWA PVC Copper Conductor	4 core x 150mm2 XLPE/SWA/PVC Aluminium Conductor
Current Carrying Capacity (Ampacity)	304 Ampères	305 Ampères
Cable Weight kg/m	5.51 kg/m	4.5 kg/m
Cable Diameter mm	37.7 mm	47.9 mm
Bending Radius (minimum multiple of diameter)	X 8	X 10
Minimum Bending radius (mm)	302 mm	479 mm

Table 4 – Cable Properties Comparison for equal ampacity (4)

Weight and Volume

From table 3, copper is approximately 3 times as dense as aluminium and approximately one-and-a-half times as conductive. Therefore, a copper conductor is approximately twice as heavy as a bare aluminium conductor of equivalent conductivity while the aluminium conductor has one-and-a-half times the volume. When, instead of conductors, cables of equivalent ampacity are compared inclusive of insulation materials and armouring as seen in the example of Table 4, the copper cable's weight differential decreases markedly, to less than 20%, whereas the aluminium cable has a 60 % larger cross-section and volume. Therefore, the implication for the relative loads imposed on the structure and on the supporting containment is much lesser than the relative densities of the two metals would suggest. In fact, as the aluminium cable has a larger cross sectional area than copper for the required ampacity, a larger containment is required and as a consequence there is an increase in the overall system weight. In sum, the relative loads imposed on the building structure are broadly similar for both cable types and any advantage perceived for aluminium due to its lower density is neutralised, by the weight of the additional insulation materials, armoring and containment required due to its larger volume.

Proof Stress, Mechanical Strength & Drawing in Capability

Proof stress is the stress required to produce a permanent 0.2% extension / deformation of a cable. Referring to Table 3, copper withstands between 3 to 6 times higher proof stress than aluminium, making it strong under tension without losing its pliability. It is this physical property in addition to copper's inherent tensile stress and pliability that allows for copper cables to be easily drawn through conduits and trunking with minimal risk of necking (which cannot occur below the proof stress), stretching or even breaking when mechanical cable pulling is employed.

Conversely, while aluminium cabling exhibits a marginal weight advantage over copper for equal ampacity as seen above and the mechanical forces required for pulling in are usually lower to this extent, these are not low enough to mitigate the large differences in proof stress and tensile strength.

Therefore, when long runs of aluminium conductor cables are pulled through containment systems, and subjected to high pulling forces, these can stretch and "neck-down", reducing the current carrying capacity of the cables which may result in dangerous overheating. In extreme cases, mechanical drawing in of aluminium conductor cables over long or multidirectional routes can even result in irreparable physical damage. A significantly higher skill level is usually required to ensure aluminium conductor cables are not damaged during installation.

Thermal Expansion, Creep and Cold Flow

From Table 3, it can be seen that the coefficient of thermal expansion for Aluminium is some 35% greater than that of Copper. This characteristic is of concern in the study of the expansion and contraction of conductors at electrical connections and terminations caused by thermal cycling – a result of variable electrical loads on the cable – usually an inherent function of electrical loads within buildings. Equally, for aluminium, the thermal expansion experienced linearly along a cable during normal operation can introduce some deformation, particularly at the point where cable cores are separated out for terminations. The problem is exacerbated when cable glands are in close proximity to terminations.

Creep is the plastic deformation (strain) of metal conductors that occurs when these are subjected to external pulling forces (stresses). Creep is irreversible, unlike elastic elongation which reverses as soon as the external force is removed. Creep depends on the stress level, its duration and the temperature, and is different for each metal. The effect of creep in conductor terminations serves to reduce contact pressure leading to higher joint resistance and potential overheating. Table 3 indicates that aluminium exhibits significant creep at ambient temperature (20^{o}C) when stressed, for example by termination. Copper would exhibit similar creep only when exposed to temperatures of 150°C, which are well beyond the normal operating temperatures of cable terminations for building wiring.

