Lightweight clad bi-metal conductors for cryogenic applications

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Abstract. Lightweight cryogenic conductors are required for applications in electric propulsion, such as cryogenically-fueled electric airplanes and ships. Clad bi-metal conductors allow to consider certain conductor metals that would not be feasible as a single conductor. This includes materials that are chemically reactive and materials that would not have the right mechanical properties to draw wires. The Ashby method is used to compare material combinations systematically. Manufacturing techniques and applications are also discussed. Copper-clad lithium wire stands out as one of the promising new types of clad bi-metal conductors for cryogenic applications.

1. Introduction

There is renewed interest in lightweight, cryogenic, electrical conductors, especially for electric aircraft and electric ship applications. Superconductors are the most common choice. However, there are cases in which a non-superconducting (i.e., resistive) wire is preferred, such as under higher frequency applications, impulse currents, irregular shapes, or when the conductor has to connect between parts of the system that are under widely different temperature conditions (such as ambient-to-cryogenic terminations).

This paper builds upon the concepts presented in [1], where (resistive) coper clad lithium wires are compared to superconducting technologies. The focus of this study is mostly on clad bi-metal conductors, which consist of two distinct layers of metals joined together to form a composite structure. The core material in clad bi-metal conductors refers to the inner layer, which is usually responsible for carrying the electrical current. The core material is selected based on its electrical conductivity, mechanical properties, and compatibility with the outer cladding material. On the other hand, the outer cladding is typically chosen for different properties, such as corrosion resistance, environmental protection, or mechanical strength, and it surrounds the core material to form a single conductor. Some common examples of clad bi-metal conductors include (1) Copper-Clad Aluminum (CCA) Conductors, which have a core made of aluminum enclosed within a layer of copper. Copper provides excellent electrical conductivity, while aluminum reduces the overall weight and cost of the conductor. CCA conductors are commonly used in power cables and other electrical applications. Furthermore, high-purity aluminum conductors at cryogenic temperatures have inspired many studies for a wide range of applications spanning several decades [2–5]. (2) Copper-Clad Steel (CCS) Conductors have a core made of steel and are coated with a layer of copper. CCS conductors offer a

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combination of high tensile strength from the steel core and good electrical conductivity from the copper cladding. They are often used in overhead transmission lines. (3) Nickel-Clad Copper Conductors have a nickel layer used as the cladding material to provide specific properties, such as high resistance to corrosion or harsh environments. The advantage of clad bi-metal conductors lies in their ability to combine the benefits of two different materials into a single conductor, optimizing performance and cost-effectiveness for various applications.

Ongoing research and development of electrical cryogenic aircraft introduces novel challenges and opportunities for innovative technologies. Among these opportunities is the enhancement of electrical conductivity in metals at low temperatures, where the scattering of electrons and phonons is minimized, leading to an increase in electron mobility [6]. This phenomenon is commonly observed in superconducting materials, which display zero electrical resistance below the critical temperature. However, it is essential to acknowledge that the behavior may vary based on the metal's properties and the presence of impurities or defects. Nevertheless, the improved material characteristics have sparked interest in exploring the use of "exotic" metals as lightweight cryogenic conductors. One can consider employing lightweight metals like lithium, beryllium, sodium, magnesium, potassium, and calcium by leveraging their enhanced electrical properties. The use of these metals presents mechanical and chemical challenges that clad bi-metal conductors could help overcome.

In the following sections, we present a systematic approach to selecting the core and clad material. We further discuss the mechanical, chemical, and manufacturing challenges of clad bi-metal conductors and present potential applications.

2. Material selection

The Ashby method is a systematic approach used to select materials based on specific design criteria. The method involves creating charts that plot two relevant material properties against each other [7]. The goal is to identify materials that possess the desired combination of properties for the specific application. This method comprises several key steps to guide the material selection process effectively. Firstly, the design requirements are translated into well-defined objectives, functions, constraints, and free variables. These elements help frame the specific goals and criteria that the chosen material must fulfill. Secondly, materials are screened based on the identified constraints. This step involves eliminating materials that fail to meet the essential design requirements, ensuring that only suitable candidates are considered. Next, the materials are ranked according to their ability to achieve the established objectives. This ranking process allows for a clear evaluation of the materials' potential performance, aiding in the selection of the most promising candidates. Finally, additional supporting information is sought through a detailed study of the top-ranked materials.

