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Temperature's Impact on the Conductivity of Common Metals

[redacted]

Hands-ON Experimental

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1 Introduction

The conductivity of a material describes its ability to carry electrical current. Most materials exhibit a resistivity to current that is typically negligible, however they do have some resistivity. [Wol, 2015] The overall resistivity has been shown to partially depend on temperature in an approximately linear fashion however this appears to bottom as they reach lower temperatures. [Fac, 2015] This paper seeks to confirm this relationship in the context of common metals and determine the coefficients in the linear relationship for each. The goal is to answer the question:

What is the relationship between temperature and the resistance of common metals?

I was interested in this question because I am pursuing a career in electrical engineering, and the results of this experiment might have implications in that field because of the temperature increases associated with computing processes. I was also interested by our experiments in class with electrical resistance. My hypothesis is that there will be a linear relationship between temperature and conductivity with conductivity falling as temperature falls because superconductors having such a high conductivity with low temperatures and resistors in class gaining resistance through extended use because of the temperature rise from the current. On a molecular level this would be due to the atoms forming a lattice allowing for easier movement of electrons at low temperatures. The scattering of atoms, and therefore elections at high temperatures then limits their movement and then increases resistance. [Fac, 2015] Additionally, I doubt I will be able to produce low enough temperatures that will have a peak in conductivity as described above.

2 Methodology

2.1 Materials

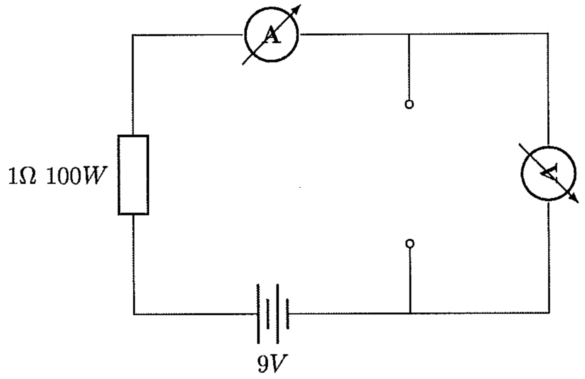
- 1Ω, 100 W Resistor

#4

- 5.08 cm, 18 AWG Copper Wire
- 5.08 cm, 18 AWG Steel Wire
- 5.08 cm, 18 AWG Aluminum Wire
- 5.08 cm, 16 AWG Brass Wire
- (3) 9V Batteries
- 10A Ammeter
- Alligator Clips
- Excess 18 AWG Copper Wire
- Subzero and Near-Zero °Celsius Environments (Refrigerator and Freezer)
- Infrared Thermometer
- Voltmeter
- Video Camera

2.2 Procedure

1. Using 9V battery, Resistor, Ammeter, Voltmeter, Excess Copper Wire and Alligator Clips assemble the circuit defined in this diagram:



2. Record environment temperature using infrared thermometer.
3. Position camera to record ammeter and voltmeter readings and begin recording.
4. Place Copper Wire segment on open terminals to complete the circuit and ensure meters are reading.

5. Create an audible cue for the recording when the meters are reading.
6. Repeats steps 4 and 5 with Steel, Aluminum, and Brass wire segments.
7. Stop recording
8. Move circuit into subzero environment (freezer) and repeat steps 2-7.
9. Move circuit into near-zero environment (refrigerator) and repeat steps 2-7.
10. Review recordings by going to each audio cue and recording the meter's measurements in 5 sequential frames.

2.3 Saftey Considerations

- With the resistor in series, the circuit had a low enough voltage and current such that there was no risk of electrical shock.
- Care was used when cutting wires to length.
- A test in an oven was removed after it was deemed to have too high of a risk for burns.

2.4 Rationale

Many factors played into how this procedure was designed. It required a lot of trial and error to get to this finalized method. I initially could not find an ohmmeter I could use that was precise enough to measure the resistance of the wires I was testing. Instead I applied the definition of resistance which led me to use an ammeter and voltmeter in series with a 1 ohm resistor and 9V battery to calculate the resistance. When initially attempting to collect a single data point from the ohmmeter and ammeter I found the values fluctuated too fast for me to read. To solve this issue I decided to set up a camera to record the displays of the instruments and average the values displayed across 5 sequential frames. All of this resulted in the above procedure being used.

