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Year 9-10

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Investigation written and conducted by Mahir Monsur

Year 10

Metal-Air Batteries (MAB): Anionic Electrochemistries of the Electrolyte

KEYWORD

MAB
Zinc-air
Ionic mobility
Ionic conductivity
OCV

ABSTRACT

Lithium-ion batteries dominate over 44% of the entire battery market (**1**). However, they pose several drawbacks, including the environmental burden of lithium extraction, rarer than metals such as aluminum or zinc (**2**), along with additional serious safety concerns due to thermal runaway and the reactivity of lithium metal (**3**). In response, metal-air batteries (MABs) have gained attention as a promising alternative. "Lithium-ion technology continues to dominate consumer electronics, but ongoing innovation is leading to the development of new chemistries, such as lithium-sulfur and zinc-air batteries, promising enhanced performance for next-generation electronics." These batteries rely on the oxidation of earth-abundant, metals, such as zinc, magnesium, iron, and aluminum, in conjunction with ambient oxygen, offering both high theoretical energy densities (e.g., up to 1.3 kWh/kg for zinc-air and over 8.1 kWh/kg for aluminum-air)(**4**) and recyclable potential. Among them, the zinc-air battery (ZAB) is the most commercially mature, utilized in hearing aids, medical devices, and compact electronics (**5**). Aluminum and magnesium air technologies are being explored for large-scale and automotive applications, with notable investment such as Tesla's metal-air battery system patent in 2021 (**6**).

HIGHLIGHTS

- The performance of various metal-air batteries under different electrolyte systems were investigated.
- KOH+KCL+KI yielded the most optimum results across all metal-air battery groups.
- More investigations are required to gauge understanding.

ELECTROCHEMICAL CELLS

Metal-air electrochemical cells consist of the metal anode where oxidization occurs and an air cathode where reduction occurs, along with an electrolyte though which the ions travel between the electrodes (**7**). E.g. in a zinc–air battery system, Zinc reacts with hydroxide ions to form a soluble zincate ion, releasing two electrons in the process: $Zn + 4OH^- \rightarrow [Zn(OH)_4]^{2-} + 2e^-$. The zincate ion is unstable and tends to decompose in the electrolyte, precipitating as insoluble zinc oxide whilst generating hydroxide ions and water. At the cathode, molecular oxygen from the air is reduced by electrons arriving from the external circuit. It combines with water to produce hydroxide ions: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$. These OH^- ions migrate back toward the anode to participate in continuous oxidation, enabling continuous current flow. Overall, the battery's net reaction produces zinc oxide as a solid discharge product. (**8**)

Electrolyte	**Dissociation**	**pH** (9)(10)	**Ionic Conductivity at Inf. Dil. ($S\cdot cm^2/mol$)** (11)	**Ionic Mobility ($\times 10^{-8}$ $m^2\cdot V^{-1}\cdot s^{-1}$)($\lambda = zF\mu$)**
KOH	$K^+ + OH^-$	10-13	K^+: 73.5 OH^-: 198.0	K^+: 7.63 OH^-: 20.55
KCl	$K^+ + Cl^-$	7	K^+: 73.5 Cl^-: 76.3	K^+: 7.63 Cl^-: 7.93
KI	$K^+ + I^-$	7-9	K^+: 73.5 I^-: 76.8	K^+: 7.63 I^-: 7.98
K_2CO_3	$2K^+ + CO_3^{2-}$	11	K^+: 73.5 CO_3^{2-}: 138.6	K^+: 7.63 CO_3^{2-}: 7.19

1: Table of electrochemical properties for each ion (Various sources)

The hydroxide ion is a preferred option in most commercial cells, tied to its strong alkaline environment, high ionic conductivity and direct participation in ORR reactions. Albeit the ion is noted for its indulgence in corrosivity and passivation of the cell from insolubles. As of now these insolubles pose a major challenge to MAB rechargeability, stability and performance, particularly with ZABs (passivation, precipitates, etc.). Carbonate ions can form in metal-air batteries unintentionally, which can block cathodic pores in the cathode (**12**). These insoluble precipitates can also passivate the battery, creating a "poisoning" effect. CO_3^{2-} also plays a role interestingly as a buffer, helping to regulate pH stability in an electrolyte environment. Chloride ions form highly soluble compounds and corrode the materials within the cell (see appendix). The CL- ion is noted for its corrosive properties and tendency to dissolve oxide layers. (13). The Iodide ion acts as a redox mediator and a catalyst (I-, I2, I¬3-) Iodide harbors a lower standard electrode potential than chloride, making it easier to oxidize. ZABs with potassium iodide (KI) electrolyte added to KOH were investigated, the study found an overall performance boost with the addition, which may be attributed Iodide redox reactions. (**14**)

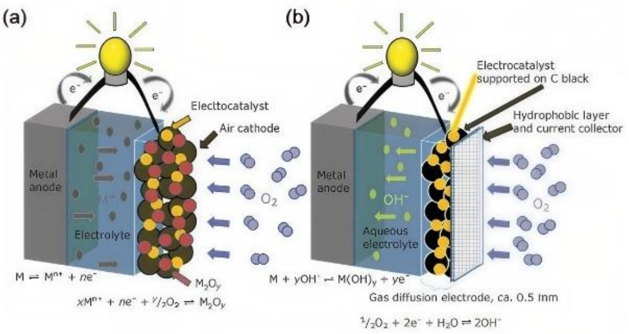


Fig. 1. : An image of a metal-air battery, one features alkaline chemistry whilst the other favours a neutral or acidic reaction.

Electrolytes enables the active transport of ions between the electrodes. (**15**). The ionic movement between electrodes occurs due to these electrolytes. Attributes such as ionic conductivity, mobility, and pH of an electrolyte directly influence the reactions that allow the battery to conduct and produce current. Electrolytes can either be solid, aqueous, gel-based, or hybrid based. The potassium ion has been observed in zinc-air battery systems in KOH electrolyte systems, due to its high ionic conductivity of **73.5 $S\cdot cm^2\cdot mol^{-1}$** (compare to Na+ with 50.1 $S\cdot cm^2\cdot mol^{-1}$)**.** Additionally**,** the cation's high ionic radii (**16**) results in its charge is distributed over a larger volume, this weaker electrostatic field reduces the strength of ion-dipole interactions with surrounding water molecules, allowing the ion to harbor less resistance in its movement through the electrolyte. Moreover, Group 1 hydroxides are known for their high solubility and the alkaline feature of these electrolytes are known to prove beneficiary to alkaline cells. (**17**)

Battery	Theoretical voltage, (V) (vs. SHE)	Practical operation voltage (V)	Theoretical energy density ($Wh\cdot kg^{-1}$)	Practical energy density ($Wh\cdot kg^{-1}$)
Zn-air	1.65	1.0–1.2	1,350	350–500
Al-air	2.4	1.2–1.6	8,076	300–500
Mg-air	3.1	1.2–1.4	6,815	600–1,300
Ni-air (calculated)	0.65	0.1-0.4	595	100-150

2: Properties of various metals – for relevancy see theoretical and practical voltages. Source: https://www.sciencedirect.com/science/article/pii/S2213956721001146

Lithium is a core component in commercial batteries due to its monovalent nature and strong electrochemical reactivity, making it highly efficient in discharging. Its standard reduction potential of -3.04 V versus SHE (**18**) underscores its position as the most electrochemically reactive metal, enabling high voltage and energy density. Lithium's theoretical specific capacity of around 3860 mAh/g (**19**) as an air-battery is one of the highest among metals, contributing significantly to the energy output of Li-air systems. However, while Li-air batteries have immense theoretical potential, most are solid-state or gel-based, which restricts ionic mobility and creates significant internal resistance, thereby bottlenecking their practical performance. In comparison, divalent metals such as zinc (Zn) and magnesium (Mg) offer slower reaction rates due to their higher ion charge, with trivalent aluminum (Al) being even slower due to the additional charge in its ions. Furthermore, the rate of precipitate formation and passivation within the battery cells varies based on metal reactivity: Mg > Al > Zn > Ni (**20**), where more reactive metals, like magnesium, tend to form insulating layers (e.g., $Mg(OH)_2$) that hinder long-term performance. While nickel, being less reactive, provides more stability, its relatively lower capacity and slower kinetics make it less desirable for high-performance metal-air systems. Though MABs and AABs are currently under research, the ZAB is commercial and has been explored in hearing aids, military grade applications and EV's.