Cold flow is a related term that also refers to the permanent deformation of a material when subjected to a force; however, cold flow is the result of a momentary force and does not vary over time. Cold flow is a necessary property of metals that allows a good connection to be made between separate components during the connection process. The greater hardness of copper compared to aluminium tends to show that clamped joints or terminations suffer from significantly reduced cold flow under the application of high contact pressures. Again this effect can lead to a reduction in contact pressure and increased joint resistance.

All of these effects result in the much poorer electrical connectivity of aluminium wires with the mechanical connectors typically used in building installations, in comparison with copper wires.(8)

STIFFNESS - SOLID VERSUS STRANDED CONDUCTORS

For cable constructions typically used within buildings (in accordance with IEC 60228), both solid (class 1) and stranded (class 2) copper and aluminium conductors are permitted. The standard sets the minimum size for class 1 and class 2 aluminium conductors at $10mm^2$ and for copper conductors starting from $0.5mm^2$.

Referring back to the relative cross sectional areas for the same ampacity, a copper conductor cable will be easier to install - the "stiffness" of a cable being determined by the cross sectional area and ultimately the diameter – the smaller diameter copper cable being less stiff. Stranded aluminium cables are only available at cross-sectional areas exceeding $10mm^2$ with individual conductor strands being larger compared to their respective copper equivalents.

This inherent "stiffness" impacts the installation process in many cases. The relative stiffness also means that aluminium cables can become "set" during installation if the minimum bending radii are exceeded, resulting in kinks in the cable that are difficult if not impossible to remove, and remain as potential weaknesses or hot spots if the cable is subsequently straightened during installation.

CONTAINMENT SIZES AND MINIMUM BENDING RADII

As highlighted earlier, for comparable ampacity, the difference in the weights of cables with copper and aluminium conductors is relatively small. However, the impact of the larger diameter of aluminium conductor cables often results in common containment types such as cable trays or baskets being larger than those required for copper conductor cables.

Reference to Table 4 shows the increase in cable diameter to be some 27% with the resultant increase in containment size and space taken within cableways.

The limiting internal bending radii for copper and aluminium conductor cables are broadly similar and for comparable cable types are likely to be not less than 6-10 times the respective cable overall diameters, depending on cable construction, with aluminium usually having larger bending radii than copper. When considered from an equivalent ampacity perspective, the aluminium conductor cable will have a larger overall cross sectional area with a greater bending radius and thus require a physically larger space in which to achieve the bend. Table 4 shows the bending radii being increased (in this case) by some 58%.

Based on equivalent ampacity and comparing stranded copper conductors with solid aluminium conductors the bending radii of aluminium cable types will be greater than those for copper cable types, with a consequent increase in space allocation and potential headroom issues when entering switchgear or equipment.

The increased size and increased bending radii often result in larger containment systems being required, which impact on available building void space and often cause conflicts with other installed systems such as HVAC.

Conversely, it is possible to install more copper cables into a given containment size, providing future flexibility for future modifications or expansion.

Summary

In summary, the arguments for copper conductors presenting a more flexible, strong, and mechanically robust conductor choice compared with aluminium would appear to be supported. Disadvantages of additional weight exhibited by copper compared with aluminium are limited when overall cable and containment weight is considered, and any disadvantage is outweighed by the increased size of cabling and containment installation required for equivalent ampacity cables with aluminium conductors.

Connections and Terminations

Exposing the conductor

The relative hardness of copper compared with aluminium makes it more resistant to the scratches and nicks that may occur during the process of stripping insulation from the conductor prior to termination. The common practice of "ringing" the insulation at the point where it is to be removed also introduces a continuous "cut" in the conductor material.

Where aluminium conductors are subject to nicks, scratches or "ringing", these flaws can lead to "fatigue failure" when subjected to movements due repeated expansion and contraction or vibration. The significantly higher rate of thermal expansion in aluminium compared with copper when exposed to thermal cycling due to load changes can create sufficient movement such that minor flaws in the aluminium conductor may deteriorate into areas of high resistance, causing hot spots or even breakage of the conductor.

