

Zinc-Copper Galvanic Half-Cells: LED Powering and Real-World Potential

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Abstract

This experiment investigated the production and performance of zinc-copper galvanic cells using accessible materials, with a focus on optimizing voltage output and understanding factors influencing cell efficiency. By varying the factors such as electrolyte concentration, electrode materials, and cell configuration (single cells vs. series connection), we analysed their impact on voltage, current, and ability to power LEDs of varying voltage thresholds. Three electrolyte concentrations (0.1M, 0.5M, 1M, 2M) were tested in different combinations for both zinc sulfate and copper(II) sulfate solutions. Results showed minimal variation in voltage with changing concentration alone, with values ranging from approximately 0.9996 V to 1.0293 V. However, connecting multiple cells in series significantly increased voltage, with three cells in series reaching a voltage of 3.0656 V, which was sufficient to power all tested LED colors. These findings combined with theoretical predictions of Zn-Cu cells, demonstrated fundamental electrochemical principles such as redox reactions and ion migration via salt bridges. The experiment highlights the scalability and practical relevance of galvanic cells for real-world energy applications, reinforcing their role in the ongoing pursuit of efficient, low-cost, and sustainable battery technologies.

1. Introduction

The escalating demand for portable and sustainable energy solutions has catalysed advancements in electrochemical systems, notably galvanic (voltaic) cells, which facilitate the conversion of chemical energy into electrical energy through spontaneous redox reactions.¹ In galvanic cells, oxidation and reduction processes occur at separate

electrodes, generating a flow of electrons through an external circuit which produces an electrical current. This fundamental principle underpins the operation of various battery types, including primary cells such as zinc-carbon batteries and secondary cells like lithium-ion batteries.²

A galvanic cell comprises two half-cells, each containing an electrode immersed in an electrolyte

solution, which are connected by a salt bridge or porous membrane. In this electrochemical system, oxidation occurs at the anode - where metal atoms lose electrons to form cations - which then enter the electrolyte solution. The free electrons flow through an external circuit to the cathode, where reduction takes place - cations in the electrolyte gain electrons and are reduced to neutral atoms.¹ The salt bridge preserves the electrical neutrality of the galvanic cell by facilitating the migration of ions between the half-cells, thereby completing the circuit and sustaining the continuous flow of electrons necessary to generate an electrical current.³

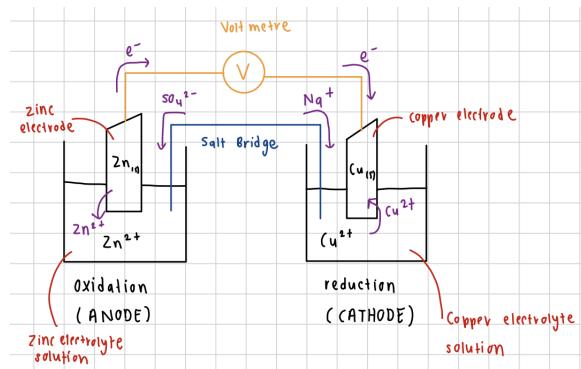


Image 1: Diagram of Zn/Cu half cells with indicated species flows shown

A comprehensive understanding of such principles is fundamental in the field of electrochemical engineering, particularly in the design and optimisation of battery technologies.⁴ For instance, the performance characteristics of a battery - voltage, capacity, and efficiency - are influenced by various factors, including the selection of electrode materials, the composition of the electrolyte, and the internal resistance of the cell.⁵ By systematically applying this foundational knowledge, engineers can produce energy storage systems that are optimized for safety, longevity, and environmental sustainability, further aligning with the specific demands of the diverse applications of such batteries, including electric vehicles and future developments of sustainable energy solutions.⁶

2. Materials and Methods

2.1: Materials

Copper foil (electrode)	Zinc foil (electrode)
Cotton rope and plastic salt-bridge spacer	Centrifuge tubes
2M Copper(II) sulfate (CuSO ₄) solution	Centrifuge tube holder
2M Zinc sulfate (ZnSO ₄) solution	Multimeter
2M Potassium chloride (KCl) solution	5 LED lights (green, blue, white, yellow, red)
Wires	Alligator Clips
Scissors	3 AA Batteries