QUESTIONING & PREDICTING

Question:	What is the most optimal potassium anion in an electrolyte solution when it comes to the open-circuit voltage of various MABs?
Aim:	This experiment will assess the performance of MABs under different electrolyte systems and report the most optimal ones for different metals and varying groups.
Hypothesis:	KOH+KI+KCl will be the highest performing overall electrolyte across all metals in the 3rd group, KOH+KI will be the highest in the 2nd group, KOH will be the highest in the 1st group due to being standard electrolyte across multiple systems. This is suspected as halogen chemistry is corrosive. KOH is standard preferred electrolyte in alkaline systems; therefore, it is expected to generally outperform the rest.

PLANNING & CONDUCTING

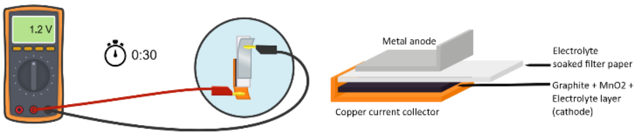
The experiment will test single electrolytes, double electrolytes, and then tri-electrolyte combinations, each electrolyte solution will be tested against 4 metals (Zn, Al, Mg, Ni). The list is as follows:

1st group	KOH, KCl, KI, K_2CO_3
2nd group	KOH+KI, KOH+KCl, K_2CO_3
3rd group	KOH+KI+KCl, KOH+KCl+K_2CO_3, KOH+KI+K_2CO_3

The first group are single electrolytes, for the observation of pure singular performance of the electrolyte, the combinatory (2nd group) with KOH explores if these electrolytes work well within a stronger alkaline system, the tri-combinatory (3rd group) electrolytes explore stronger halide environments (halide + halide + hydroxide) and 2 (halide+buffer+hydroxide)s, this determines if the addition of a third electrolyte in equal part antagonises the system or benefits it. A fair test is achieved by keeping key variables constant: metal dimensions and mass, procedure, and measurement conditions remain consistent across all trials, ensuring that only the electrolyte/metal composition affects the observed outcome.

Method

1. Calibrate the digital scale to 0 g.
2. Prepare metal anodes (~0.5 g each, ~0.75 for copper).
3. Mix the cathode paste in a 50 mL beaker:
   i. Add 1.5 g graphite and 1.5 g MnO_2.
   ii. Add electrolyte in staged volumes with circular stirring:
      ○ Group 1: 2 mL → stir 10 s → 2 mL → stir 10 s → 1 mL → stir 10 s.
      ○ Group 2: 2 mL KOH → stir 15 s → 2 mL electrolyte B → stir 15 s.
      ○ Group 3: 1.7 mL KOH → stir 10 s → 1.7 mL electrolyte A → stir 10 s → 1.7 mL electrolyte B → stir 10 s.
   iii. Prepare 3 or 4 batches based on the electrolytes in the current group; pick one.
4. Set up the cell environment:
   i. Soak filter paper in chosen electrolyte (in 1st Petri dish):
      ○ Group 1: 3 drops single electrolyte
      ○ Group 2: 1 drop KOH + 2 drops B
      ○ Group 3: 1 drop KOH + 1 drop B + 1 drop C
   ii. In a 2nd Petri dish, bend copper collector at 1 cm and lay flat.
   iii. Spread ~0.1 cm of paste over copper using a spatula.
   iv. Place soaked filter paper over the paste.
   v. Bend the selected metal anode at 1 cm (same direction as copper).
5. Set up the multimeter:
   i. Red probe to VΩ port, black to COM.
   ii. Attach alligator clips and set to DC voltage (20 V range).
   iii. Ensure reading is 0 when idle.
6. Measure OCV:
   i. Connect black clip to metal anode, red clip to copper.
   ii. Press anode and cathode together (no short-circuit or leaks).
   iii. Start stopwatch; after 30s, record OCV.
7. Clean up:
   i. Remove clips, discard cell, rinse Petri dishes, dry for 5 min.
   ii. Repeat steps 2–7 for each metal in the group and electrolyte.
8. Repeat for next group:
   i. Replace electrolytes and catalytic mix.
   ii. Repeat steps 2–7 for Groups 2 and 3.
   iii. Rinse and dry all glassware between groups.



(Diagram made with Chemix.org) Calibrating and weighing the metals, as well as following uniform sizes helps maintain a strictly controlled experiment, the volumes and masses of other materials are controlled and kept constant to strictly measure OCV without fluctuation. The paste is required as the cathode and catalytic layer, the metal is needed for releasing current and the copper is for current collection, which acts as a ground for the clips to connect to and provide a reading. Petri dish provides a controlled environment for the cell. The 1x1.5cm or 1x2cm bend area provides a large enough area for the clips to latch on to, therefore, the reaction area is 3x1.5cm with varying thickness. 30 s provides time for the cell to stabilise.

EQUIPMENT & MATERIALS

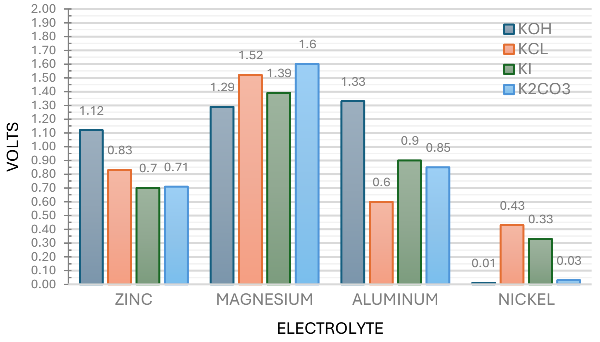
Independent:	Electrolyte, Metal
Dependent:	Open-Circuit voltage (OCV)
Controlled:	1. Catalytic layer ratio (5 g activated carbon + 5 g MnO_2+ 5 ml electrolyte) 2. Electrolyte used (Total 6.25ml per cell) 3. Filter paper dimensions (matched to width, and double the length of copper piece) 4. Metal dimensions (~2cmx4cm with varying thickness, consistently ~0.5 grams) 5. Cathode material (copper) 6. Measurement timing interval (30s) 7. Measurement device (multimeter, stopwatch_ 8. Measurement procedure 9. Experiment environment (room)

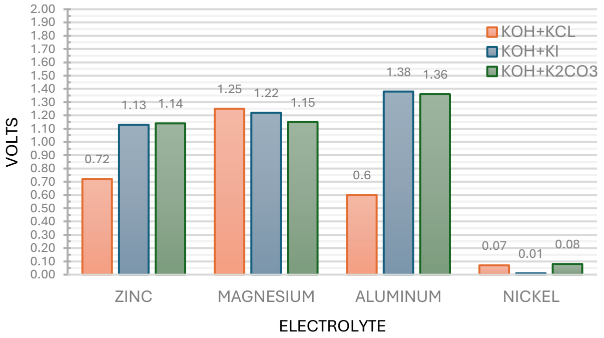
You will need -

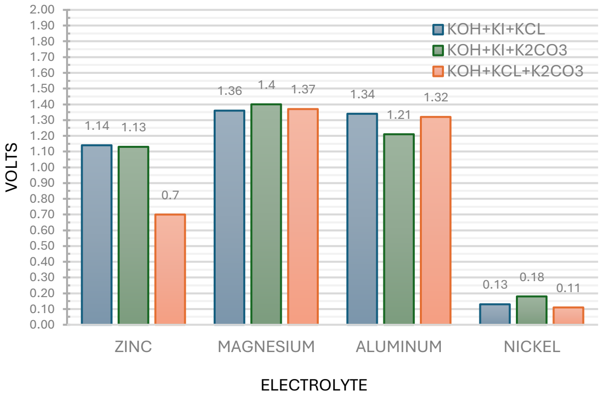
- *100ml bottles, 1 mol concentration of each electrolyte(KOH, KI, KCl, K_2CO_3)*
- *Activated carbon/graphite powder jar*
- *Manganese(IV) dioxide powder jar*
- *40x Filter paper (1.5x6cm minimum)*
- *40x Metal sheets (10x each) (Zn, Mg, Al, Ni) (1.5x3cm minimum, ~0.5 g weight, may vary)*
- *40x Copper sheet (1.5x3cm, 0.75 g weight, may vary)*