The material selection analysis was conducted independently for both the core material and the cladding material. Granta EduPack R1 Version 22.1.2 served as the primary source of material data and was utilized to create the Ashby plots presented in this analysis. This software provides comprehensive and up-to-date material property information, allowing for accurate and reliable material selection and comparison. Some of the considered materials were not included in the EduPack database. Those material properties were added manually from [8–11]. A comprehensive list of the material compositions presented in this paper can be found in Table 1 in the Appendix.

2.1. Core material

The core material serves as the primary pathway through which electricity flows. The selection can be narrowed to elemental metals due to their higher electrical conductivity compared to alloys. At cryogenic temperatures, the core material must capitalize on the enhanced electrical properties of metals. Additionally, the use of a cladding metal to isolate and protect the core material opens up opportunities to explore and utilize metals that might not be suitable for use in ambient conditions. The cladding acts as a shield, safeguarding the core from the harsh cryogenic environment and providing mechanical strength and other desirable properties. This allows engineers to consider "exotic" metals, which may possess exceptional density-adjusted electrical conductivities at cryogenic temperatures but might not be practical for direct exposure to ambient conditions due to factors such as corrosion or mechanical limitations. For example, for a given application, the core material must be a good thermal conductor ≥ 173 W/mK (λ of tungsten); it must be of low density ≤ 8942.5 kg/m^3 (ρ of copper) and have a solid bulk form. The objective of the core material selection process is to identify a suitable metal that minimizes weight and maximizes electrical and thermal conductivity.

To identify the materials that possess the desired combination of properties for the core material in lightweight cryogenic conductors, one must plot the material's electrical conductivity against its density. For this analysis, 77 K has been set as the reference temperature of the material's electrical conductivity. Figure 1 plots the electrical conductivity at 77 K and the mass density at room temperature of metals. Materials that are closer to the upper-left corner of the chart, mostly alkali and alkaline earth metals, have higher electrical conductivity and lower density, making them attractive choices for the core. As can be noted, beryllium has the highest conductivity of all other metals at 77 K and is significantly lighter than copper. It is also very important to note that beryllium is highly toxic and is associated to very serious health risks. On the other hand, lithium also stands out as the lightest metal, seven times less conductive than copper but over sixteen times lighter. The yellow ellipse highlights the metals of interest that will be further studied in this paper.