A further consideration when exposing the conductor to the atmosphere is the formation of surface contaminants. Oxides, chlorides and sulphides of the base conductor metal are common when the conductor is exposed to the atmosphere at terminations. The principal difference is that the oxides of aluminium are effective electrical insulators, whereas the oxides of copper, whilst not as conductive as copper, remain conductive when formed. The key difference is that aluminium conductors require surface preparation to remove these oxides (usually by mechanical means such as wire brushing) immediately before any further attempt to terminate is made, and also require ongoing protection by means of contact compounds that exclude air (and also moisture).

Corrosion, Dissimilar Metals and Galvanic Reaction

Two factors are associated with corrosion – atmospheric action and galvanic action.

For atmospheric action to result in corrosion there must be moisture and oxygen present. It is unusual to have significant moisture present at electrical terminations; however moisture in the form of condensation may be present within high humidity environments. Naturally occurring oxides on both aluminium and copper conductors tend to prevent significant corrosion of the conductor when in the presence of small quantities of moisture.

Galvanic action results in corrosion when two dissimilar metals in the electrolytic series, such as aluminium and copper, are in physical contact. In this case, moisture acts as an electrolyte. In such an instance, the copper conductor becomes the cathode and receives a positive charge; the aluminium conductor becomes the anode and receives a negative charge. The resultant current flow from anode to cathode attacks the aluminium, leaving the copper unharmed.

Copper used in building wiring is not subject to galvanic corrosion when connected to other less noble metals and alloys, typically used in equipment and accessories, ensuring the reliability and longevity of a building wiring installation. Copper conductor building wire is compatible with a wide range of materials, so that corrosion at contacts is less likely.

Conversely, aluminium conductors require a number of jointing techniques dependent on the materials used for the equipment or accessory terminals, not least the use of contact sealants, bi-metal terminations or special equipment terminals if corrosion is to be avoided.

Thermal Expansion and Dissimilar Materials

As highlighted earlier, the thermal coefficient of expansion for copper and aluminium is such that when heated by load current, the two materials expand at significantly different rates. For copper to copper, copper to brass or copper to plated steel terminations, the relatively similar rates of thermal expansion tend not to loosen the connection which thus remains secure throughout the installation life.

Conversely, with aluminium conductors in similar terminations the relatively high difference in thermal conductivity exacerbated by changes in electrical load and hence variable heating can result in loosened terminations over time. These will exhibit increasingly high resistance and lead to overheating, arcing and potential fire risks.

From table 3, as highlighted earlier, creep is also a significant issue when examining copper and aluminium terminations. Due to the low rate of creep exhibited by copper at normal conductor temperatures, simple connections such as bolted or clamped terminations may be securely made. In order to combat creep (and cold flow) in aluminium conductors, special arrangements are required which include the use of constant tension washers and specially plated bolts/clamps. Attention to manufacturers torque settings is critical in ensuring longevity of the termination.

One method used to combat the issues of dissimilar metals and thermal expansion is the use of bi-metallic copper/aluminium pin or lug terminations. These effectively allow the aluminium conductor to be terminated in an aluminium socket (usually by crimping) and the termination contains a copper pin or tinned copper lug exothermically welded to the aluminium at manufacture, and presents a copper material for connection to the equipment terminals. These are effective, but carry a cost premium and a size disadvantage that often requires larger termination chambers at equipment.

Workmanship

It is clear that whilst effective terminations may be made in aluminium conductors, the required skill level is also higher if problems relating to dissimilar metals, galvanic corrosion, stress breakage and creep are to be avoided. This additional skill and effort required for reliable aluminium conductor terminations carries a cost premium.