3 Results and Analysis

Table 1: Copper Voltage and Amperage and Calculated Resistance

Temperature(°C) ± 0.05°C	Frame	Voltage (V) $\pm 5.0 * 10^{-5}$ V	Amperage (A) $\pm 0.005A$	Resistance (Ω)
-4.3	1	$2.2 * 10^{-3}$	1.52	$1.4 * 10^{-3} \pm 3.8 * 10^{-5}$
-4.3	2	$2.2 * 10^{-3}$	1.52	$1.4 * 10^{-3} \pm 3.8 * 10^{-5}$
-4.3	3	$2.6 * 10^{-3}$	1.53	$1.4 * 10^{-3} \pm 3.8 * 10^{-5}$
-4.3	4	$2.6 * 10^{-3}$	1.53	$1.7 * 10^{-3} \pm 3.8 * 10^{-5}$
-4.3	5	$2.4 * 10^{-3}$	1.52	$1.7 * 10^{-3} \pm 3.8 * 10^{-5}$
-4.3	AVE	$2.4 * 10^{-3}$	1.52	$1.5 * 10^{-3} \pm 3.8 * 10^{-5}$
8.8	1	$1.1 * 10^{-3}$	1.28	$8.6 * 10^{-4} \pm 4.2 * 10^{-5}$
8.8	2	$1.1 * 10^{-3}$	1.26	$8.7 * 10^{-4} \pm 4.3 * 10^{-5}$
8.8	3	$1.1 * 10^{-3}$	1.26	$8.7 * 10^{-4} \pm 4.3 * 10^{-5}$
8.8	4	$1.1 * 10^{-3}$	1.26	$8.7 * 10^{-4} \pm 4.3 * 10^{-5}$
8.8	5	$1.1 * 10^{-3}$	1.26	$8.7 * 10^{-4} \pm 4.3 * 10^{-5}$
8.8	AVE	$1.1 * 10^{-3}$	1.26	$8.7 * 10^{-4} \pm 4.3 * 10^{-5}$
26.2	1	$1.3 * 10^{-3}$	1.74	$7.5 * 10^{-4} \pm 3.1 * 10^{-5}$
26.2	2	$1.2 * 10^{-3}$	1.74	$6.9 * 10^{-4} \pm 3.1 * 10^{-5}$
26.2	3	$1.2 * 10^{-3}$	1.74	$6.9 * 10^{-4} \pm 3.1 * 10^{-5}$
26.2	4	$1.2 * 10^{-3}$	1.78	$6.7 * 10^{-4} \pm 3.0 * 10^{-5}$
26.2	5	$1.2 * 10^{-3}$	1.72	$7.0 * 10^{-4} \pm 3.1 * 10^{-5}$
26.2	AVE	$1.2 * 10^{-3}$	1.74	$7.0 * 10^{-4} \pm 3.1 * 10^{-5}$

Table 2: Steel Voltage and Amperage and Calculated Resistance

Temperature(°C) ± 0.05°C	Frame	Voltage (V) $\pm 5.0 * 10^{-5}$ V	Amperage (A) $\pm 0.005A$	Resistance (Ω)
-4.3	1	$2.6 * 10^{-3}$	0.80	$3.3 * 10^{-3} \pm 8.3 * 10^{-5}$
-4.3	2	$2.6 * 10^{-3}$	0.80	$3.3 * 10^{-3} \pm 8.3 * 10^{-5}$
-4.3	3	$2.6 * 10^{-3}$	0.81	$3.2 * 10^{-3} \pm 8.2 * 10^{-5}$
-4.3	4	$2.6 * 10^{-3}$	0.81	$3.2 * 10^{-3} \pm 8.2 * 10^{-5}$
-4.3	5	$2.6 * 10^{-3}$	0.81	$3.2 * 10^{-3} \pm 8.2 * 10^{-5}$
-4.3	AVE	$2.6 * 10^{-3}$	0.81	$3.2 * 10^{-3} \pm 8.2 * 10^{-5}$
8.8	1	$5.0 * 10^{-4}$	0.26	$1.9 * 10^{-3} \pm 2.3 * 10^{-4}$
8.8	2	$4.0 * 10^{-4}$	0.26	$1.5 * 10^{-3} \pm 2.2 * 10^{-4}$
8.8	3	$4.0 * 10^{-4}$	0.21	$1.9 * 10^{-3} \pm 2.8 * 10^{-4}$
8.8	4	$4.0 * 10^{-4}$	0.21	$1.9 * 10^{-3} \pm 2.8 * 10^{-4}$
8.8	5	$4.0 * 10^{-4}$	0.21	$1.9 * 10^{-3} \pm 2.8 * 10^{-4}$
8.8	AVE	$4.2 * 10^{-4}$	0.23	$1.8 * 10^{-3} \pm 2.6 * 10^{-4}$
26.2	1	$2.1 * 10^{-3}$	1.68	$1.3 * 10^{-3} \pm 3.3 * 10^{-5}$
26.2	2	$2.1 * 10^{-3}$	1.68	$1.3 * 10^{-3} \pm 3.3 * 10^{-5}$
26.2	3	$2.0 * 10^{-3}$	1.61	$1.2 * 10^{-3} \pm 3.5 * 10^{-5}$
26.2	4	$2.0 * 10^{-3}$	1.61	$1.2 * 10^{-3} \pm 3.5 * 10^{-5}$
26.2	5	$2.0 * 10^{-3}$	1.61	$1.2 * 10^{-3} \pm 3.5 * 10^{-5}$
26.2	AVE	$2.0 * 10^{-3}$	1.64	$1.2 * 10^{-3} \pm 3.4 * 10^{-5}$