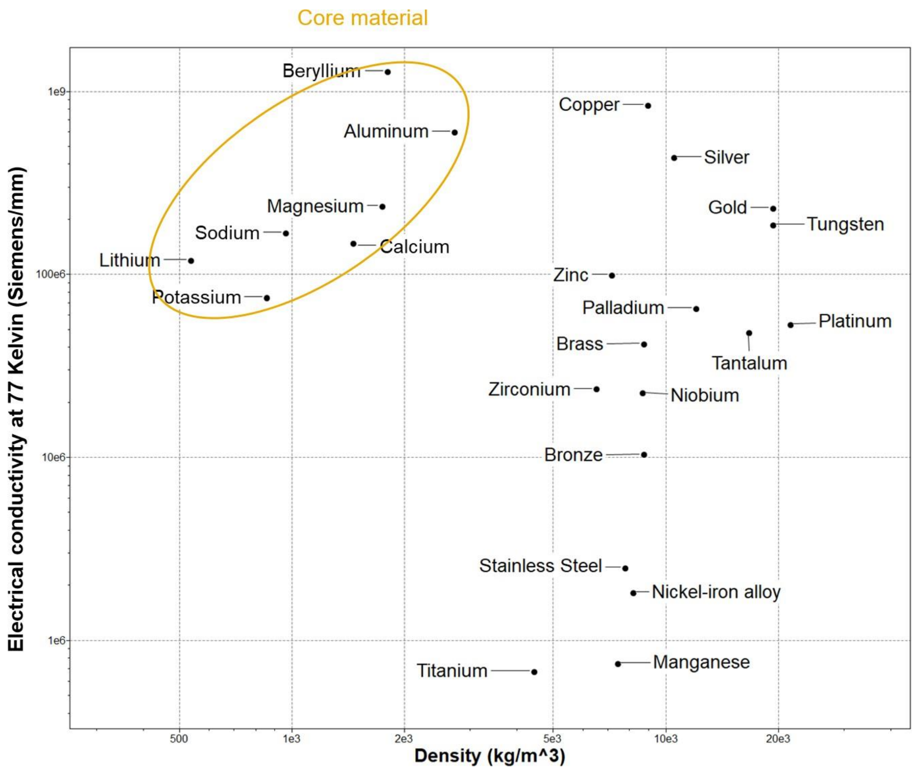


Figure 1: Electrical conductivity at 77 K and the mass density at room temperature of metals. Materials that are closer to the upper-left corner of the chart will have higher electrical conductivity and lower density, making them attractive choices for lightweight conductors.

2.2. Clad material

The function of the clad material is to serve as an outer layer that surrounds and shields the core material from the surrounding environment, preventing direct exposure to potentially harsh conditions. The clad material is chosen to offer specific characteristics such as corrosion resistance, environmental protection, mechanical strength, or other properties not inherently present in the core material. By selecting an appropriate clad material, the overall conductor can be optimized to meet the requirements of the intended application and enhance its performance and longevity.

To enable the use of the “exotic” metals identified in the previous section as cores, it is paramount that the clad material provides chemical and mechanical protection from the environment. Additionally, to ensure that the benefits derived from the core’s density-adjusted electrical conductivity are preserved, the clad material should possess a low density and exhibit high electrical conductivity. In [1], we study the impact on density adjusted conductivity per core and clad fill ratios. For proper material selection, one must study the materials’ mechanical properties at 77 K. Due to the limited data sets at these temperatures, Figure 2 presents mechanical properties at room temperature and serves as a good starting point for clad material selection. It should be mentioned that both aluminum and copper have face-centered cubic (FCC) crystal structures, and so do not undergo temperature-dependent ductile to brittle transitions. Figure 2 plots the materials Young’s modulus versus its tensile strength. Young’s modulus, also known as the modulus of elasticity, is a measure of a material’s stiffness or ability to resist deformation when subjected to an external force. It quantifies the relationship between stress and strain in a material under mechanical loading, while tensile strength is a mechanical property of a material that measures its ability to withstand tensile or stretching forces without breaking or undergoing permanent deformation. It represents the maximum tensile stress a material can sustain before failure occurs [12].