Summary

In summary, the claim that copper is a better conductor material for termination at a wide range of electrical equipment used in buildings would appear to be supported based on the criteria of strength, durability, corrosion resistance and thermal influences. Conversely, whilst terminating aluminium conductors is entirely possible on a similar range of electrical equipment, special terminations, techniques and a higher degree of skill coupled with increase in equipment size and time are required.

RELATIVE ECONOMIC COMPARISONS

The cost difference between copper and aluminium varies with the fluctuating cost of the base metals on the world commodities market. The historic trend for the raw material costs is highlighted within figure 1 (7).

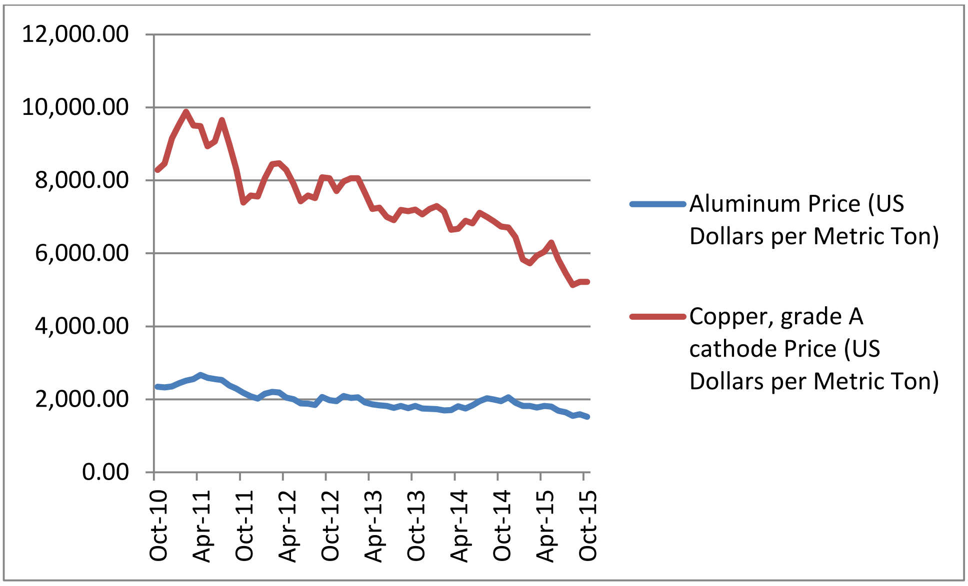

Figure 1 – Historic Raw Costs for Copper and Aluminium (7)

The raw cost of aluminium is far lower than that of copper, currently about thirty percent of the cost of copper.

When considered from a cable perspective, for equal cable sizes, aluminium conductor cable is cheaper than copper conductor cable for almost all cable types. When compared on the basis of equivalent ampacity however, the increase in cable size (usually by some 60%) starts to make the cost difference smaller. When the costs of specialist terminations, increased containment size and increased skill levels required for installation are taken into account, the overall cost difference for either of the conductor types installed to serve a particular load is negligible. Where equipment is modified to provide compatible aluminium friendly terminations or bus bars, the cost balance moves quickly towards copper and away from aluminium.

The real economy should, however, be reviewed in terms of the life time of the system, which includes energy losses, service calls, repairs and potential for expansion of the system. Maintenance requirements for aluminium cables are higher due to creep and degradation of cables over the lifetime of the building. Copper due to its physical properties does not creep or loosen at connections, presents no problem of incompatibility of dissimilar materials, and can be easily joined. The ongoing cost of ownership associated with a copper conductor installation is therefore substantially lower over the installation lifetime.

CONCLUSION

This paper has carried out a comparative evaluation of wires and cables used in building installations with copper and aluminium conductors respectively. Arguments relating to the physical properties of copper and aluminium have been examined and comparisons between the two types of wires and cables made for ampacity, thermal capacity, weight, size, strength, ease and reliability of installation, reliability of connections and terminations, corrosion aspects and relative costs.

Based on these arguments, the paper concludes that in each respect, copper conductors out-perform aluminium conductors for all wire and cable types used within buildings.

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