Table 3: Aluminum Voltage and Amperage and Calculated Resistance

Temperature(°C) ±0.05°C	Frame	Voltage (V) $\pm 5.0 * 10^{-5}$ V	Amperage (A) $\pm 0.005A$	Resistance (Ω)
-4.3	1	$1.3 * 10^{-2}$	0.81	$1.6 * 10^{-2} \pm 1.6 * 10^{-4}$
-4.3	2	$1.3 * 10^{-2}$	0.81	$1.6 * 10^{-2} \pm 1.6 * 10^{-4}$
-4.3	3	$1.3 * 10^{-2}$	0.81	$1.6 * 10^{-2} \pm 1.6 * 10^{-4}$
-4.3	4	$1.3 * 10^{-2}$	0.81	$1.6 * 10^{-2} \pm 1.6 * 10^{-4}$
-4.3	5	$1.3 * 10^{-2}$	0.87	$1.4 * 10^{-2} \pm 1.6 * 10^{-4}$
-4.3	AVE	$1.3 * 10^{-2}$	0.82	$1.5 * 10^{-2} \pm 1.5 * 10^{-4}$
8.8	1	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
8.8	2	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
8.8	3	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
8.8	4	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
8.8	5	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
8.8	AVE	$1.6 * 10^{-3}$	0.97	$1.6 * 10^{-3} \pm 6.0 * 10^{-5}$
26.2	1	$8.3 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$
26.2	2	$8.2 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$
26.2	3	$8.2 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$
26.2	4	$8.2 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$
26.2	5	$8.2 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$
26.2	AVE	$8.2 * 10^{-3}$	1.47	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$

Table 4: Brass Voltage and Amperage and Calculated Resistance

Temperature(°C) ±0.05°C	Frame	Voltage (V) $\pm 5.0 * 10^{-5}$ V	Amperage (A) $\pm 0.005A$	Resistance (Ω)
-4.3	1	$3.0 * 10^{-3}$	1.07	$2.8 * 10^{-3} \pm 6.0 * 10^{-5}$
-4.3	2	$3.0 * 10^{-3}$	1.07	$2.8 * 10^{-3} \pm 6.0 * 10^{-5}$
-4.3	3	$3.0 * 10^{-3}$	1.07	$2.8 * 10^{-3} \pm 6.0 * 10^{-5}$
-4.3	4	$3.0 * 10^{-3}$	1.01	$3.0 * 10^{-3} \pm 6.4 * 10^{-5}$
-4.3	5	$3.0 * 10^{-3}$	1.01	$3.0 * 10^{-3} \pm 6.4 * 10^{-5}$
-4.3	AVE	$3.0 * 10^{-3}$	1.05	$2.9 * 10^{-3} \pm 6.2 * 10^{-5}$
8.8	1	$5.1 * 10^{-3}$	2.21	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$
8.8	2	$5.1 * 10^{-3}$	2.21	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$
8.8	3	$5.1 * 10^{-3}$	2.21	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$
8.8	4	$5.1 * 10^{-3}$	2.21	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$
8.8	5	$5.1 * 10^{-3}$	2.26	$2.3 * 10^{-3} \pm 2.7 * 10^{-5}$
8.8	AVE	$5.1 * 10^{-3}$	2.22	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$
26.2	1	$1.4 * 10^{-3}$	0.70	$2.0 * 10^{-3} \pm 8.6 * 10^{-5}$
26.2	2	$1.4 * 10^{-3}$	0.70	$2.0 * 10^{-3} \pm 8.6 * 10^{-5}$
26.2	3	$1.4 * 10^{-3}$	0.66	$2.1 * 10^{-3} \pm 9.2 * 10^{-5}$
26.2	4	$1.4 * 10^{-3}$	0.66	$2.1 * 10^{-3} \pm 9.2 * 10^{-5}$
26.2	5	$1.4 * 10^{-3}$	0.66	$2.1 * 10^{-3} \pm 9.2 * 10^{-5}$
26.2	AVE	$1.4 * 10^{-3}$	0.68	$2.1 * 10^{-3} \pm 8.9 * 10^{-5}$