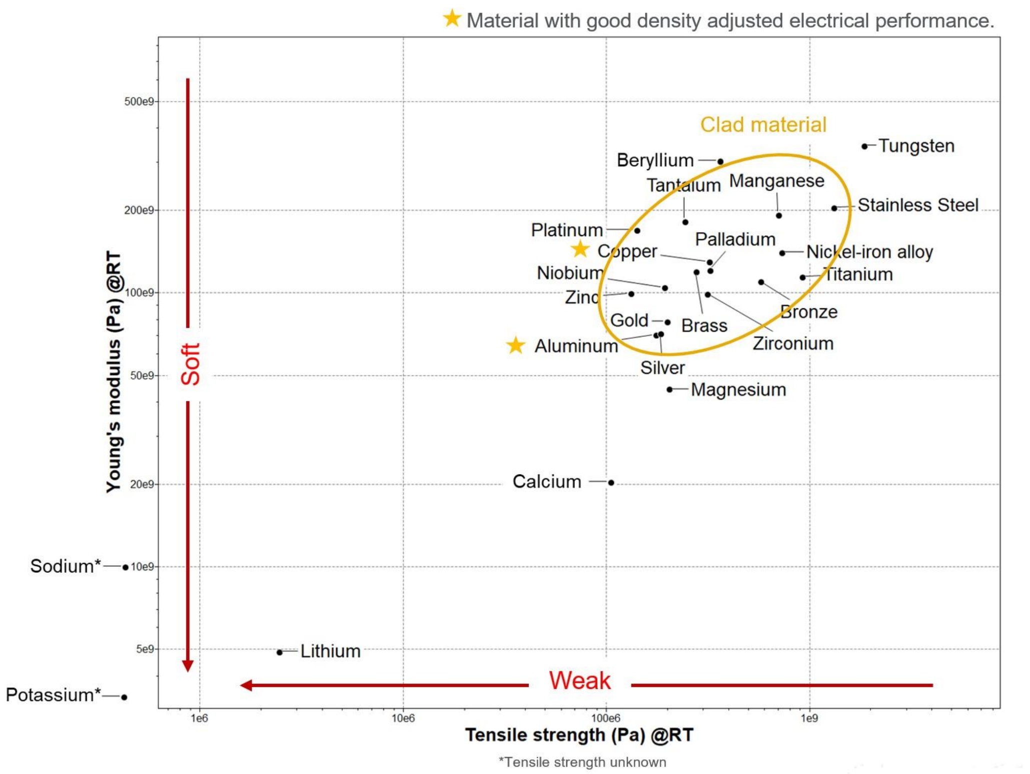


Figure 2: Young’s modulus and tensile strength of cladding metals (at RT)

In Figure 2, the significance of bi-metal clad conductors is evident. When considering lithium as a standalone material, its poor Young’s modulus and tensile strength make it unsuitable as an electrical wire. However, by employing bi-metal clad conductors, the drawbacks of individual materials can be overcome. The yellow ellipse highlights potential candidates that meet the desired mechanical needs. Yet, its important to reference Figure 1 as the clad materials’ density and conductivity are of key interest. From both figures, one can deduce that the top candidates for clad materials are copper and aluminum. At room temperature, aluminum and copper are soft, malleable, and ductile, which means they can be easily shaped and formed into various conductor designs. This characteristic is crucial for the fabrication process. Additionally, at 77 K, aluminum exhibits remarkable conductivity, ranking as the third most conductive metal per unit density. Copper, while not as conductive per unit mass at 77 K, possesses its own set of valuable characteristics that make it an excellent choice as clad material. One of its notable advantages is its high solderability, which enables seamless connections between the clad bi-metal conductors and existing electrical components.

For cladding purposes, metal alloys could potentially have superior properties compared to elemental metals. For example, AA8093 is an Al-Li alloy that has a lower density than pure aluminum and shows excellent low-temperature ductility [13]. However, in this analysis, we limited the selection of cladding materials mostly to elemental metals due to the overwhelming number of candidate alloys. Future studies will include alloys.