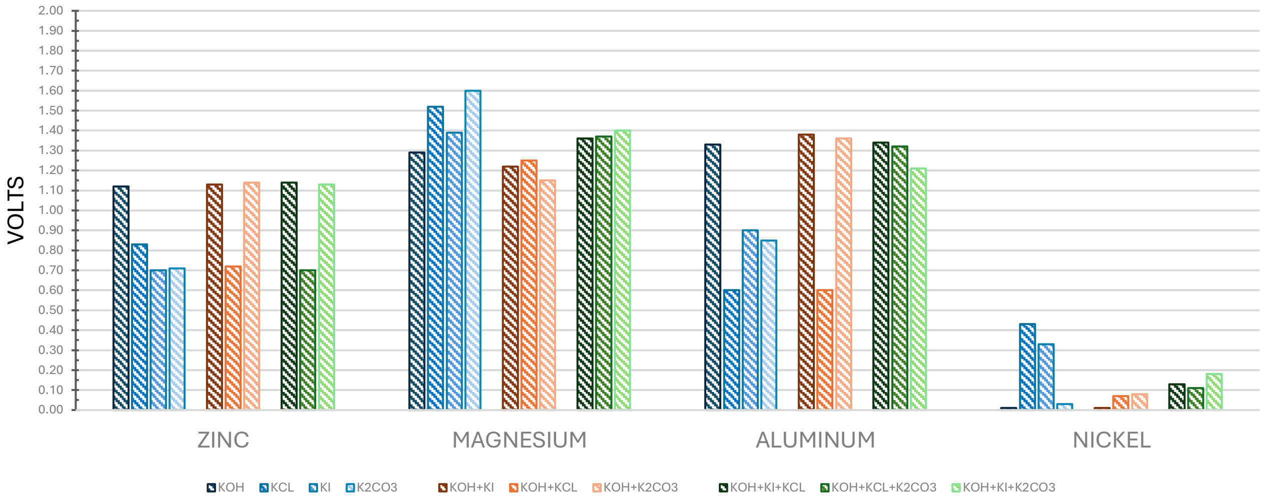
-1x Precision scale
-1x Negative multimeter probe
-1x Positive multimeter probe
-2x Alligator clips
-4x 50ml Beaker
-1x Graduated cylinder
-1x Stirring rod
-4x Spatula
-6x Petri dish
-1x Digital multimeter
-1x Stopwatch
-1x Scissor
-1x Notetaking device

DATA









Electrolyte/Metal	Zn-air	Mg-air	Al-air	Ni-air
KOH	1.12	1.29	1.33	0.01
KI	0.70	1.39	0.90	0.33
KCl	0.83	1.52	0.60	0.43
K_2CO_3	0.71	1.60	0.85	0.03
KOH+KI	1.13	1.22	1.38	0.01
KOH+KCL	0.72	1.25	0.60	0.07
KOH+K_2CO_3	1.14	1.15	1.36	0.08
KOH+KI+KCL	1.14	1.36	1.34	0.13
KOH+KI+K_2CO_3	1.13	1.40	1.21	0.18
KOH+KCL+K_2CO_3	0.70	1.37	1.32	0.11

a) The Open-Circuit voltages of different metal-air batteries (Zinc, Magnesium, Aluminum, Nickel) under Group 1 electrolytes.

b) The Open- Circuit voltages of different metal-air batteries (Zinc, Magnesium, Aluminum, Nickel) under Group 2 electrolytes.

c) The Open-Circuit voltages of different metal-air batteries (Zinc, Magnesium, Aluminum, Nickel) under Group 3 electrolytes.

d) The Open-Circuit voltages of different metal-air batteries (Zinc, Magnesium, Aluminum, Nickel) under all electrolytes tested.

e) Data table

DISCUSSION

The investigation explored the performance of various potassium-based electrolytes on the open-circuit voltage (OCV) performance of four different metal-air batteries (Zn, Mg, Al, Ni). The goal was to determine which electrolyte combination provided optimal electrochemical conditions for different metal systems. Across every trial, **magnesium consistently demonstrated the highest OCVs among electrolytes**, particularly with K_2CO_3 (1.60 V) and KCl (1.52 V), likely due to magnesium's high theoretical voltage (3.1 V vs SHE), K_2CO_3 is a strong performer, due to the fact KOH was expected to outperform K_2CO_3, this may be due to the fact magnesium carbonate is more soluble than magnesium hydroxide (refer to appendix). However, the practical application of magnesium-air batteries still face limitations due to these precipitates ($Mg(OH)_2$ formation), which was not observed directly in the OCV-specific study. **Zinc-air cells performed best with KOH+KI+KCl (1.14 V)**, supporting the hypothesis that combining halides and hydroxides can enhance redox reactions. KOH, the standard alkaline electrolyte, alone achieved 1.12 V, close to the combined variant. This reinforces that KOH still remains a robust baseline electrolyte due to its high ionic conductivity and hydroxide participation in oxygen reduction reactions (ORR). **Aluminum-air systems peaked with KOH+KI (1.38 V)** and KOH+K_2CO_3 (1.36 V), suggesting that while KOH is necessary for high performance, carbonate buffering may play a stabilizing role in pH and precipitate formation. Despite aluminium's high theoretical energy density, its practical voltages were modest, possibly due to the formation of passive $Al(OH)_3$ layers. **Nickel-air systems performed the weakest overall**, with maximum voltages rarely exceeding 0.2 V, except in the KI and KCL electrolytes (0.33 & 0.43). Nickel's low theoretical voltage (0.65 V) may account for this, despite its stability and corrosion resistance. The **tri-electrolyte systems (Group 3)** yielded the most consistent and enhanced performances across metals, when observing the 1.1 V to 1.4 V range, KOH + KI + KCl performed consistently within this window across multiple metals, providing support for the hypothesis. This may be attributed to synergistic effects between iodide's redox mediation, chloride's high solubility, and hydroxide's conductive, alkaline environment. These ions likely enhance oxygen reduction and ion transport dynamics, though not reliable as individual electrolytes. The experiment also reveals that no single solution outperforms across all metals, suggesting the importance of tailoring electrolyte composition to the specific anode chemistry. Strong contenders include KOH + K_2CO_3, KOH + KI, KOH+KI+K_2CO_3.

LIMITATIONS & ERRORS

OCV was measured only 30 seconds after assembly, which does not account for long-term behaviour, stability, or plateauing. Batteries may have experienced voltage decay or improvement over time that was likely not captured. Only one OCV reading was taken per configuration. Multiple replicates would help average out anomalies and improve the reliability of the results. Although all efforts were made to keep metals around 1.5x3cm, slight inconsistencies in thickness or surface area likely have influenced the reaction rate and OCV, especially with reactive metals like magnesium and aluminum. All electrolytes were used at 1 M concentration, but small variations in actual molarity or impurities could affect conductivity and reaction efficiency. The experiment was conducted under ambient room conditions, but temperature, humidity, and air exposure (oxygen concentration) were not strictly controlled which could impact cathodic reactions. The physical pressing of electrodes for measurement may vary between trials may have introduced contact resistance fluctuations which affects voltage readings. The batteries were not tested under load (e.g., through a resistor), so practical current output and power characteristics were not evaluated, only the initial voltage potential. Manual stirring and spreading of the MnO_2-graphite paste could introduce inconsistency in catalytic layer thickness or distribution, impacting electron transfer kinetics at the cathode.

CONCLUSION

The investigation identifies electrolyte compositions that affect the open-circuit voltage of various metal-air batteries. Among all tested combinations, the tri-electrolyte system of KOH, KI, and KCl demonstrated the most consistent and elevated performance across zinc, magnesium, and aluminum anodes, supporting the hypothesis. Additionally, a lot of tri-electrolyte species showed competitive performance compared to single or double, with nearly a 1V+ voltage output, this suggests that multi-ion species cater to and specialize in different needs and abilities for the anode This suggests that incorporating multiple ionic species can improve electrochemical activity by facilitating ion transport and supporting favourable redox reactions. While performance was various by metal, the results confirm that anionic electrolyte chemistry acts a fundamental determiner in cell performance. These findings support and recommend further developments of specialised electrolyte systems for specific metal-air needs, with levels of potential for optimization in both portable and large-scale energy storage technologies.