Table 5: Computed Average Resistivity and Conductivity

Temperature (°C) ±0.05°C	Resistance (Ω)	Resistivity ($\Omega * m$)	Conductivity (S/m)
	Copper		
−4.3	$1.7 * 10^{-3} \pm 3.8 * 10^{-5}$	$2.8 * 10^{-8} \pm 6.4 * 10^{-10}$	$3.6 * 10^{7} \pm 8.5 * 10^{5}$
8.8	$1.6 * 10^{-3} \pm 4.3 * 10^{-5}$	$2.5 * 10^{-8} \pm 7.1 * 10^{-10}$	$3.9 * 10^{7} \pm 3.6 * 10^{6}$
26.2	$7.0 * 10^{-4} \pm 3.1 * 10^{-5}$	$1.1 * 10^{-8} \pm 5.1 * 10^{-10}$	$8.8 * 10^{7} \pm 4.0 * 10^{6}$
	Steel		
−4.3	$3.2 * 10^{-3} \pm 8.2 * 10^{-5}$	$5.2 * 10^{-8} \pm 1.4 * 10^{-9}$	$1.9 * 10^{7} \pm 5.1 * 10^{5}$
8.8	$1.8 * 10^{-3} \pm 2.6 * 10^{-4}$	$2.9 * 10^{-8} \pm 4.2 * 10^{-9}$	$3.4 * 10^{7} \pm 5.0 * 10^{6}$
26.2	$1.2 * 10^{-3} \pm 3.4 * 10^{-5}$	$2.0 * 10^{-8} \pm 5.8 * 10^{-10}$	$5.0 * 10^{7} \pm 1.4 * 10^{6}$
	Aluminum		
−4.3	$1.5 * 10^{-2} \pm 1.5 * 10^{-4}$	$2.5 * 10^{-7} \pm 2.8 * 10^{-9}$	$4.0 * 10^{6} \pm 4.4 * 10^{4}$
8.8	$6.2 * 10^{-3} \pm 6.0 * 10^{-5}$	$1.0 * 10^{-7} \pm 1.1 * 10^{-9}$	$1.0 * 10^{7} \pm 1.1 * 10^{5}$
26.2	$5.6 * 10^{-3} \pm 5.3 * 10^{-5}$	$9.1 * 10^{-8} \pm 9.5 * 10^{-10}$	$1.1 * 10^{7} \pm 1.2 * 10^{5}$
	Brass		
−4.3	$2.9 * 10^{-3} \pm 6.2 * 10^{-5}$	$7.4 * 10^{-8} \pm 1.7 * 10^{-9}$	$1.4 * 10^{7} \pm 3.0 * 10^{5}$
8.8	$2.3 * 10^{-3} \pm 2.8 * 10^{-5}$	$5.9 * 10^{-8} \pm 7.8 * 10^{-10}$	$1.7 * 10^{7} \pm 2.2 * 10^{5}$
26.2	$2.1 * 10^{-3} \pm 8.9 * 10^{-5}$	$5.3 * 10^{-8} \pm 2.4 * 10^{-9}$	$1.9 * 10^{7} \pm 8.3 * 10^{5}$

