Lightweight Clad Bimetal Conductors for Cryogenic Applications

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M4Or1B-06

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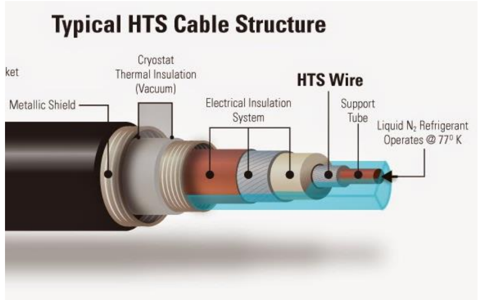
Clad Bimetal Conductors

Two diverse metals or alloys are metallurgically bonded to achieve functional advantages that cannot be obtained with a single metal.

Lightweight cladded conductor applications



*Images extracted from Google

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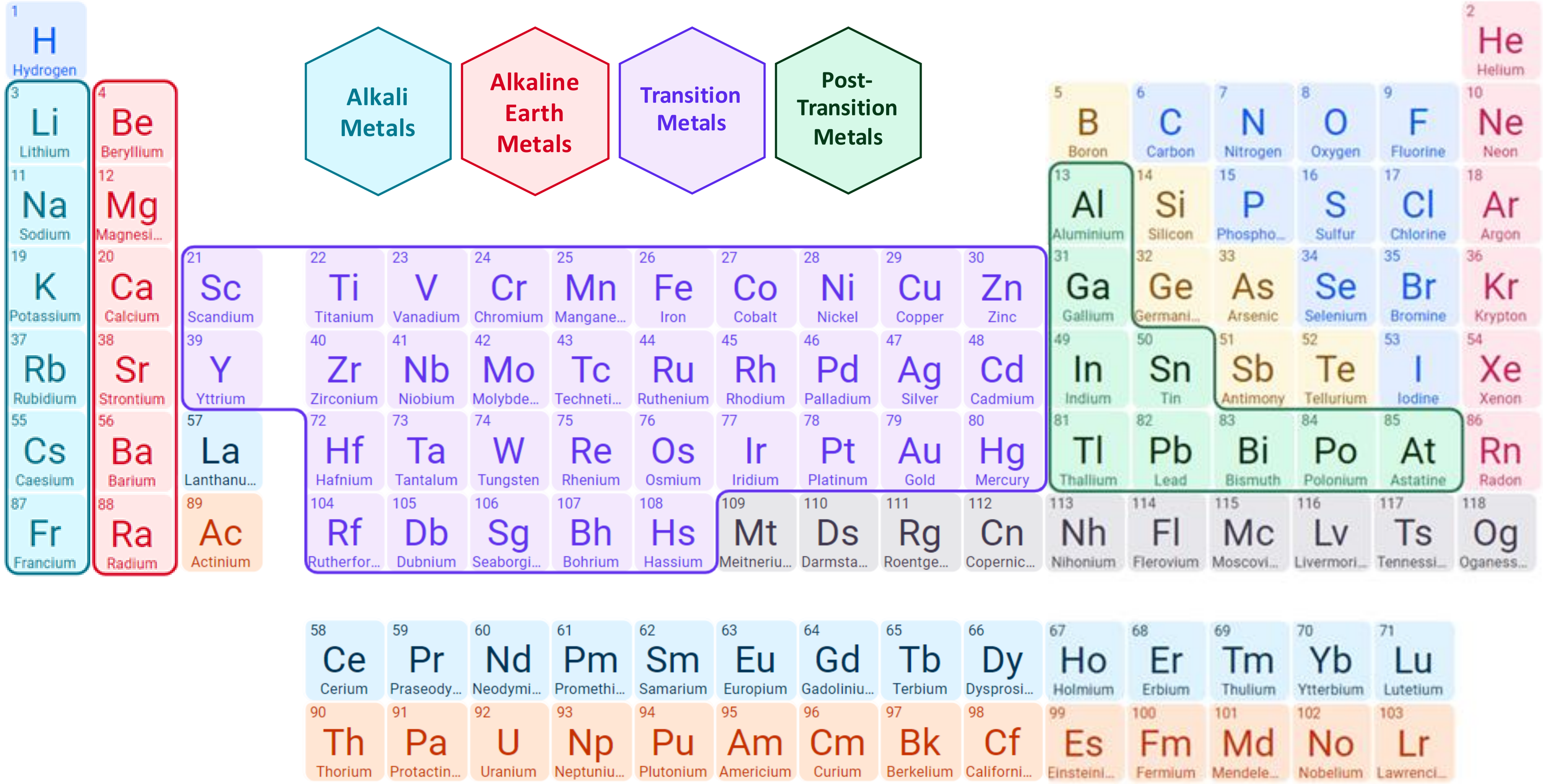
Clear Elemental Trends



Note: While cryogenic data are often available, they are sometimes not for required **level of purity**...

Core Material Selection- Requirements

Function

Lightweight and highly conductive core material

Constraints

- Good electrical/thermal conductor
- Low Density
- High specific heat
- Bulk material

Objective

- Minimize weight
- Maximize electrical and thermal conductivity

Free Variable Choice of Material

Core material

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Clad Material Selection- Requirements