2.2: Experimental Method

2.2.1: Preparation of materials and solutions

Copper and zinc foils were prepared by cutting out four 3 cm × 6 cm strips of each electrode species. 10mL of the 2M potassium chloride (KCl) solution was added to a 500mL beaker, along with 190mL of water, to produce a 0.1M KCL solution. The other electrolyte solutions (copper (II) sulfate (CuSO₄) and zinc sulfate (ZnSO₄)) were prepared in separate 500mL beakers at four different concentrations: 0.1M, 0.5M, 1M and 2M:

0.1M solution: 10mL of 2M base solution and 190mL of water added to a 500mL beaker

0.5M solution: 50mL of 2M base solution and 150mL of water added to a 500mL beaker

1M solution: 100mL of 2M base solution and 100mL of water added to a 500mL beaker

2M solution: 200mL of 2M base solution added to a 500mL beaker.

A strip of cotton rope was placed in the 0.1M KCl solution, allowing the material to soak up the solution. The strip of cotton rope was then placed

into the plastic salt-bridge spacer. Five LEDs of varying colours (and thus varying voltages required) were collected and tested in increasing voltage requirements (red → green) using one or more AA batteries to determine which terminal was negative and positive.

2.2.2: Testing varying electrolyte concentrations in galvanic half-cells

Four galvanic half-cells were made using varying electrolyte concentrations (0.1M, 0.5M, 1M, and 2M). For each galvanic half-cell, one centrifuge tube filled approximately two thirds full with CuSO_4 , and second approximately two thirds full with ZnSO_4 . Both electrolyte solutions would be of the same concentration. A strip of copper foil was placed in the copper (II) sulfate centrifuge tube, and a strip of zinc foil was placed in the zinc sulfate centrifuge tube. The salt bridge (cotton rope in plastic spacer) was placed in the two centrifuge tubes to connect the solutions. See *Figure 1* below for an image of a prepared galvanic half-cell. Wires were then attached to the electrode foils using crocodile clips.

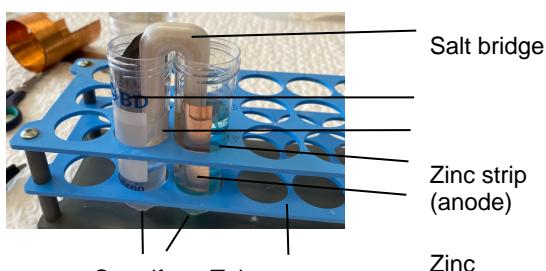


Figure 1: Annotated image of a zinc-copper galvanic half-cell

The wire from the copper electrode was connected to the positive terminal of the multimeter, and the wire from the zinc electrode was connected to the negative terminal of the multimeter. Voltage readings were taken for each of the electrolyte concentrations. The wires from each galvanic half-cell were then disconnected from the multimeter and connected to the appropriate terminals on the green LED to determine whether the voltage was high enough to power it or not.

2.2.3: Testing several galvanic half-cells in Series

Following the voltage and current readings using individual galvanic half-cells, the galvanic half-cells were connected in series. This was achieved using wires with alligator clips connecting the anode (zinc foil) to the cathode (copper foil). First, only two galvanic half-cells (0.1M and 1M concentrations) were connected in series, and voltage readings were taken using the multimeter. Then, three galvanic half-cells (0.1M, 1M and 2M concentrations) were connected in series, and voltage readings were taken using the multimeter. The wires were then disconnected from the multimeter and connected to the appropriate terminals on the LEDs to determine whether each colour could be turned on or not, starting with green (highest voltage requirement), and then blue, white, yellow and finally red (lowest voltage requirement).

2.2.4: Analysis Techniques

Several forms of raw data were collected and analysed during this process. A multimeter was used to measure voltage and current of the various individual galvanic half-cells, as well as that of several galvanic half-cells in series. Additionally, LEDs of different colours were used to test the performance of multiple galvanic half-cells in series by their ability to power the LED. The voltage, current and LED data was then analysed using a range of appropriate equations to derive properties of the galvanic half-cells, such as power output, specific power, energy output, specific energy, and cell voltage, which can be compared to a theoretical value ($\text{Zn}-\text{Cu} \sim 1.10 \text{ V}$). These equations include:

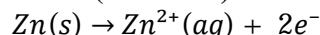
- Power output (watts): $P = V \times I$
($P = \text{power}$, $V = \text{voltage}$, $I = \text{current}$)
- Energy output (joules): $E = P \times t$
($E = \text{energy}$, $P = \text{power}$, $t = \text{time}$)