3.1 Computation of Resistivity and Conductivity

Resistivity

$$\text{Resistance } (R) = \text{Resistivity } (\rho) * \frac{\text{Length } (L)}{\text{Cross-Sectional Area } (A)}$$

$$R = \rho * L/A$$

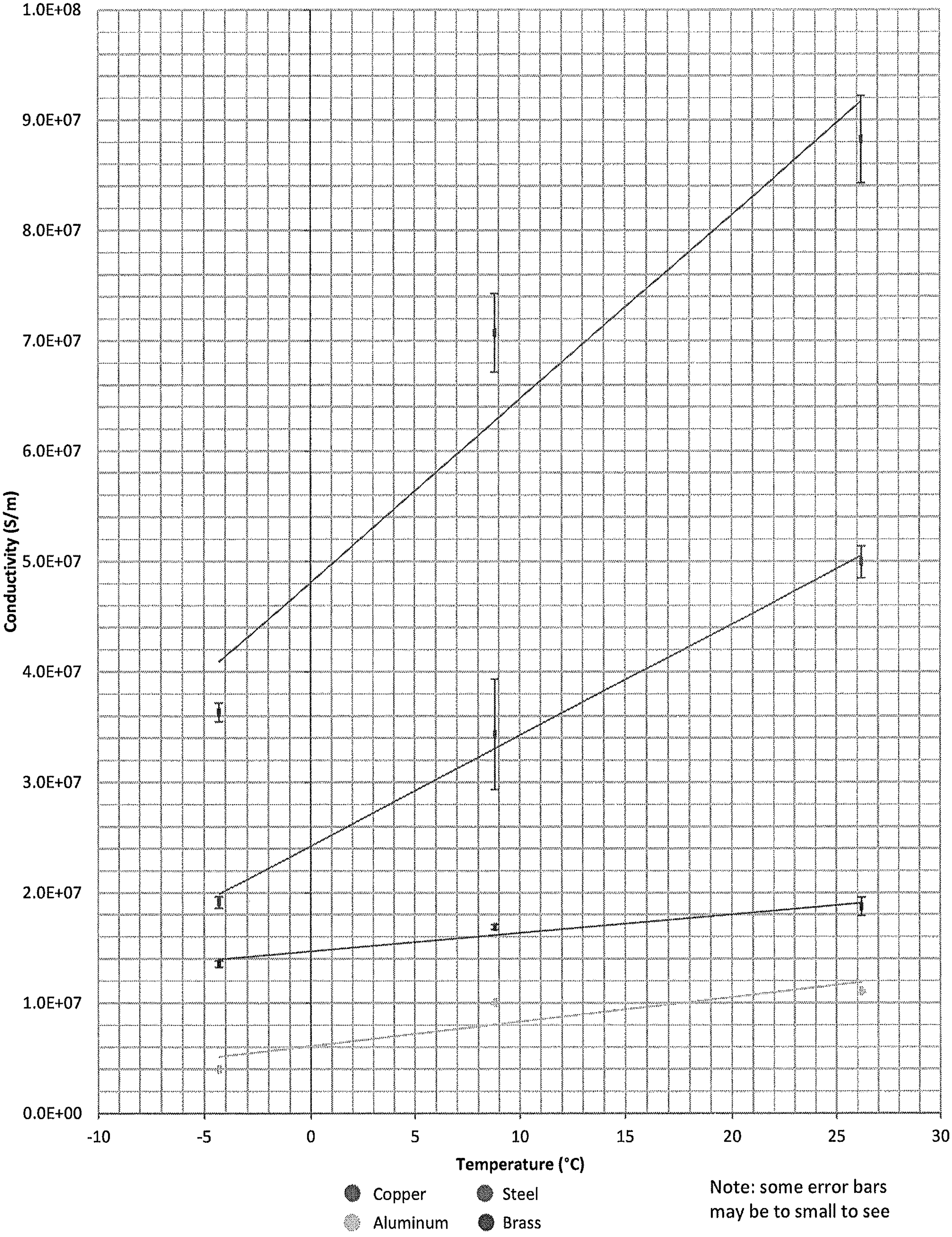
$$\rho = R * A/L$$

$$\rho = R * \frac{8.2322*10^{-7} \pm 5.0*10^{-11} m^2}{0.0508 \pm 5.0*10^{-5} m}$$ [Wol, 2015]

Conductivity

$$\sigma = 1/\rho$$

Graph 1: Conductivity vs. Temperature



Note: some error bars may be to small to see

3.2 Qualitative Interpretation

Graph 1 strongly suggests strong a positive correlation between Conductivity and Temperature for all 4 metals. However with only 3 averages per metal it is difficult to determine the exact relationship. A linear trend is sufficient but has in all 4 metals the $8.8°C$ conductivity is notably higher than the trend line which gives it the potential to be a quadratic or power relationship. Yet, all of those possibilities may be encompassed by the random error of the measurements. Additionally, there appears to be a relationship between the slope of each linear trend and its y-intercept: as the y-intercept increases, so does the slope of the trend-line.