Function

Lightweight and highly conductive clad material

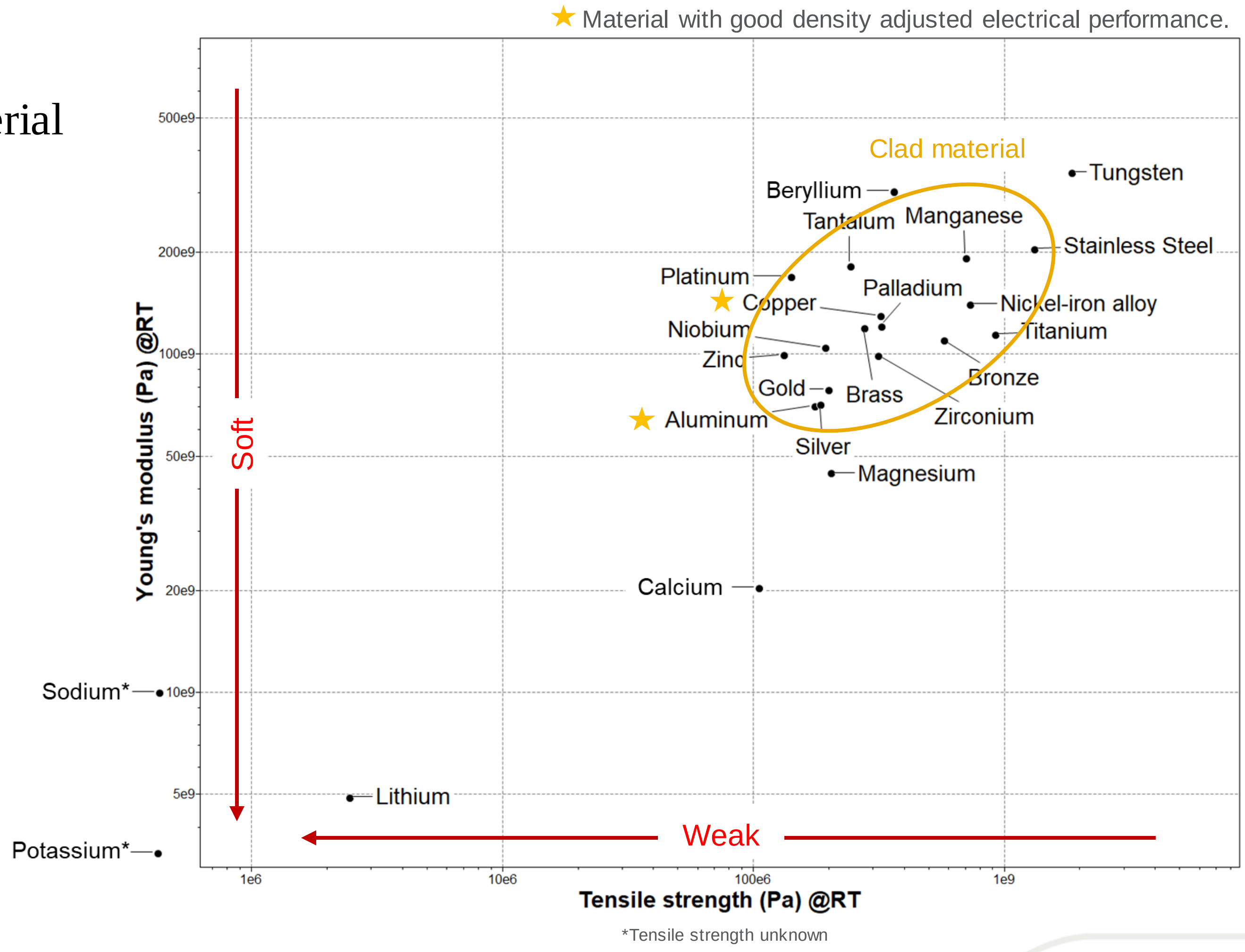
Constraints

- Good electrical/thermal conductor
- Low Density
- Chemically stable
- High specific heat
- Adequate structural strength
- Bulk material

Objective

- Minimize weight
- Maximize conductivity
- Serve as a structural and chemically stable barrier for the core material.

Free Variable Choice of Material



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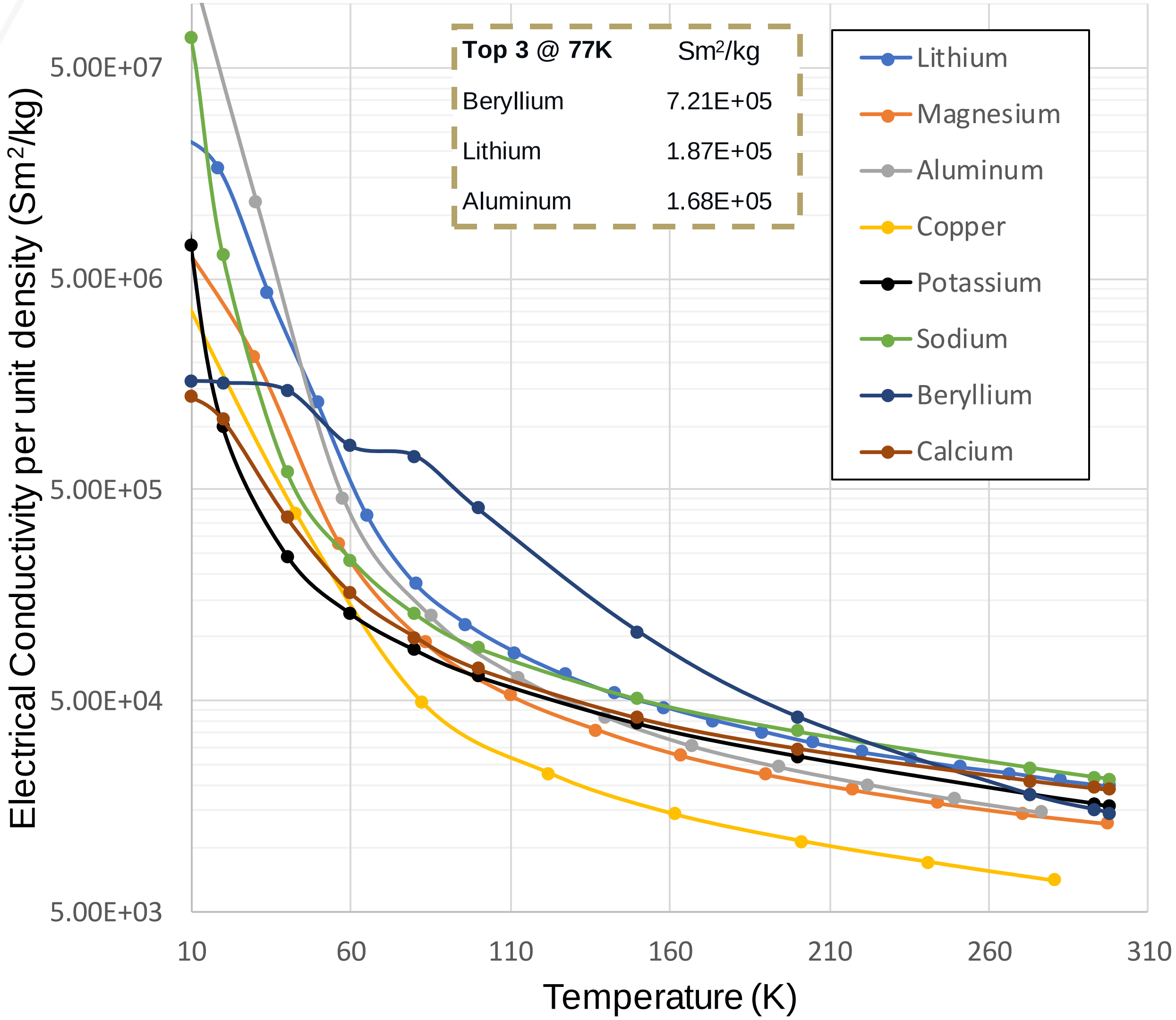
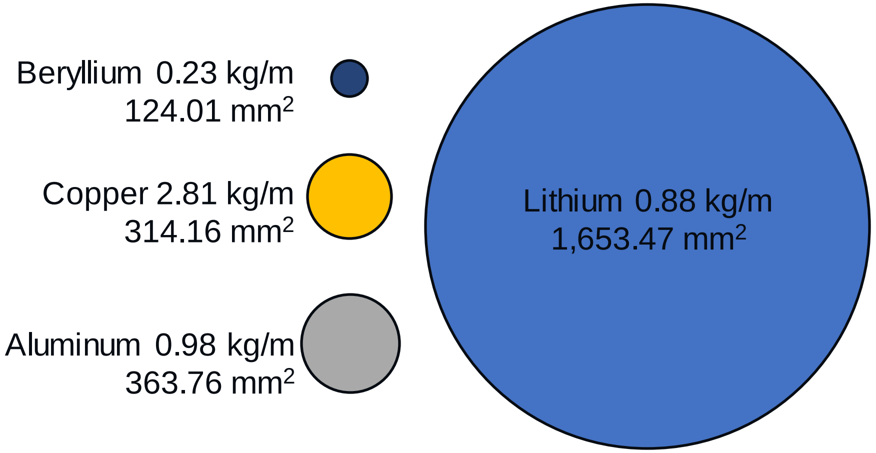
Material Selection- Electrical Performance