3. Results & Discussion

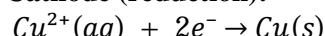
3.1: Effect of electrolyte concentration on voltage and current

In a half-cell, oxidation at the anode releases electrons that flow through an external wire to the cathode, where reduction occurs; ions migrate through the electrolyte to maintain charge balance.⁷

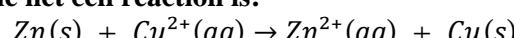
Anode (oxidation):



Cathode (reduction):



The net cell reaction is:



The reaction has a theoretical standard cell potential of approximately 1.10 V, based on standard reduction potentials (E°) ($Cu^{2+}/Cu = +0.34$ V and $Zn^{2+}/Zn = -0.76$ V), under standard conditions: 1M concentrations, 25°C temperature, and 1 atm pressure. The initial experiment was to test how electrolyte concentrations of half cells would affect the voltage. Changing concentrations of both electrolytes didn't seem to largely affect the voltage. This minimal change is shown in Table 1.

Concentration of Zn^{2+}/Cu^{2+}	Voltage (V)
0.1M / 0.1M	1.0293
0.5 M / 0.5M	1.0408
1.0 M / 1.0M	1.0209
2.0M / 2.0M	0.9996

Table 1: Voltage readings under same concentrations of Zn^{2+}/Cu^{2+}

This trend suggests that the Nernst equation's concentration effect was relatively weak under our experimental setup, possibly due to factors such as electrode surface condition or limitations in our measurement precision.⁸

Further tests examined the effect of unequal concentrations between half-cells. Again, changes were minor, shown in Table 2.

Zn^{2+}	Cu^{2+}	Voltage (V)
0.1	2.0	1.0020
2.0	0.1	1.0212

Table 2: Voltage readings under same concentrations of Zn^{2+}/Cu^{2+}

The slightly higher voltage in the second case (more Zn^{2+} and less Cu^{2+}) could be due to the direction of the Nernst shift, which favors higher potential when the oxidized form (Zn^{2+}) is more concentrated and the reduced form (Cu^{2+}) is more dilute, therefore shifting the equilibrium potential of the reaction. However, these differences are minor and the observed voltages were consistently slightly lower than the theoretical 1.10 V, likely due to internal resistance like ohmic resistance, imperfect electrodes, or non-ideal conditions.⁹

While voltage remained fairly stable across concentrations, current output showed a small peak at 0.5 M, suggesting a subtle influence of ion availability on current flow.¹⁰

Concentration of Zn^{2+}/Cu^{2+}	Current (mA)
0.1M / 0.1M	0.270
0.5 M / 0.5M	0.283
1.0 M / 1.0M	0.265

Table 4: Voltage readings in different number series

These values suggest that there may be an optimal concentration (~0.5 M) where ion mobility and conductivity are most favorable. At lower concentrations (0.1 M), limited ions may restrict current flow, while at higher concentrations (1.0 M), increased ionic interactions or electrode

fouling may reduce efficiency slightly.

3.2: Effect of cell configuration on voltage

When multiple galvanic half cells were connected in series, their voltages added up approximately linearly.¹¹ This demonstrates the fundamental principle of series circuits in electrochemistry: total voltage is the sum of the individual cell voltages.¹² Shown in Table 4.

Configuration	Voltage (V)
One cell (0.1M)	1.0293
Two cells (0.1M and 1M)	2.0290
Three cells (0.1, 1M, and 2M)	3.0656

Table 4: Voltage readings in different series

When all three cells were placed in series, the cumulative voltage was enough to light up all the different colours of LEDs, each requiring a specific forward voltage with green being the highest at 3.0-3.2V and red being the lowest at 2.0-2.2V. This highlights the usefulness of series configurations for applications requiring higher voltages.¹³

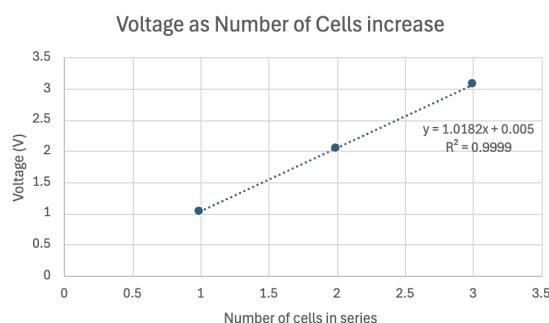


Figure 2: Graph of voltage against number of cells in series

There would be another way to increase the voltage generated with the same cell arrangement. This can be done through the use of an alkaline electrolyte for each half cell instead of a neutral electrolyte.¹⁴