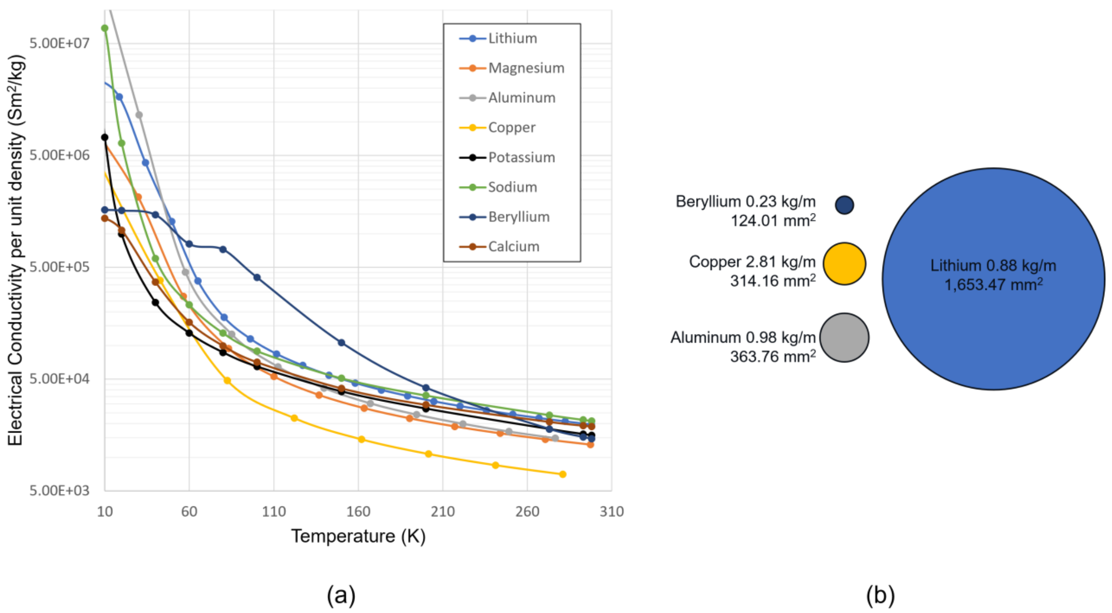


Figure 3: (a) Electrical conductivity per unit density as a function of temperature. (b) Mass and cross-sectional areas of one-meter conductors with equivalent resistance (6.05 $\mu\Omega$/m) at 77 K.

2.3. Density adjusted electrical performance

Traditionally, conductivity has been defined as the measure of a material's ability to conduct electricity per unit volume. However, there is an alternative perspective that considers the ability of a unit mass of the material to conduct electricity, which can also be a valuable characterization. By shifting the focus to density-adjusted electrical performance, we gain a more insightful understanding of a material's conductivity capabilities. When the concept of conductivity was initially defined, the distinction between the volume and mass of conductors was not particularly relevant, as there was little concern about reducing the weight of electrical wires. As the world seeks innovative solutions for increasingly mobile and energy-conscious technologies, exploring materials with favorable density-adjusted electrical properties can lead to groundbreaking advancements in various industries. In fact, as seen in Figure 3, even at room temperature, all the metals selected in Section 2.1 exhibit higher density-adjusted electrical conductivity than copper. The concept of designing electrical wires prioritizing mass is not new and numerous patents have been filed on their design, manufacturing, and applications at room temperature [14-17].

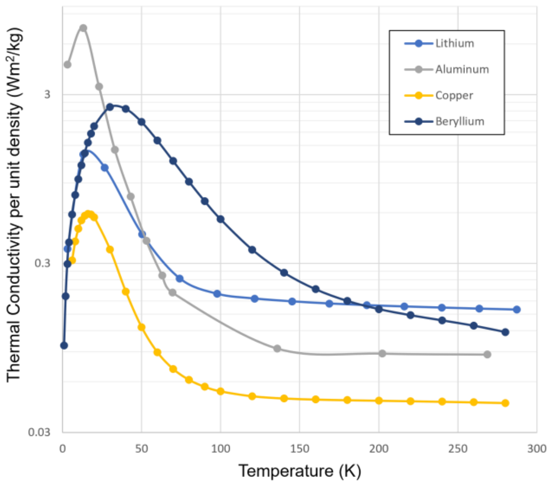
As we venture into cryogenic conditions, the concept of density-adjusted electrical performance becomes increasingly relevant. The electrical conductivity per unit density as a function of temperature for the materials selected in Sections 2.2 & 2.3 is presented in Figure 3. As a general trend, all the metals in question exhibit an increase in density-adjusted conductivity as the temperature drops. At 77 K the top performers, in order, are beryllium ($7.21 \cdot 10^5$ Sm^2/kg), lithium ($1.87 \cdot 10^5$ Sm^2/kg) and aluminum ($1.68 \cdot 10^5$ Sm^2/kg).

While there are many combinations of materials for the core and cladding possible, the authors picked copper-clad lithium (CuCLi) as an interesting combination for further studies. This combination is expected to strike a good balance of electrical conductivity per unit density, low toxicity, cost of materials, mechanical properties, and specific heat capacity.