3.3 Calculation of Linear Regressions

$$m = \frac{\Delta y}{\Delta x}$$

Copper

$$\frac{9.2*10^7 S/m - 4.1*10^7 S/m}{26.2°C - -4.3°C} = 1.7*10^6 S/m/°C$$

$$4.1*10^7 S/m - (1.7*10^6 S/m/°C * -4.3°C) = 4.8*10^7 S/m$$

$$\sigma = 1.7*10^6 S/m/°C * T + 4.8*10^7 S/m$$

Steel

$$\frac{5.0*10^7 S/m - 2.0.*10^7 S/m}{26.2°C - -4.3°C} = 1.0*10^6 S/m/°C$$

$$2.0*10^7 S/m - (1.0*10^6 S/m/°C * -4.3°C) = 2.4*10^7 S/m$$

$$\sigma = 1.0*10^6 S/m/°C * T + 2.4*10^7 S/m$$

Aluminum

$$\frac{1.9*10^7 S/m - 1.4*10^7 S/m}{26.2°C - -4.3°C} = 1.6*10^5 S/m/°C$$

$$1.4*10^7 S/m - (1.6*10^5 S/m/°C * -4.3°C) = 1.5*10^7 S/m$$

$$\sigma = 1.6*10^5 S/m/°C * T + 1.5*10^7 S/m$$

Brass

$$\frac{1.2*10^7 S/m - 5.1*10^6 S/m}{26.2°C - -4.3°C} = 2.3*10^5 S/m/°C$$

$$5.1*10^6 S/m - (2.3*10^5 S/m/°C * -4.3°C) = 6.1*10^6 S/m$$

$$\sigma = 2.3*10^5 S/m/°C * T + 6.1*10^6 S/m$$

4 Conclusion and Evaluation

This investigation attempted to determine the relationship between conductivity and temperature for copper, steel, aluminum and brass. The results themselves prove insufficient to draw a strong conclusion of a relationship. Although the data suggest a positive correlation with all metals having positive gradients, Copper having one of $1.7 * 10^6 S/m/^\circ C$ and Steel having $1.0 * 10^6 S/m/^\circ C$, with only 3 data points per metal a conclusion about whether the relationship is linear of quadratic cannot be made. This unusually appears to be the opposite of the drop in conductivity that is the currently recognized relationship. This would suggest that the higher energy of the atoms would allow for easier movement of electrons but it is know that the greater temperature causes lattice structures to breakdown and scatter electrons, creating resistance. This differing result may have been due to multiple potential sources of error described later. [Fac, 2015] However, the data does suggest that metals with a higher initial conductivity have a greater gradient, with Copper's y-intercept of $4.8 * 10^7 S/m$ add a gradient of $1.7 * 10^6 S/m/^\circ C$ while Aluminum's y-intercept of $1.5 * 10^7 S/m$ and a gradient of $1.6 * 10^5 S/m/^\circ C$. This may be explained that the metals with a higher initial conductivity had more electrons per atom to move. As the mobility for each electron increased, possessing more electrons would lead to a larger increase in conductivity. Due to the difficulty conducting this experiment with the resources I had there were several items that may have produced errors. The video recording of the instruments was poor and so there is a small possibility some numbers may have been misread, specifically the $-4.5^\circ C$ trial. The battery had to be swapped at multiple points and was constantly discharging as the tests continued and so the inconsistent voltage may have had an impact, although the current should have dropped in proportion to this per Ohm's Law. Additionally, the temperature measured was not directly the wire but the air surrounding and this temperature rose towards room temperature as the experiment continued which may have reduced the overall scale of the coefficient determined. In future experiments would use a digital Ohmmeter that is precise enough, connected to a computer to measure the resistance. I'd measure the temperature of the wire using an infrared camera, and most importantly would expand the variance of temperatures at which the resistance was measured.

References

[Fac, 2015] (2015). Factors affecting electrical conduction. `http://www.doitpoms.ac.uk/tlplib/thermal_electrical/composition.php`.

[Wol, 2015] (2015). Wolfram alpha. `http://www.wolframalpha.com/`.