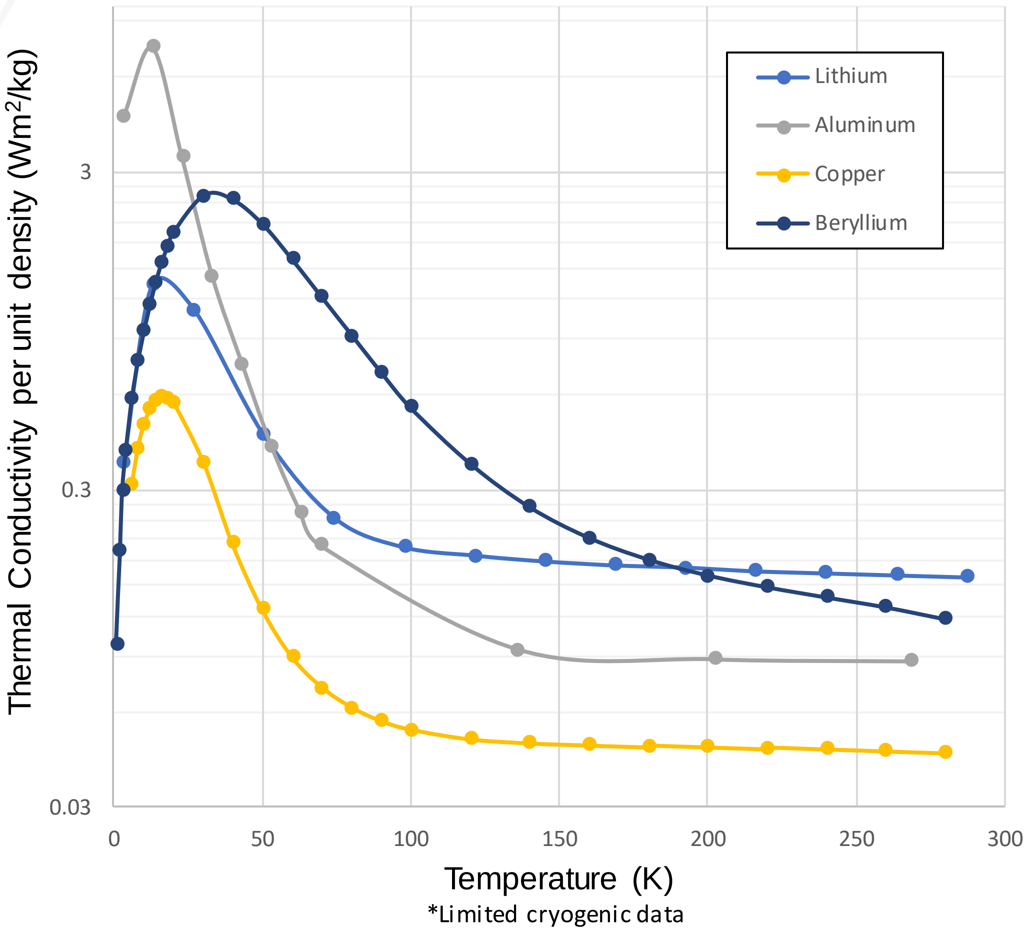


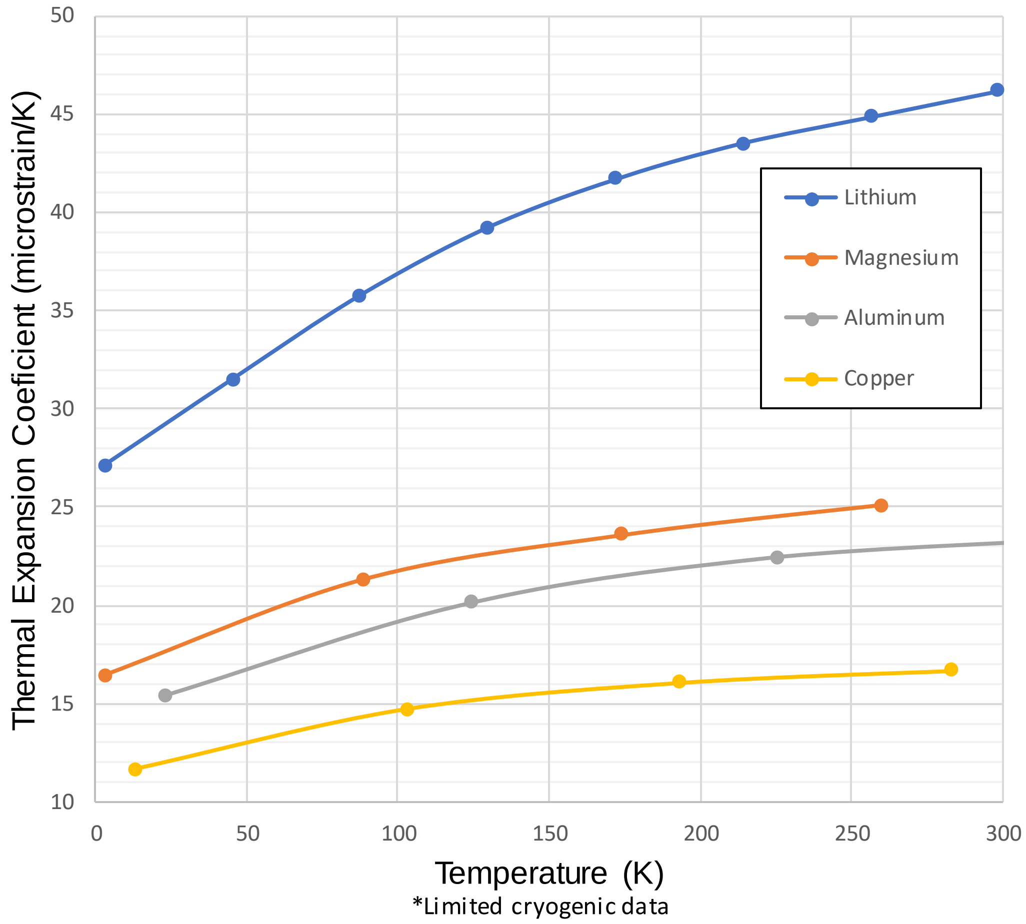
Mass and cross-sectional areas of one-meter conductors with equivalent resistance (6.05 μΩ/m) at 77 Kelvin



Note: At low temperatures, particularly below 50 K, the electrical resistivity of a material is highly sensitive to sample purity due to the dominance of quantum mechanical effects.