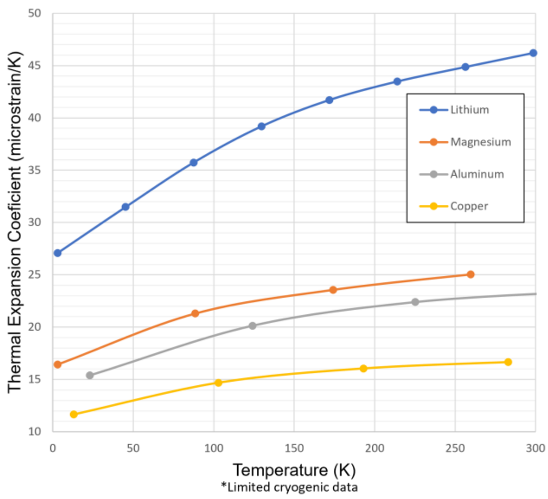
2.4. Thermal performance

At cryogenic temperatures, the thermal properties of materials can significantly impact the functionality and efficiency of the entire system. Some key aspects of material thermal performance in cryogenic environments are thermal conductivity, coefficient of thermal expansion (CTE), and specific heat capacity. High thermal conductivity ensures efficient heat transfer and thermal management, which is essential for maintaining desired temperatures and preventing overheating. In Figure 4 (a), the plot of specific thermal conductivity against temperature, it is evident that beryllium exhibits the highest specific thermal conductivity among the materials considered, followed by lithium and aluminum at 77 K. Figure 4 (b), the plot of the coefficient of thermal expansion against temperature, shows the extent to which the cryogenic environments cause the material to contract. In clad bi-metal conductors understanding the materials CTE and their potential mismatch is of paramount importance as a large mismatch could lead to warping, delamination, reduced reliability, performance degradation, and ultimately, a mechanical failure. Lithium experiences the largest change in CTE, and information on beryllium was not available at these temperatures.

For electrical conductors, having a high specific heat is often beneficial because it allows them to absorb heat effectively and maintain a more stable operating temperature, especially under impulse conditions. This property is essential for preventing overheating and ensuring the safe and reliable operation of electrical systems. Additionally, conductors with high specific heat can help in managing temperature fluctuations, minimizing the risk of thermal damage or performance degradation in electrical components. This is also an area where resistive conductors have an advantage over superconductors: In the case of superconductors, the amount of superconducting material is chosen to always stay within the critical current and critical field limits. In impulse applications, the maximum peak current determines the size of the superconductors. This is in contrast to resistive conductors, in which the heat capacity of the conductor can absorb the peak. Thus, the amount of conductor materials is governed by the average current, not the peak current.