EVALUATION

The results of this investigation provide valuable insight into the influence of potassium-based electrolytes on the performance of various metal-air batteries (MABs). **From a performance standpoint**, the tri-electrolyte combinations, esp. KOH+KI+KCl demonstrated high or near-optimal open-circuit voltages across all tested metals. This supports that multi-ion electrolyte systems have the possibility of enhancing ion transport, redox mediation, and overall cell kinetics, especially when combining a strong base (KOH) with redox-active (KI) and solubility-enhancing (KCl) ions. The mere fact that this combination outperformed KOH alone in some cases implies that the synergy between ions may be more beneficial than maximizing individual conductivity. Moreover, the data supports **magnesium-air and aluminum-air batteries as substantially high-potential candidates**, both exhibiting voltages exceeding 1.3 V with the several electrolytes. This affirms the potential use of these systems for rapid-energy applications, especially where cost and resource availability are critical. **Zinc-air**, while slightly lower in voltage, remains a reliable contender and continues to justify its commercial use (~1.2 practical voltage), especially in small electronics and medical devices. Conversely, nickel-air batteries displayed limited performance which reinforces their unsuitability for high-performance applications despite their corrosion resistance. Their use may be more appropriate in low-energy systems or where long-term durability outweighs energy density. Such uses may be delegated to:

- **Off-grid and emergency energy systems** could benefit from aluminum- or magnesium-air batteries enhanced with KOH+KI-based electrolytes for lightweight, high-output setups.
- **Electric vehicles and grid storage** may use this information to optimize rechargeability and energy output by fine-tuning ion blends to reduce passivation and improve cycle life.
- In **developing nations**, the ability to substitute rare materials like lithium with abundant metals like Zn or Mg, alongside inexpensive salts (e.g., KCl, KI), could democratize access to reliable power sources.

Additionally, this study introduces a framework for further investigations, such investigations may include the feasibility of other metals under the same electrolytes, aqueous versus solid versus gel state electrolytes with different ionic liquids, gel polymers and the like. In the end metal-air batteries remain a highly promising competitor to li-ion, yet future developments are crucial.

APPENDIX

	I^-	OH^-	CO_3^{2-}	Cl^-
Ni	15.4	1.5×10^{-5}	4.3×10^{-4}	6.75
Mg	14.6	6.2×10^{-6}	1.8×10^{-2}	5.60
Al	—	—	—	4.51
Zn	43.8	4.2×10^{-6}	9.1×10^{-6}	40.8

Note: Solubilities in g/10ml and 20-25 C°. **CRC Handbook of Chemistry and Physics, 88th Edition**

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OSA RISK ASSESSMENT FORM

for all entries in (✓) ☐ Models & Inventions and ■ Scientific Inquiry

This must be included with your report, log book or entry. One form per entry.

STUDENT(S) NAME: Mahir Monsur ID: 0206 - 014

SCHOOL: Glenunga International High School

Activity: Give a brief outline of what you are planning to do.

Investigate the Open-Circuit Voltage performance of metal-air batteries (Zn, Mg, Al, Ni) under various electrolytes

Are there possible risks? Consider the following:

- Chemical risks: Are you using chemicals? If so, check with your teacher that any chemicals to be used are on the approved list for schools. Check the safety requirements for their use, such as eye protection and eyewash facilities, availability of running water, use of gloves, a well-ventilated area or fume cupboard.
- Thermal risks: Are you heating things? Could you be burnt?
- Biological risks: Are you working with micro-organisms such as mould and bacteria?
- Sharps risks: Are you cutting things, and is there a risk of injury from sharp objects?
- Electrical risks: Are you using mains (240 volt) electricity? How will you make sure that this is safe? Could you use a battery instead?
- Radiation risks: Does your entry use potentially harmful radiation such as UV or lasers?
- Other hazards.

Also, if you are using other people as subjects in an investigation you must get them to sign a note consenting to be part of your experiment.

Risks	How I will control/manage the risk
See below	

(Attach another sheet if needed.)

Risk Assessment indicates that this activity can be safely carried out

RISK ASSESSMENT COMPLETED BY (student name(s)): Mahir Monsur

SIGNATURE(S):

■ By ticking this box, I/we state that my/our project adheres to the listed criteria for this Category.

TEACHER'S NAME: Ian Lau

SIGNATURE: DATE: 26/06/25

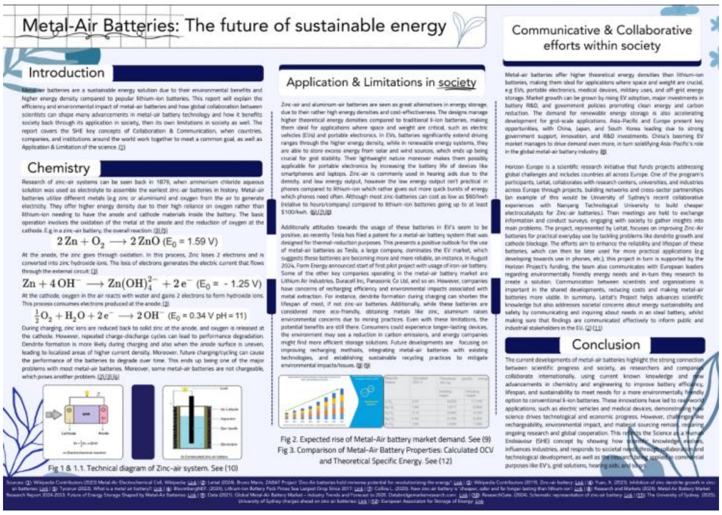
RISK ASSESSMENT

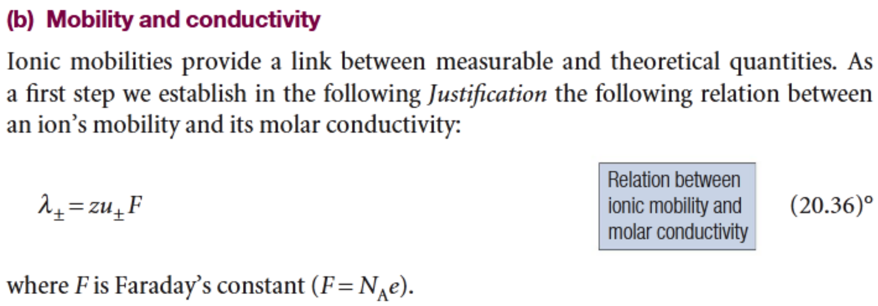
Risks		How the risk is being controlled
Potassium Hydroxide ≤ 1 M (caustic potash) Harmful if swallowed. Extremely corrosive, may cause burns and irritative to skin, eyes, lungs. CAS No.	$\text{KOH}^{(aq)}$ ⚠ ⚠	**Standard Handling Procedure** Wear gloves and necessary skin protection (long sleeves, closed shoes, safety glasses and apron) to mitigate contact, avoid rapid movements with chemical (to avoid splashes), avoid bringing near to mouth areas. In case of contact rinse area with water (eyewash station, distilled water or sink.) **Disposal** Low concentrations may be flushed down the drain.
Potassium Iodide ≤ 1 M Gastro-intestinal irritation, rashes, and inflammation of the salivary glands. Allergic reaction, highly excessive consumption/contact may lead to illness. CAS No.	$\text{KI}^{(aq)}$ ⚠	**Standard Handling Procedure** Wear gloves and necessary skin protection (long sleeves, closed shoes, safety glasses and apron) to mitigate contact, avoid rapid movements with chemical (to avoid splashes), avoid bringing near to mouth areas. In case of contact rinse area with water (eyewash station, distilled water or sink.) **Disposal** Low concentrations may be flushed down the drain.
Potassium Chloride ≤ 1 M Mostly safe and used as table salt substitute, notable allergic reaction, hyperkalaemia possible in excess. CAS No.	$\text{KCl}^{(aq)}$	**Standard Handling Procedure** Wear gloves and necessary skin protection (long sleeves, closed shoes, safety glasses and apron) to mitigate contact, avoid rapid movements with chemical (to avoid splashes). Avoid general skin contact. In case of allergy rinse area with water and seek medical attention if severe. **Disposal** Low concentrations may be flushed down the drain.
Potassium Carbonate ≤ 1 M Harmful if swallowed. Corrosive, can cause irritation and light burns to skin, eyes, and lungs. May cause pain, vomiting, vision loss on contact of area. CAS No.	$\text{K}_2\text{CO}_3^{(aq)}$ ⚠	**Standard Handling Procedure** Wear gloves and necessary skin protection (long sleeves, closed shoes, safety glasses and apron) to mitigate contact, avoid rapid movements with chemical (to avoid splashes), avoid bringing near to mouth areas. In case of contact rinse area with water (eyewash station, distilled water or sink.) **Disposal** Low concentrations may be flushed down the drain.
Manganese(IV) Dioxide ≤ 100g (powder) Harmful if inhaled, harmful if swallowed. CAS No.	$\text{MnO}_2^{(s)}$ ⚠	**Standard Handling Procedure** Avoid bringing near nose and mouth, wear safety glasses and gloves. **Disposal** Low amounts (~10g) may be flushed down the drain.
Graphite ≤ 100g (powder) Harmful if inhaled, low toxicity in small amounts. CAS No.	C	**Standard Handling Procedure** Avoid bringing near nose and mouth, wear safety glasses and gloves. **Disposal** Low amounts (~10g) may be flushed down the drain.
Metal sheet (Zinc, Magnesium, Aluminum, Nickel, Copper) Sharp edges can cause cuts. CAS No.	Zn, Mg, Al, Ni, Cu	**Standard Handling Procedure** Wear safety glasses, closed shoes, and gloves. Avoid touching corner and edge of metal sheet. In case of cut dress the wound with a bandage. **Disposal** Small sizes may be disposed of via bin, recyclable.
Glass beaker, Petri dish If dropped, glass shards may be flung, shards are notably sharp.	Borosilicate glass	**Standard Handling Procedure** Wear safety glasses, closed shoes and gloves. In case of cut dress the wound with a bandage/wrapping depending on the severity. **Disposal** Using a brush and pan, pick up the shards of glass and dispose via bin.
Scissor Notably sharp, risk of cuts/wounds.		**Standard Handling Procedure** Wear safety glasses, closed shoes and gloves. In case of cut dress the wound with a bandage. **Disposal** Broken shards of plastic and metal may be collected through brush and pan in similar manner to glass.
Stopwatch **Multimeter** **Spatula** **Stirring rod**		No significant risk noted.