Material Selection – Thermal Performance

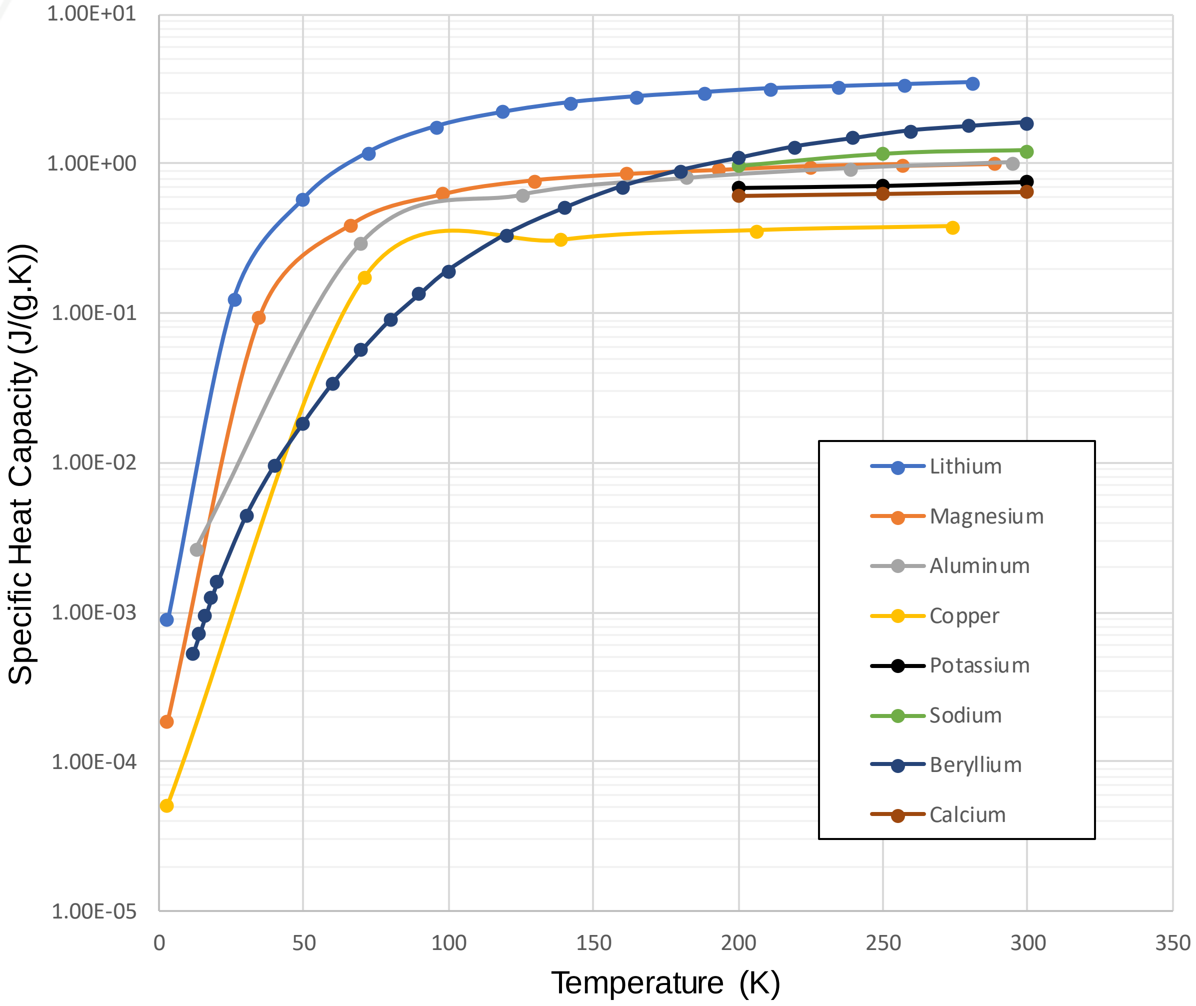




Large CTE mismatch between potential core and clad materials.

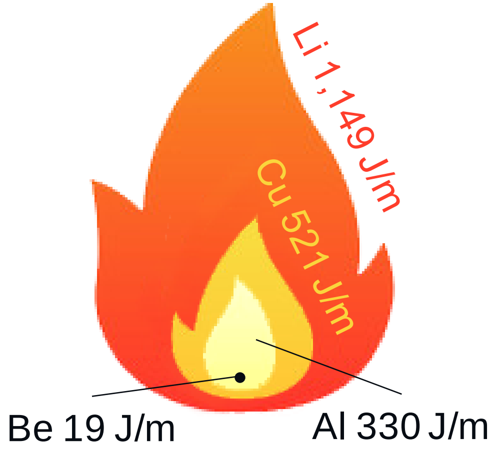
Coefficient of linear expansion at 25 °C ($10^6\alpha/K^{-1}$)	Al	Be	Ca	Cu	Li	Ma	K	Na
	23.1	11.3	22.3	16.5	46	24.8	83.3	71

Material Selection – Thermal Performance Cont.



*Limited cryogenic data

The energy required to raise the temperature by 1 Kelvin of conductors with equivalent resistance at 77 Kelvin