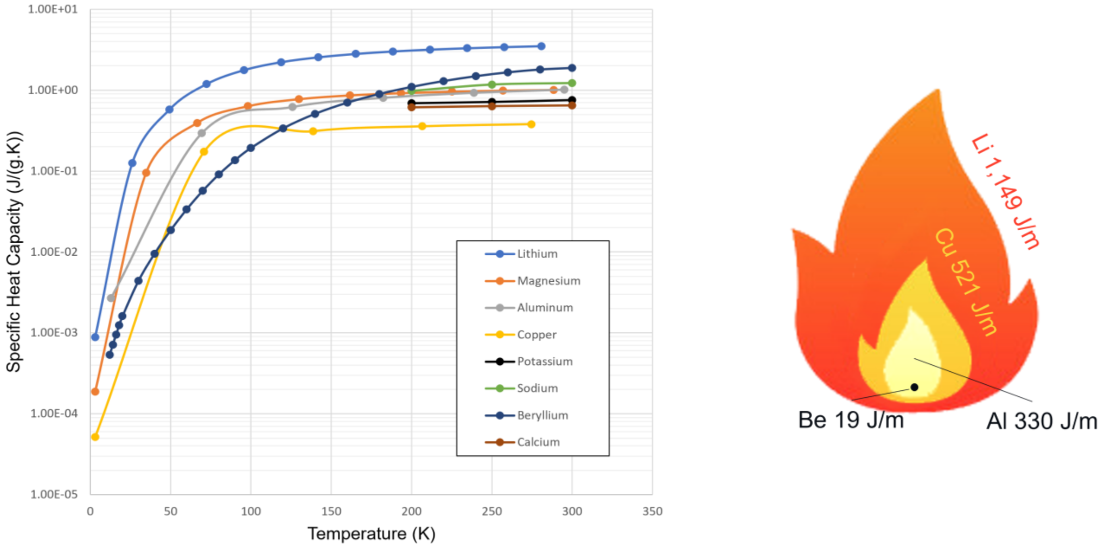


(a)



(b)

Figure 4: (a) Thermal conductivity per unit density as a function of temperature. (b) Coefficient of thermal expansion as a function of temperature.



(a) (b)

Figure 5: (a) Specific heat capacity as a function of temperature. (b) The energy required to raise the temperature by 1 K of conductors with equivalent resistance at 77 K.

2.5. Purity of materials

The purity of materials affects many of the properties of interest, including electrical conductivity. At deep cryogenic temperatures (below 15 K), purity is often even the dominating factor. But also, mechanical properties can be affected by purity. In this conceptual study, the focus was mostly on the 60...100 K temperature range, in which purity has less impact. The values for the properties in the material selection are based on "commercial" purity as used by Granta EduPack, i.e., do not meet the criteria of ultra-high purity. Furthermore, the purity might be different from material to material.

In addition to the material properties, the cost of materials also depends on purity. While aluminum is typically not considered a costly material, ultra-pure aluminum is very expensive and difficult to obtain. Materials of great industrial use, which are used for applications where high purity is required, are generally more available and less expensive. None of this was considered in the cost analysis presented in Figure 6, which illustrates the relationship between density-adjusted electrical conductivity and "commercial" purity material cost. The material located in the top left corner represents the most cost-effective option, with the highest conductivity among the materials considered in the analysis.

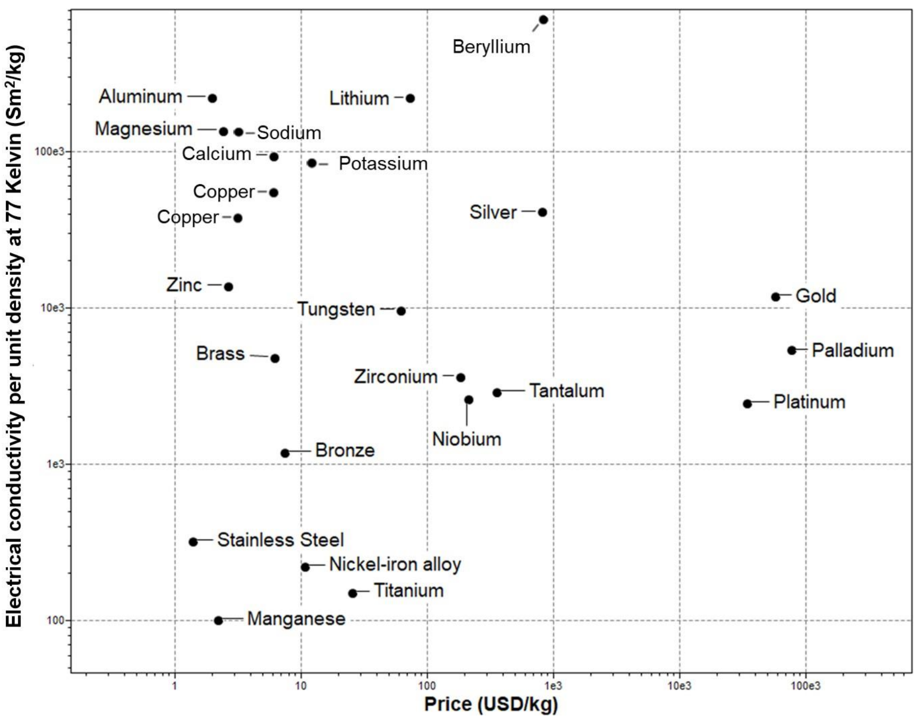


Figure 6: Electrical conductivity per unit density and cost of materials (not at the required level of purity)