Scientific Journal of

Metal-Air Batteries (MAB): Anionic Electrochemistries of the Electrolyte

Written by Mahir Monsur – Science inquiry

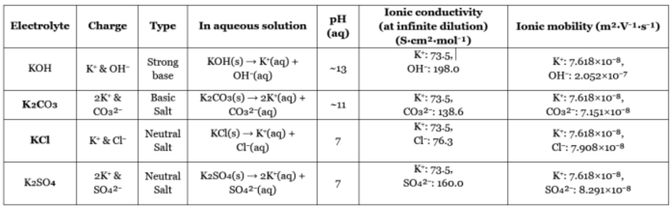
Date	Reflection writing	Takeaway
Information	This is the reflection space for ideas, thoughts, logical processes that have occurred in order to build the writing paper for the investigation. Word count of the original document (excluding headings, titles, figure captions, tables, references and journal): 2241 *There may be a 10% tolerance of the word limit.	
Pilot **26th March**	It has occurred; a novel idea, a passion to sate curiosity, the idea of **metal-air** batteries, while interesting (since it uses oxygen as a fundamental cathode material), research is quite underdeveloped, the need for investigation is crucial. Though it should be noted, that during this time I had a very limited view of chemistry, whilst undertaking a specialist chemistry course, I mainly borrowed the chemical information from sources like ScienceDirect but not a valued depth of understanding, I took such ideas at face-value. This is the SHE Task – It was on metal-air batteries as well (found the idea from a environmentally-friendly batteries list online), so I generally thought to build on that.  Metal-Air Batteries: The future of sustainable energy Introduction Chemistry $2\,Zn + O_2 \longrightarrow 2\,ZnO$ (E_0 = 1.59 V) $Zn + 4\,OH^- \longrightarrow Zn(OH)_4^{2-} + 2\,e^-$ (E_0 = - 1.25 V) $\frac{1}{2}O_2 + H_2O + 2\,e^- \longrightarrow 2\,OH^-$ (E_0 = 0.34 V pH = 11) Fig 1 & 1.1. Technical diagram of Zinc-air system. See (10) Application & Limitations in society Fig 2. Expected rise of Metal-Air battery market demand. See (9) Fig 3. Comparison of Metal-Air Battery Properties: Calculated OCV and Theoretical Specific Energy. See (12) Communicative & Collaborative efforts within society Conclusion *1: SHE (Science as a Human Endeavour) Task for Yr 10 Specialist Chemistry*	Deciding to work on a cool idea from one of my assignments
28th March	First research and rebuilding understanding – Looking into metal-air batteries, what are they really? Metal-air batteries, pretty much use a metal anode, then an electrolyte, then a cathode, it is fundamentally an electrochemical cell (like li-ion and lead acid but not solar panels or wind, those are different.) Looked into. –What is a cathode Positive terminal of the battery – accepts electrons and reduction reactions occur. –What is an anode Negative terminal of the battery – gives electrons and oxidation reactions occur. –What is an electrolyte Ionic medium for ions to travel through and from in the solution. (This can be pretty much any salt) –What is an electrolyte in a battery Previous –How to make a metal-air battery at home. Found a video! Found the following – https://byjus.com/chemistry/cathode-and-anode/ https://www.youtube.com/watch?v=7Mh3P3G-EqQ	A metal-air battery is an electrochemical cell, similar to li-ion. Found a useful video that spurred on research. Decided to test different metals with different electrolytes.

	What I found interesting is that the video used different electrolytes, Some ideas –Maybe I could, potentially experiment across different electrolytes? –I could also potentially experiment across different metals, like in the video. –Is straightforward – measure the voltage of the battery.	
1st April	Haven't touched in a while, right now the current objectives are – –Look at electrolytes and different metals. –Start building the doc. KOH and NaOH seem to be the standard, since metal-air batteries are typically alkaline pH (strong presence of OH-), which promotes the reduction reaction: $\frac{1}{2}O_2 + H_2O + 2e^- \longrightarrow 2OH^-$ (E_0 = 0.34 V pH=11) Source: https://en.wikipedia.org/wiki/Zinc%E2%80%93air_battery From the following – https://www.sciencedirect.com/science/article/abs/pii/S0360319922055653 https://www.sciencedirect.com/science/article/abs/pii/S0378775305016691 https://www.sciencedirect.com/science/article/abs/pii/S1385894723038858 Seems interesting, there seems to be different types of electrolytes –Solid-state –Aqueous –Gel I think the most re-creatable seems to be the aqueous ones, though currently all I'm seeing is NaOH and KOH, some mentions of carbonate, what I might do is add carbonate to the roster (both potassium and sodium forms) for investigation.	Found out about different electrolytes. Various categories of electrolytes. Found a common electrolyte – KOH & NaOH and its indulgence in alkaline batteries.
2nd April	I found an interesting source, while reviewing some papers, I found instances of ionic mobility and ionic conductivity, what are those? Well, I'm not sure exactly, but it appears to be related to how well an ion can carry its charge through something. The source is: https://is.muni.cz/el/sci/podzim2016/C4020/um/pom/Ionic_Conductivity_and_Diffusion_at_Infinite_Dilution.pdf It's interesting because it has ionic conductivities of various ions, though not fully sure on what infinite dilution is, I take inspiration. Sulfate ions seem high in conductivity, so I decide to add it my roster. Currently – –NaOH, KOH –K_2SO_4, Na_2SO_4 – pretty high in conductivity and I've encountered these a lot in class chemistry experiments. –I also decide to add NaCL, and KCl to explore these as more common cost-effective options. Couldn't find any direct information of a formula for ionic mobility, I think this is highly relevant since it's the speed of which the ions move through a field. I couldn't find a general table either. The formulas seem to be highly complex and require properties such as drift velocity and electric field in: $u = v/E$. This isn't reliable since it doesn't relate to ionic conductivity (which is, I assume correlated) and therefore I can't use it.	Cool source, ionic conductivity, my next aim is to figure out mobility as it might help predict trends and observations. Added a few more electrolytes to the roster because of their ionic mobility properties and commonness (I was considering to test out perchlorates but a quick search revealed they are very oxidizing and dangerous, this posed a safety hazard and was therefore excluded)
3rd April	Found it!  **(b) Mobility and conductivity** Ionic mobilities provide a link between measurable and theoretical quantities. As a first step we establish in the following *Justification* the following relation between an ion's mobility and its molar conductivity: $\lambda_\pm = zu_\pm F$ Relation between ionic mobility and molar conductivity (20.36)° where F is Faraday's constant ($F = N_A e$).	Began doc! Tried to make it feel academic and professional based off the papers I read online.