At 77 Kelvin **Lithium**

- Generates the 2nd least amount of heat per unit mass.
- Very high specific heat means that the generated resistive heat increases the temperature of the material very little.
- Large surface area improves heat transfer.

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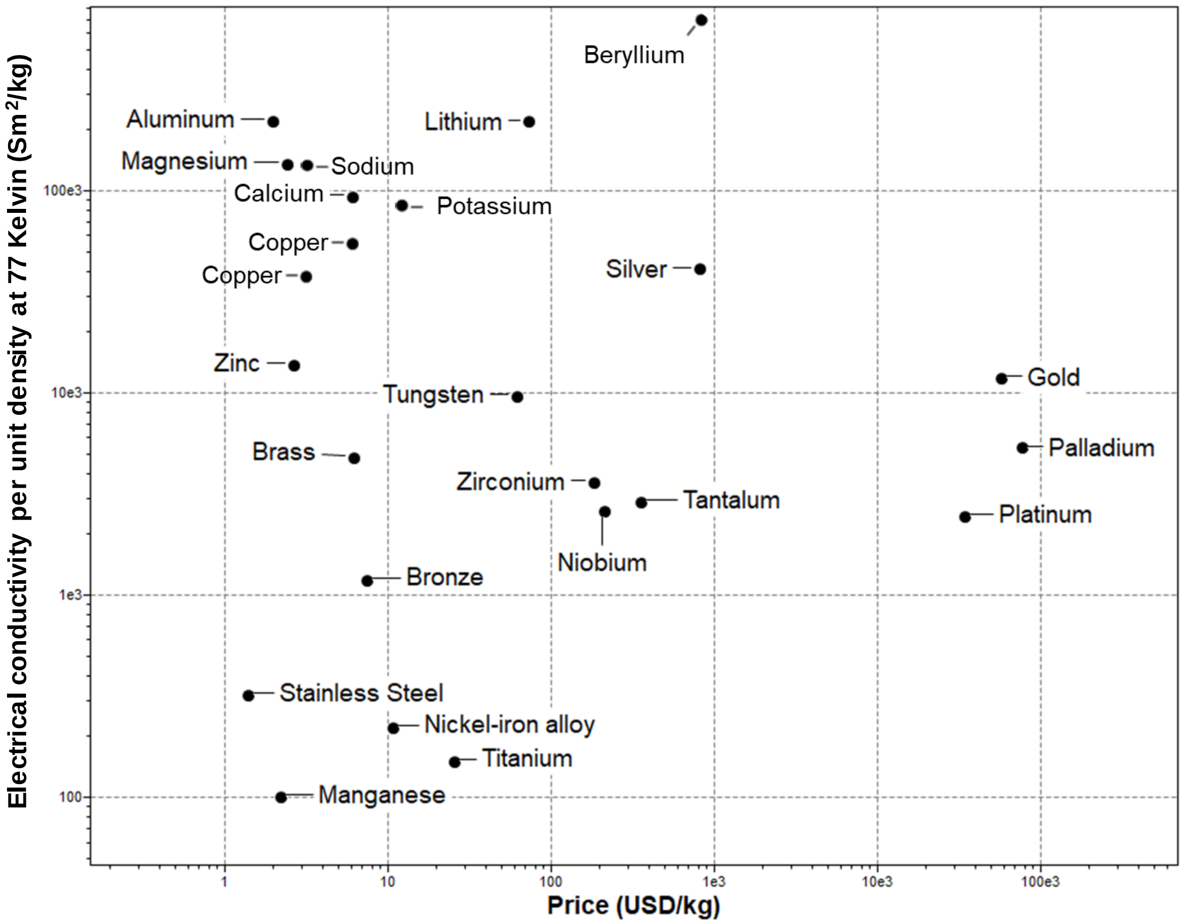
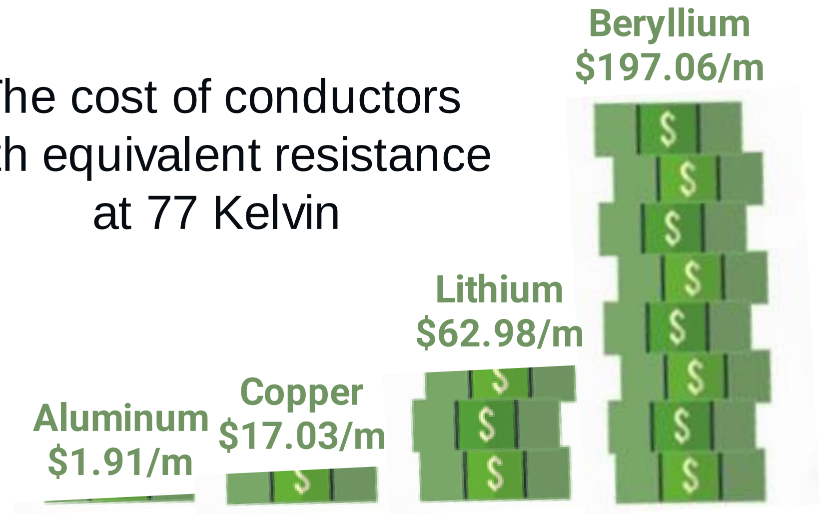
*The energy required to raise the temperature by 1 Kelvin is estimated based on the conductor characteristics presented on slide 6.