By increasing the alkalinity of the electrolyte, another path is formed for a more efficient flow cell battery system as there is an increase in the redox potential of the metals in electrolytes of higher pH values.¹⁵ With this increased efficiency, comes various possible downsides which could affect the cell potential. There is a greater chance of precipitation of the metal and effervescence of hydrogen in higher pH conditions which would reduce the surface area of the electrodes and lead to drastic reductions in the rate of the redox reactions.¹⁶

3.2 Reducing low-grade energy waste

When operating with half-cells, large amounts of heat dissipation should be taken into account for various reasons. The heat that's released is a low-grade energy waste which plays a big role in the ongoing climate crisis.¹⁷ Furthermore, efficiency is increased when heat loss is reduced which shows that there are environmental and economical benefits.¹⁸

A viable solution to reduce heat emitted from the cells would be to recycle the heat back into the system to further drive the redox reactions happening based on the thermally regenerative electrochemical cycle (TREC).¹⁹ By installing a heat exchanger²⁰ between the 2 half-cells, the heat exchanger could be used to recover the heat dissipated throughout the process²¹ that is brought about from factors such as the electrolyte flow across the cell and ohmic effect present at the electrodes of the cell. However, this would only be reasonable to apply if the galvanic cell is being utilised on a large scale. At a large scale, temperature of the electrolytes are raised to high levels hence causing there to be sufficient heat dissipation.²² This allows for the addition of a heat exchanger as a significant amount of heat to be recycled back into the system and generate a much greater voltage so that the cost of the heat exchanger would be offset by the increased efficiency of the system on top of the positive environmental impact it will have.

3.3 Thermogalvanic cells

Building on what was previously mentioned and by adding an external natural heat source to the system, thermogalvanic single cells can be brought by the combined utilisation of both low-grade waste heat and the external heat source to generate larger voltage outputs and hence greater energy and power outputs too,²³ augmenting the sustainability factor of energy generation.²⁴ The primary driving power for electrolyte flow would be the natural heat source, which could be solar energy or geothermal energy, instead of the redox reactions. The heat source would heat the anode and hence cause a temperature gradient between the anode and cathode to be formed. The temperature gradient is maintained by the heat exchanger which would also act as a membrane between the half-cells to accommodate for ions to flow between the two half-cells. This gradient would generate a voltage which would supplement the voltage produced by the redox reactions occurring in the half cells to produce a larger combined voltage.

Utilising the capabilities thermogalvanic cells have to continuously generate electrical output²⁵ and the trends shown in *Figure 2*, voltage and electrical energy output can be further improved which is vital for developing countries which are in need of a large constant supply of electricity at minimal cost.²⁶

4. Conclusion

This experiment shows how basic zinc-copper galvanic cells can generate electrical power and what factors affect their performance. It was found that varying the concentration of the electrolyte solutions had minimal impact on the voltage output. The result of the experiment was close to the initial value, with the voltage values being next to 1.0V, a bit less than the theoretical value of 1.10V. This small difference is thought to be due to internal resistance or other practical limitations within the system.

On the other hand, attaching a few more cells in series produced a considerable change in the total voltage. A total voltage of 3.07 V was produced with 3 interconnected cells, which was used to light LEDs of different colours. This experiment shows that basic electrochemical systems can be used to transform energy to produce larger requirements, which proves the real-world applicability. Additionally, there are ways to enhance the system's efficiency, like using alkaline electrolytes or applying thermally regenerative systems to recover heat. Thus, the ideas serve as an example that galvanic cells are not only instruments but also permit the use of renewable and affordable energy storage solutions.

In conclusion, all our theoretical topics were brought into the realm of real life, which has given birth to future developments leading to an improved design and innovation of battery technology.

Appendix

Zinc Concentration (M)	Copper Concentration (M)	Volts Direct Current (V)
2	0.1	1.0212
0.1	2	1.0020
2	2	0.9996
0.1	0.1	1.0293
1	1	1.0209
Two in series (0.1M, and 1M)		2.0290
Three in series (0.1M, 1M, 2M)		3.0656

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