Very useful because I can simply divide the ionic conductivity by the ion's charge and Faraday's constant. Source: https://tech.chemistrydocs.com/Books/Physical/Atkins-Physical-Chemistry-9e-by-Peter-Atkins-and-Julio-de-Paula.pdf

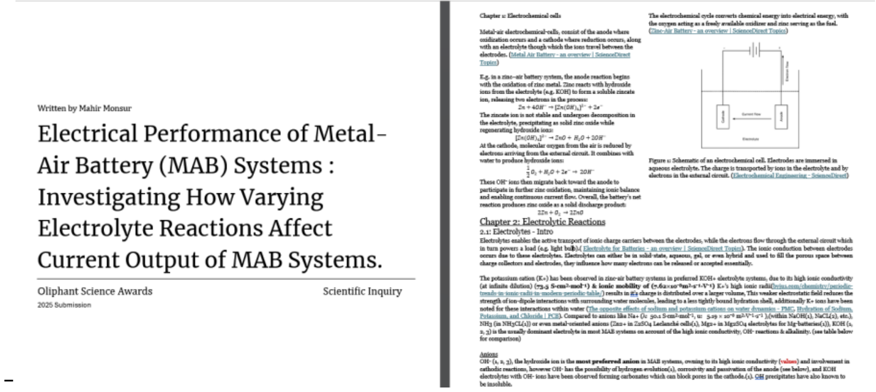
- Also removed sodium counterparts since the experiment would get lengthy (we are testing across various metals as well so just imagine how many batteries I'd need to make)

Made a table on the doc.



Electrolyte	Charge	Type	In aqueous solution	pH (aq)	Ionic conductivity (at infinite dilution) ($S \cdot cm^2 \cdot mol^{-1}$)	Ionic mobility ($m^2 \cdot V^{-1} \cdot s^{-1}$)
KOH	K^+ & OH^-	Strong base	$KOH(s) \rightarrow K^+(aq) + OH^-(aq)$	~13	K^+: 73.5, OH^-: 198.0	K^+: 7.618×10^{-8}, OH^-: 2.052×10^{-7}
K_2CO_3	$2K^+$ & CO_3^{2-}	Basic Salt	$K_2CO_3(s) \rightarrow 2K^+(aq) + CO_3^{2-}(aq)$	~11	K^+: 73.5, CO_3^{2-}: 138.6	K^+: 7.618×10^{-8}, CO_3^{2-}: 7.151×10^{-8}
KCl	K^+ & Cl^-	Neutral Salt	$KCl(s) \rightarrow K^+(aq) + Cl^-(aq)$	7	K^+: 73.5, Cl^-: 76.3	K^+: 7.618×10^{-8}, Cl^-: 7.908×10^{-8}
K_2SO_4	$2K^+$ & SO_4^{2-}	Neutral Salt	$K_2SO_4(s) \rightarrow 2K^+(aq) + SO_4^{2-}(aq)$	7	K^+: 73.5, SO_4^{2-}: 160.0	K^+: 7.618×10^{-8}, SO_4^{2-}: 8.291×10^{-8}

Here's the first rendition,
- Finished intro to metal-air batteries
- Electrolytes (with some missing stuff in brackets)



Written by Mahir Monsur

Electrical Performance of Metal-Air Battery (MAB) Systems : Investigating How Varying Electrolyte Reactions Affect Current Output of MAB Systems.

Oliphant Science Awards Scientific Inquiry
2025 Submission

Chapter 1: Electrochemical cells

Metal-air electrochemical-cells, consist of the anode where oxidization occurs and a cathode where reduction occurs, along with an electrolyte though which the ions travel between the electrodes. (Metal Air Battery - an overview | ScienceDirect Topics)

E.g. in a zinc–air battery system, the anode reaction begins with the oxidation of zinc metal. Zinc reacts with hydroxide ions from the electrolyte (e.g. KOH) to form a soluble zincate ion, releasing two electrons in the process:

$$Zn + 4OH^- \rightarrow [Zn(OH)_4]^{2-} + 2e^-$$

The zincate ion is not stable and undergoes decomposition in the electrolyte, precipitating as solid zinc oxide while regenerating hydroxide ions:

$$[Zn(OH)_4]^{2-} \rightarrow ZnO + H_2O + 2OH^-$$

At the cathode, molecular oxygen from the air is reduced by electrons arriving from the external circuit. It combines with water to produce hydroxide ions:

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

These OH^- ions then migrate back toward the anode to participate in further zinc oxidation, maintaining ionic balance and enabling continuous current flow. Overall, the battery's net reaction produces zinc oxide as a solid discharge product:

$$2Zn + O_2 \rightarrow 2ZnO$$

The electrochemical cycle converts chemical energy into electrical energy, with the oxygen acting as a freely available oxidiser and zinc serving as the fuel. (Zinc-Air Battery - an overview | ScienceDirect Topics)

Figure 1: Schematic of an electrochemical cell. Electrodes are immersed in aqueous electrolyte. The charge is transported by ions in the electrolyte and by electrons in the external circuit. (Electrochemical Engineering - ScienceDirect)

Chapter 2: Electrolytic Reactions

2.1: Electrolytes - Intro

Electrolytes enables the active transport of ionic charge carriers between the electrodes, while the electrons flow through the external circuit which in turn powers a load (e.g. light bulb)(Electrolyte for Batteries - an overview | ScienceDirect Topics). The ionic conduction between electrodes occurs due to these electrolytes. Electrolytes can either be in solid-state, aqueous, gel, or even hybrid and used to fill the porous space between charge collectors and electrodes, they influence how many electrons can be released or accepted essentially.

The potassium cation (K+) has been observed in zinc-air battery systems in preferred KOH+ electrolyte systems, due to its high ionic conductivity (at infinite dilution) **($73.5\ S \cdot cm^2 \cdot mol^{-1}$) & ionic mobility of ($7.62\times10^{-8} m^2 \cdot s^{-1} \cdot V^{-1}$)** K+'s high ionic radii(byjus.com/chemistry/periodic-trends-in-ionic-radii-in-modern-periodic-table/) results in it's charge is distributed over a larger volume, This weaker electrostatic field reduces the strength of ion-dipole interactions with surrounding water molecules, leading to a less tightly bound hydration shell, additionally K+ ions have been noted for these interactions within water (The opposite effects of sodium and potassium cations on water dynamics - PMC, Hydration of Sodium, Potassium, and Chloride | PCB). Compared to anions like Na+ (λ: $50.1\ S \cdot cm^2 \cdot mol^{-1}$, u: $5.19 \times 10^{-8}\ m^2 \cdot V^{-1} \cdot s^{-1}$)(within NaOH(1), NaCL(2), etc.), NH_3 (in NH_3CL(1)) or even metal-oriented anions (Zn2+ in $ZnSO_4$ Leclanché cells(1), Mg2+ in $MgSO_4$ electrolytes for Mg-batteries(1)), KOH (1, 2, 3) is the usually dominant electrolyte in most MAB systems on account of the high ionic conductivity, OH- reactions & alkalinity. (see table below for comparison)

Anions

OH- (1, 2, 3), the hydroxide ion is the **most preferred anion** in MAB systems, owning to its high ionic conductivity (values) and involvement in cathodic reactions, however OH- has the possibility of hydrogen evolution(1), corrosivity and passivation of the anode (see below), and KOH electrolytes with OH- ions have been observed forming carbonates which can block pores in the cathode.(1). OH precipitates have also known to be insoluble.

–

Don't really like the design though – might rework it later.

9th April

Everything was looking pretty good – today I sent a demo of the method and materials to our lab tech and inquired if we could get on conducting.

I was told to refine it more, and that some of the metals weren't available (wanted to test calcium).