Material Selection – Cost



The cost of conductors with equivalent resistance at 77 Kelvin



Lithium's intrinsic thermal control enables the selection of conductor size by the optimal trade-off between wire mass and resistive energy loss instead of by the maximum permissible wire temperature. Leading to smaller, lighter, and cheaper conductors.

Note: This is not at the required level of purity.

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*The cost of the conductors is estimated based on the conductor characteristics presented on slide 6.

Clad Material Selection @ 77K

Copper

- High Solderability
- Soft, Malleable and Ductile
- Least conductive metal per unit density of the four selected.
- Low specific heat
- Immiscible with Li and Be at the operating temperature

Aluminum

- Inexpensive
- Soft, malleable, and ductile
- 3rd most conductive metal per unit density.
- Low specific heat
- Immiscible with Li and Be at the operating temperature

*Images extracted from Google

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Core Material Selection @ 77K

Beryllium

- Toxic
- Expensive
- Brittle and hard
- Most conductive metal per unit density.
- Low specific heat
- Small surface area impairs heat transfer.

Lithium

- Flammable & Reactive
- Low tensile strength
- Soft, malleable, and ductile
- 2nd most conductive metal per unit density.
- Very high specific heat
- Large surface area improves heat transfer.

*Images extracted from Google

More on Lithium (Alkali Metals)

- When heated, it reacts vigorously with nearly all materials, particularly in its molten state.
- It readily catches fire not only in the presence of oxygen but also in other commonly found gases.
- When in contact with water, it produces hydrogen gas.
- Although it doesn't spontaneously ignite in the presence of air, it quickly oxidizes, forming a corrosive and nonconductive substance.
- Its containment is challenging due to an exceptionally high coefficient of thermal expansion.

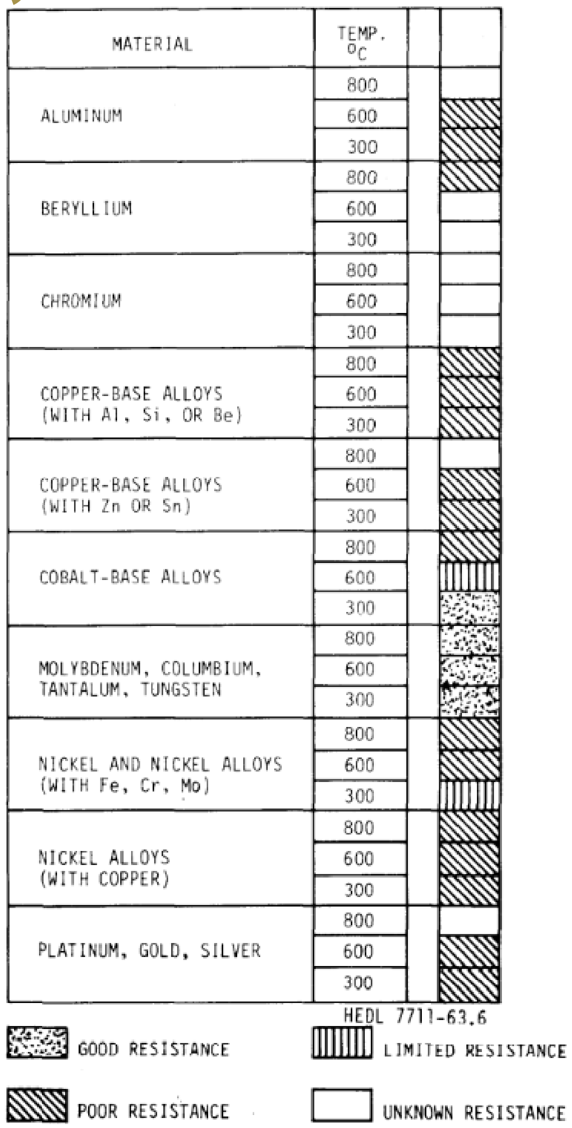

FIGURE 19. Resistance of Various Materials to Liquid Lithium.
Ref. 8; 1, Figure 11

Figure 19 from: Jeppson, D W, et al. Lithium literature review: lithium's properties and interactions.