3. Manufacturing

3.1. Manufacturing of wire billet

As outlined a year ago [1], there is a wide range of potential methods to produce a wire billet. However, to maintain the high purity of the lithium, it should not be in contact with the cladding material while liquid. Therefore, cold swaging and cold shrinking methods are preferred. One such method is to shrink high-purity lithium rods in liquid argon (87 K) and insert them into slightly undersized, thin-walled copper pipes. Copper end plugs are also inserted into the pipes to seal off both ends. This must occur in an argon gas atmosphere.

3.2. Drawing process

The drawing process into thinner and thinner wires follows the same process as for any other metal wire. However, no thermal annealing can be allowed between passes through the die. The reason is that the higher temperature during annealing could melt the lithium and dissolve copper from the cladding into the lithium phase, which would ruin the wire due to a loss of high electrical conductivity.

It is expected that the drawing process would not need to occur under an inert gas atmosphere since the conductor core is protected by the cladding material. This could help to reduce the cost of manufacturing. However, special attention must be given to checking for defects in the cladding layer. While the risk of fire is likely low due to the high aspect ratio of long conductors, the segment around the defect would need to be removed, and the ends would need to be sealed.

4. Discussion and Conclusion

At first glance, lithium might appear to be an unlikely candidate for making electrical conductors, mostly due to its high chemical reactivity. However, it has some undeniable strengths, such as high electrical conductivity per unit density (second highest after beryllium in the temperature range of 50–150 K), high specific heat capacity, low toxicity, good availability, low cost (that might potentially drop further with increasing lithium production for batteries), and good mechanical properties (soft and malleable). To shield it from chemically reacting with its environment, it requires to be exceptionally good cladding. Copper could be a suitable cladding material.

There are many potential applications beyond wires, especially where superconductors are not suitable. This includes conductors that are required to operate over a wide temperature range, such as cable terminations and high-voltage bushings. Cable accessories such as clamps, joints, formers, and connectors are another area of application where superconductor materials are difficult to use since they would need to be machined to complex geometries.

The process of producing such copper-clad lithium wires is still an ongoing research question. Initial challenges included mechanical issues with the wire drawing process as well as the manufacturing of the billet while maintaining the high purity of the lithium core. A cold swaging or thermal shrinking process is currently considered but has not been tested at the time of writing.

The health risks associated with beryllium exposure have discouraged us from further research and consideration of beryllium as a core material.

Other open research questions include the magnetoresistance effect in lithium, long-term stability, core clad heat transfer, tolerance to small defects in the cladding, manufacturing methods, and their cost.

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6. Appendix

6.1. Material compositions

Table 1: List of materials used in the material analysis. (*Incomplete data sets required the survey of multiple compositions.)

Metal	**Composition**	**Temper**	**Purity**	**Notes**
Aluminum	1050A	H19	commercial purity	
Beryllium*				
Brass	CuZn10-C22000	soft		
Bronze	CuSn4-C51000	hard		
Calcium*				
Copper	C12500	hard		
Gold	P00020	hard	min 99.5%	cold worked
Lithium			min 99.9%	
Magnesium	ASTM 9980A		commercial purity	
Manganese			commercial purity	
Nickel-iron alloy	INVAR	hard		cold worked
Niobium	Type 2		commercial purity	
Palladium	P03980	hard	commercial purity	cold worked
Platinum	P04995	annealed	commercial purity	
Potassium*				
Silver		soft	commercial purity	
Sodium*				
Stainless steel	AISI 410	hard		martensitic
Tantalum	R05200		min 99.7%	annealed
Titanium	Ti-6Al-4V			annealed
Tungsten	R07004		commercial purity	annealed
Zinc			min. 99.9%	
Zirconium	R60001		commercial purity	