Our current roster –
- KOH
- K_2CO_3
- K2SO4
- KCl

Metal roster –
- Zn
- Mg
- Al
- Fe

Since the teachers were busy – there was no one to supervise, so I had to wait until next term.

Graphite sheets weren't available, only rods were, I wasn't allowed to process them either unfortunately.

Ran through with lab tech, got rejected. (This was good though because I learned a lot later)

Unknown (during the holidays)

- Submitted a form application to register my entry.
- Decided to test out multiple combinations, because from literature what I have observed is that electrolytes can be added to other electrolytes for special different purposes.
- Replaced K2SO4 with KI: https://www.sciencedirect.com/science/article/abs/pii/S2352152X23029262 I found this particular literature interesting because it exhibits the redox active nature of the iodide-iodine redox pair, pretty cool, this might have a unique effect on the performance of metal-air batteries, also the conductivity of SO4 is high but the mobility is practically terrible when you consider its divalent anionic nature in relation to the previous formula, this applies for carbonate but I am interested in how carbonate acts as a buffer.

Submitted form entry

K2SO4 replaced with KI

Decide to test combos (expansion)

–Replaced graphite sheet with copper current collector

28th May

Looking back at previous development, I really haven't expanded on metals.
Found out about the metric I'm supposed to be measuring, OCV.

Open-circuit voltage, the voltage of a cell when no current is being ran, the maximum voltage the cell can produce essentially.

That's cool, but I also found out about mAh/g (milliamperes per hour per gram). The capacity of a cell, it's directly relevant because air-cells have considerably high energy capacities, the energy capacity helps determine the cell's energy density (Wh/kg) as well.

https://www.reddit.com/r/batteries/comments/xoddgi/please_help_me_clarify_wh_vs_mah_when_determining/
https://www.omnicharge.co/blogs/blog/mah-vs-watt-hours-whats-the-difference
https://www.batterydesign.net/electrical/open-circuit-voltage/

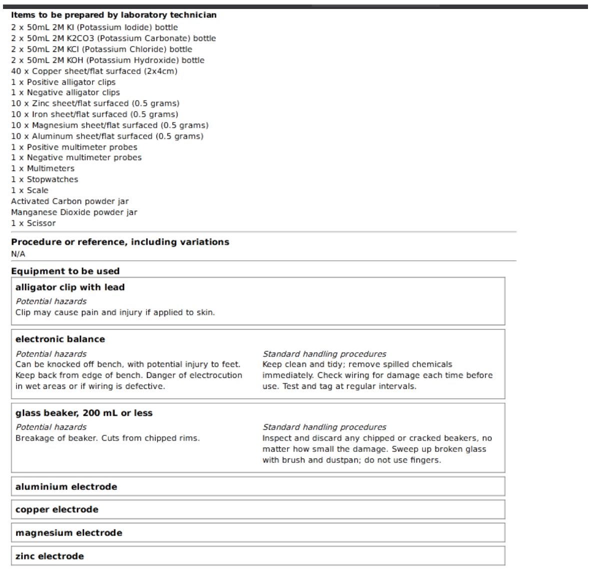
That's difficult to measure, whilst most literature I found uses mah/g and wh/kg, OCV is practically measurable via multimeter. I'm not sure what the latter requires, though I have devised a method.
–Connect cell to a resistor
–Measure voltage at the terminal
–Calculate amps
–Calculate mAh/g and Wh/kg

Though I'm not sure if this is feasible for 16 cells because you would need to record voltage until a cut off voltage is reached, and then use all the values to determine mAh/g.

This would take a lot of time, you would also need a near 1 ohm resistor if you want it to discharge for 10 minutes, even then the power released would be so much that your resistor would overheat. Not practical.

Also, our lab tech supported this and told me to just measure OCV by connecting the terminals to the respective anode and cathode.

Additionally, I talked with one of our coordinators and she said to make a school Risk Assessment.



Items to be prepared by laboratory technician
2 x 50mL 2M KI (Potassium Iodide) bottle
2 x 50mL 2M K2CO3 (Potassium Carbonate) bottle
2 x 50mL 2M KCl (Potassium Chloride) bottle
2 x 50mL 2M KOH (Potassium Hydroxide) bottle
40 x Copper sheet/flat surfaced (2x4cm)
1 x Positive alligator clips
1 x Negative alligator clips
10 x Zinc sheet/flat surfaced (0.5 grams)
10 x Iron sheet/flat surfaced (0.5 grams)
10 x Magnesium sheet/flat surfaced (0.5 grams)
10 x Aluminum sheet/flat surfaced (0.5 grams)
1 x Positive multimeter probes
1 x Negative multimeter probes
1 x Multimeters
1 x Stopwatches
1 x Scale
Activated Carbon powder jar
Manganese Dioxide powder jar
1 x Scissor

Procedure or reference, including variations
N/A

Equipment to be used

alligator clip with lead
Potential hazards
Clip may cause pain and injury if applied to skin.

electronic balance
Potential hazards
Can be knocked off bench, with potential injury to feet. Keep back from edge of bench. Danger of electrocution in wet areas or if wiring is defective.
Standard handling procedures
Keep clean and tidy; remove spilled chemicals immediately. Check wiring for damage each time before use. Test and tag at regular intervals.

glass beaker, 200 mL or less
Potential hazards
Breakage of beaker. Cuts from chipped rims.
Standard handling procedures
Inspect and discard any chipped or cracked beakers, no matter how small the damage. Sweep up broken glass with brush and dustpan; do not use fingers.

aluminium electrode

copper electrode

magnesium electrode

zinc electrode

After I did, dates were set Friday, and early morning on 4th Wednesday.

Contemplating measuring other metrics or not.

30th May

Begin!

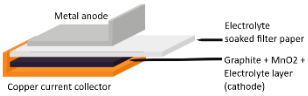
I did it in lunchtime, 12:40-1:25, a relatively small timeframe but for me to make our very first cell. A Zn-air with KCL as the main electrolyte.

Start of data collection

Reading was 0.83 volts, a little lower than expected, but an actual reading, which was pretty exciting, I expected a 0 volt reading to be honest.

No photos though! Didn't bring my phone :(

Though I do have a Chemix diagram (see right)



4th June

Finished the Zinc-air row today.

1.12 for KOH
0.70 for KI
0.83 for KCl
0.71 for K_2CO_3

Didn't get onto double or tri-groups today, unfortunately.

There was a free day on Friday however, our lab tech suggested we could complete it then, which was good news because it meant I had a full day to complete everything.

No photos though! Didn't bring my phone :(

6th June

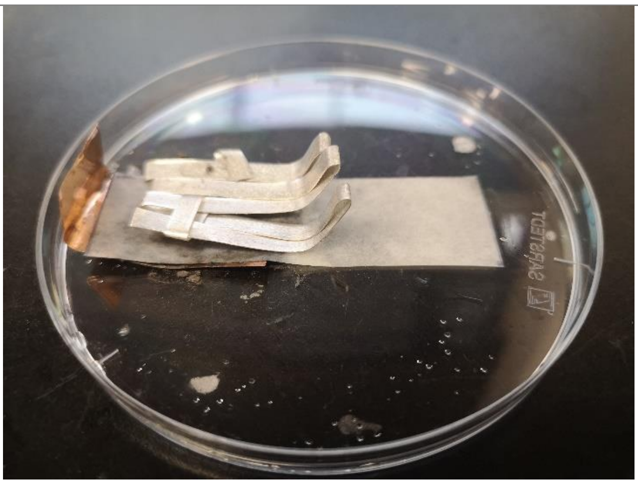
Big day.

Finished –
All Zn
All Al
1st group and 2nd group Mg
2 Fe

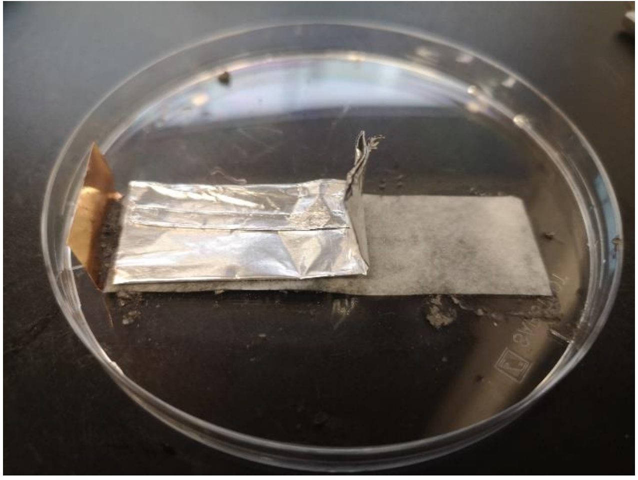
I am starting to notice some pretty nice trends in the results, I don't know why but I particularly expected it to be compromised – although this may be true to an extent (a limitation this is, no trials repeated).