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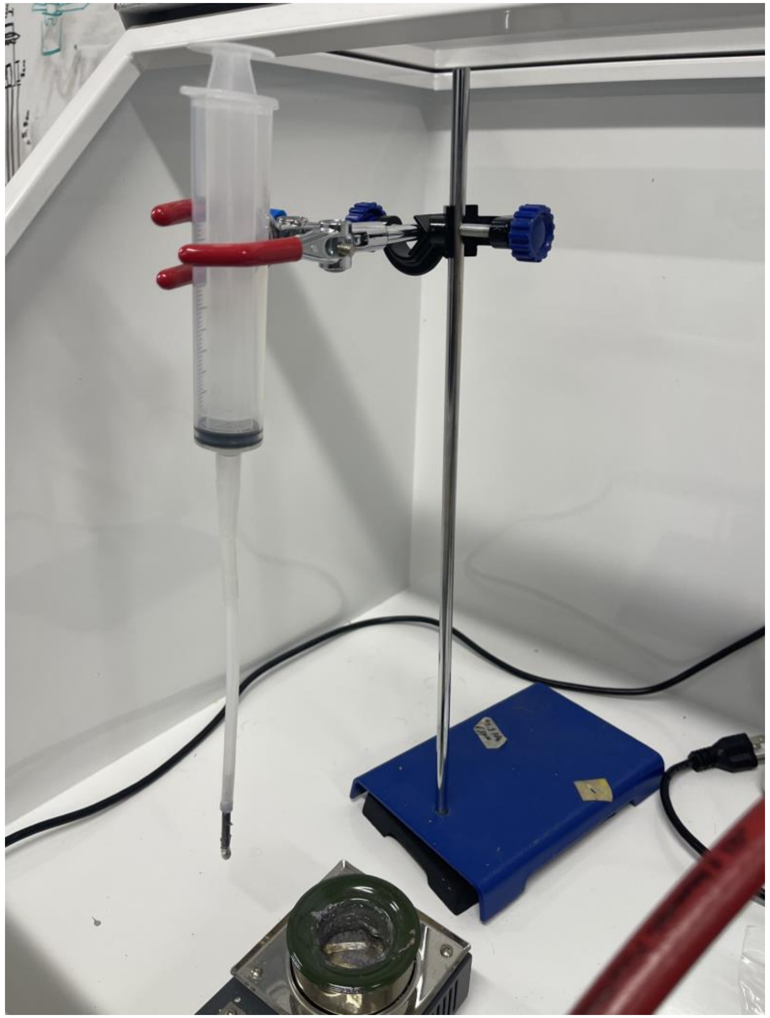
Manufacturing Copper-Clad Lithium (CuCLi) Wires



Challenges (and our failures)

- Liquid lithium dissolved cladding metal, lowering its purity and conductivity
- Inert gas atmosphere required
- Potentially incompatible even with lubricants
- Safe wire termination
- Potentially expensive means of manufacture
- Mechanical means to easily cut the wire to the desired length

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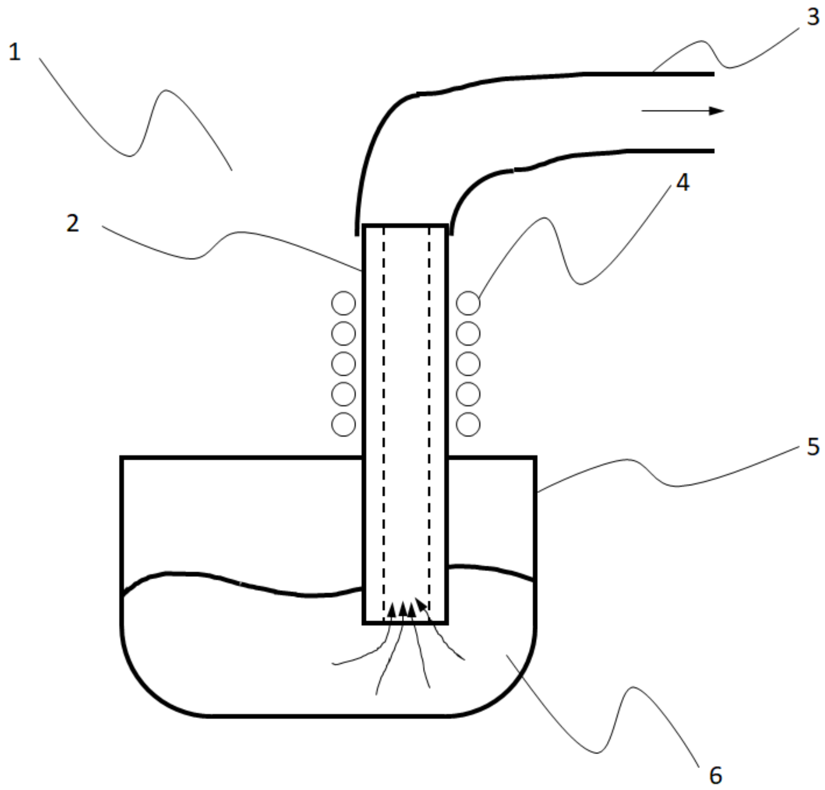
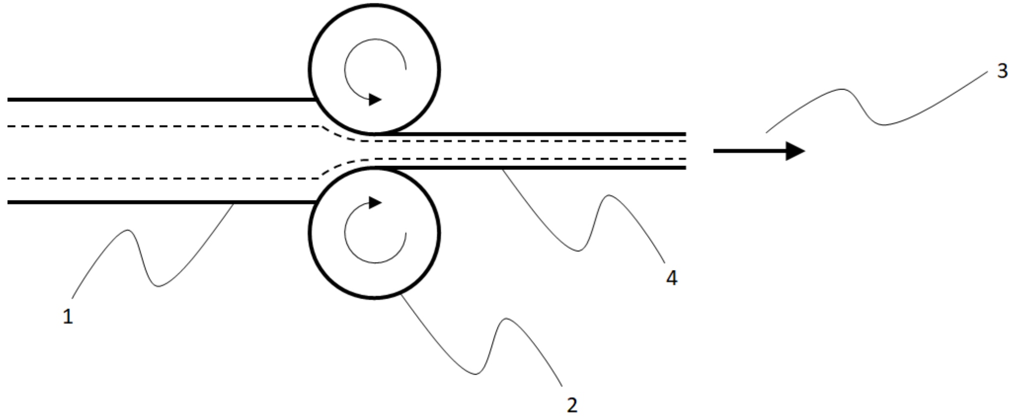
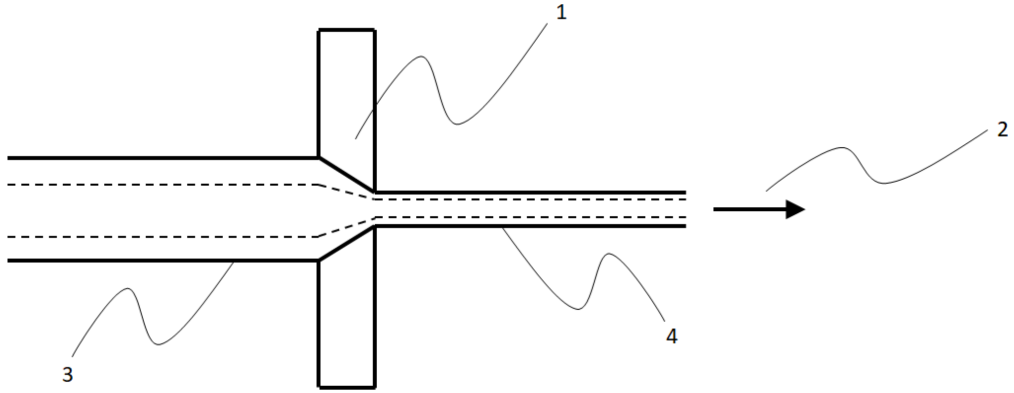
Manufacturing Copper-Clad Lithium (CuCLi) Wires