Fe tests were compromised – turns out there wasn't any iron sheets, only iron nails, the iron nails didn't produce any voltage either. This was pretty devastating. Although good news though, there was nickel, there's always nickel.

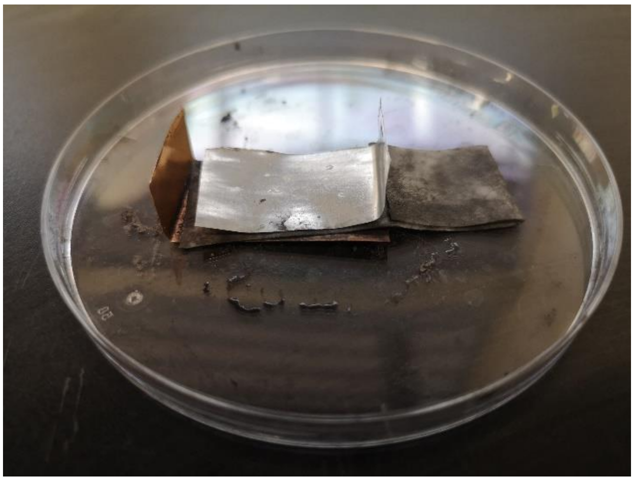
A photo I took on the day showing the assorted items (Note not all items are shown), on the upper-middle of the photo you can see some metals (Zn & Al), the large white packet (not canister) contains magnesium ribbons, with copper right beside.



Here is a pretty cool magnesium-air battery, the rest of the Mg-air cells were highly identical, magnesium came in ribbons, so I had to figure out a way to make it identical to a sheet, it was pretty niche, but I bent the ribbon into a W like shape and wrapped it in another ribbon for holding the shape. Overall, it was stable and gave feasible results.



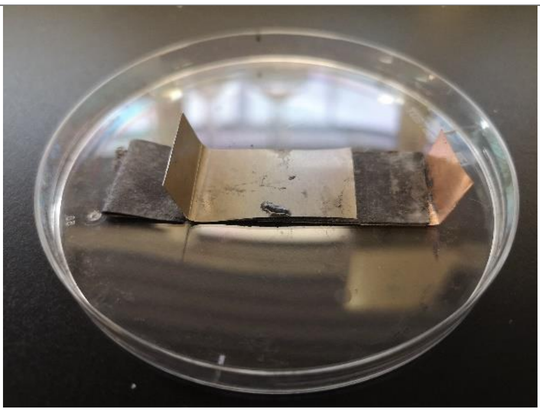
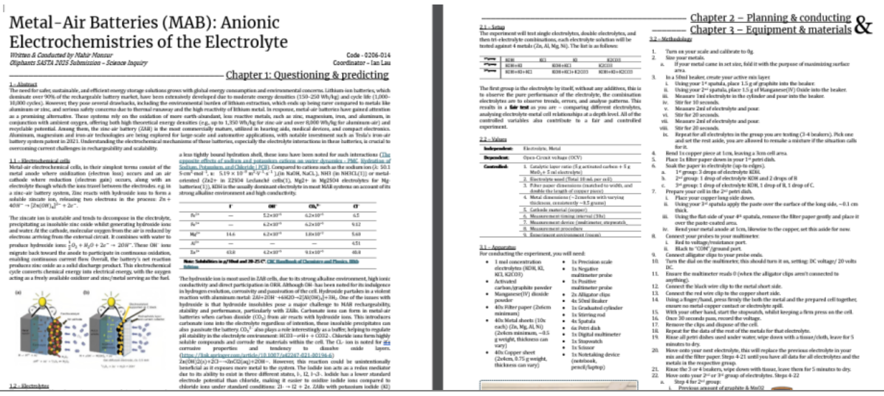
Here is an Al-air cell, you can see I pretty much did the same for aluminum, though it was easier to bend to a sheet form (it came as Aluminum-foil), although aluminum foil is likely to be highly just alumina (aluminum oxide) feasible results were still achieved.

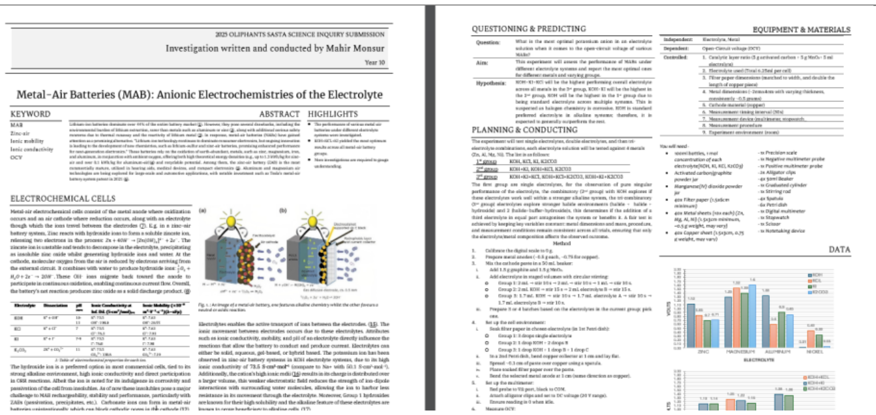


Here is a Zn-air cell! One of the many Zn-air cells, though pressing onto the cell has caused the graphite + MnO_2 + electrolyte layer to disperse through the filter paper, not sure which electrolyte this was, however.

Now, I had to shift my focus to the Ni metal and its properties.

9th June	Got nickel fortunately. Finished 3 Mg cells 1st ever nickel cell.

	 It appeared almost similar to zinc yet with a darker hue, reminiscent of tuna cans which are also sometimes made of predominantly tin.	
10th June	Finished 1st group Ni-air cells. Pretty low voltages, super low. (near ~0) Though not 0 which means there is some sort of voltage. The multimeter was always 0 at rest without any fluctuation to support this.	
11th June	Finished half of 2nd group Ni-air cells	
12th June	Finish 2nd group Ni-air cells	
13th June	Finish 3rd group Ni-air cells	Finished with data collection
23rd June	Haven't touched in a bit –Developed metal properties (source given in orig doc) –Developed ion discussion (solubility of precipitate) –Developed variables, materials and method used Here is the 2nd rendition!  Metal–Air Batteries (MAB): Anionic Electrochemistries of the Electrolyte *Written & Conducted by Nahir Monsur* *Oliphants SASTA 2025 Submission – Science Inquiry* Code – 0206-014 Coordinator – Ian Lau Chapter 1: Questioning & predicting Chapter 2 – Planning & conducting & Chapter 3 – Equipment & materials	Developed 2nd rendition
26th June	Didn't like the style of the 2nd render so I started a new one with the same info and stuff. –Incorporated the data table (I recorded the data on Windows notepad.) –Made graphs –Discussion –Limitations –Evaluation –Bibliography –Appendix –Risk assessment (risks, not the form) 3rd rendition	Developed 3rd rendition

	 2025 OLIPHANTS SASTA SCIENCE INQUIRY SUBMISSION Investigation written and conducted by Mahir Monsur Year 10 Metal-Air Batteries (MAB): Anionic Electrochemistries of the Electrolyte KEYWORD MAB Zinc-air Ionic mobility Ionic conductivity OCV ABSTRACT HIGHLIGHTS ELECTROCHEMICAL CELLS QUESTIONING & PREDICTING PLANNING & CONDUCTING EQUIPMENT & MATERIALS DATA I encountered a bunch of issues with the max word limit, it is harsh I'd say but everything's pretty much done.
28th June	Risk assessment form signed by Mr. Lau.
	The end. Acknowledgments. Thank you to coordinators – Mr. Lau and Ms. Konnie Tolios for helping me out! Thank you to our lab tech – Krishna Currie for helping provide the materials!