Filling Cu pipe with molten Li under Ar atmosphere.
Problem: Dissolves Cu into Li, increases resistivity.
Potential solution: Shrink and insert Li rod into Cu pipe.





Drawing wire from cylinder assembly.
Problem: Work hardening of Cu requires periodic annealing, melting Li, dissolving Cu into Li.
Solution: ??

Source: Lightweight Cryogenic Conductors and Methods of Making and Use Thereof, US Patent Application, 63/181,675, (2022)

Discussion & Conclusion

- At 1st glance, Li looks like an unlikely candidate for making conductors – but it has some benefits:
  - Non-toxic, good availability, low cost (and likely to drop further)
  - Soft and ductile
  - Second best conductivity per unit density (range: 50—150 K)
- Potential applications:
  - Cryogenic impulse applications
  - High-frequency applications
  - "Odd" geometries (e.g. terminations, clamps, joints, connectors)
  - Conductors in bushings/feedthroughs from RT to cryo
- However:
  - Cladding process needs to be figured out
  - Cheap materials does not necessarily lead to cost reduction

Anyone interested in a collaboration?

A HUI HOU

https://collectionsofwaikiki.com/a-hui-hou-meaning/

Backup Slides

Material Compositions

1. Aluminum, commercial purity, 1050A, H19
2. Beryllium*
3. Brass, CuZn10, C22000, soft
4. Bronze, CuSn4, C51000, hard
5. Calcium*
6. Copper, C12500, hard
7. Gold, commercial purity, P00020, cold worked, hard, min 99.5%
8. Lithium, commercial purity, min 99.9%
9. Magnesium, commercial purity, ASTM 9980A
10. Manganese, commercial purity
11. Nickel-iron alloy, INVAR, cold worked, hard
12. Niobium, commercial purity, Type 2
13. Palladium, commercial purity, P03980, cold worked, hard
14. Platinum, commercial purity, P04995, annealed
15. Potassium*
16. Silver, commercial purity, fine, soft
17. Sodium*
18. Stainless steel, martensitic, AISI 410, hard temper
19. Tantalum, commercial purity, R05200, annealed, >99.7% Ta
20. Titanium, alpha-beta alloy, Ti-6Al-4V, annealed
21. Tungsten, commercial purity, R07004, annealed
22. Zinc, commercial purity, High grade, min. 99.9%
23. Zirconium, commercial purity, R60001

*Incomplete data sets required the survey of multiple compositions.

Patents

Inventors have been striving to harness the numerous electro-thermodynamic and economic benefits of alkali metal conductors at room temperature. Here is a list of relevant patents.

1. Levine D. LIGHTWEIGHT COMPOSITE ELECTRICAL WIRE. Patent #US 7.626,122 B2
2. Humphrey L, Westfield G. ALKAL METAL COMPOSTEELECTRICAL CONDUCTORS Patent #US 3,33,049
3. Hope H.; Hope S. LIGHTWEIGHT ELECTROCONDUCTIVE WIRE Patent #US 5,057,651
4. Fanwood S, Eager G. MANUFACTURE OF BARE OR PRE-INSULATED METAL CLAD SODUM CONDUCTOR Patent #US 3,389,460
5. Atkinson C, Butler R, Ross F.METHOD OF MAKING ALKAL METAL-FILLED ELECTRICAL CONDUCTORS AND TERMINATIONS THEREFOR Patent #US 3,717,929
6. Volk V. SODIUM CONDUCTOR CABLE Patent #US 3,649,745
7. Brandt T, Netzel P, Wharton L. SODIUM FILLED FLEXIBLE TRANSMISSION CABLE. Patent #US 4,056,679
8. Iyer N, Carr W, Male A. CRYOGENEC CONDUCTOR. Patent #US 4,927,985

Material Properties Databases

Software:

1. Granta EduPack R1 Version 22.1.2

Publications:

2. T. C. Chi; Electrical resistivity of alkali elements. Journal of Physical and Chemical Reference Data 1 April 1979; 8 (2): 339–438. https://doi.org/10.1063/1.555598
3. John R. Rumble, ed., CRC Handbook of Chemistry and Physics, 104th Edition (Internet Version 2023), CRC Press/Taylor & Francis, Boca Raton, FL.
4. W., J. (2006), Experimental Techniques for Low-Temperature Measurements, Oxford University Press, Oxford, UK
5. "Strategic metals prices in February 2020". Institute of Rare Earths and Metals. 5 February 2020. Archived from the original on 2020-02-05.