XPLORLABS

EXTRACTION TO E-WASTE

EDUCATOR

TEACHER OVERVIEW OF THE MODULE

CASE STUDY OF SCIENCE AND ENGINEERING

SCIENTISTS ASK WHY. ENGINEERS ASK HOW.

AGE GROUP
Secondary School

CATEGORY
Battery Safety

COMPLETION TIME
1–2 Class Periods

BIG QUESTIONS.

- What are the trade-offs we make as we become more dependent on lithium-ion batteries?
- What is a supply chain? What are the links along the supply chain of lithium-ion batteries?
- What are the solutions to the growing epidemic of e-waste?

This module is designed to provide students with the understanding of supply chains, lithium-ion batteries and the phenomenon of thermal runaway, and the problems created by e-waste so they can aspire to the solutions being posed and begin to innovate their own ideas.

The videos and interactive investigations within the Extraction to E-waste module are designed to be applicable in a whole class or for students to engage with independently. Classroom investigations and case studies provide opportunities to deepen students' understandings through hands-on experiences with the principles introduced in the module.

The following guide provides an overview of each section for you, the educator, to provide a road map of the module and supporting content from the lithium-ion battery supply chain.

OVERVIEW OF THE TEACHER'S GUIDE

In this guide, you will find the following:

1. INTRODUCTION: EXTRACTION TO E-WASTE

WELCOME TO THE LITHIUM-ION BATTERY SUPPLY CHAIN!

Safe and sustainable cities will depend on lithium-ion batteries to power our vehicles, store renewable energy, build smarter connected cities and keep us connected through mobile phones. But what are the costs? Where do batteries come from before we get them, and where do they go once they are used? What are the hidden dangers, and what can we do about the problem of e-waste?

Take the journey of a lithium-ion battery, like the one in your phone, from extraction to e-waste to understand what the risks are and what we can do about them.

ENDURING UNDERSTANDINGS

Students will understand:

- How batteries are made from elements that must be mined and manufactured from around the world.
- A supply chain is a series of products and efforts required to create and distribute a product, like mobile phones.
- The life cycle of their phone extends beyond our actual hands-on time.
- E-waste is a global problem with risks to human and environmental health.
- There are solutions to e-waste issues that are within the control of students as well as solutions that they can aspire to.
- Safety science includes the study of lithium-ion batteries, how they are manufactured, and how they are transported.

TRADE-OFFS

Engineering design is a process in which students develop solutions to real-world problems. In order to design a solution, students must first understand the trade-offs behind both the problem and its potential solutions. Students use their knowledge of these trade-offs in order to inform their design: What must change? What are their priorities and constraints?

A trade-off is a relationship between multiple desired outcomes that are at odds with each other. This relationship is resolved through compromise. Trade-offs include factors like cost, convenience, safety, reliability, and aesthetics. They also include potential social, cultural, and environmental impacts.

Throughout the module, we explore the ways that lithium-ion technology and its supply chain can both benefit and harm our communities. Students will need to consider these benefits and harms alike when they experiment with engineering solutions to the problem of e-waste.

2. NEXT GENERATION SCIENCE STANDARDS ALIGNMENT

Extraction to E-waste supports student understandings of the Disciplinary Core Ideas (DCI) from the United States' NGSS Middle School Physical, Life, and Earth Science.

Physical science: matter and its interactions

MS-PS1-3: Gather and make sense of information to describe that synthetic materials come from natural resources and impact society. The DCIs include:

- Obtaining, evaluating, and communicating information
- Structure and properties of matter
- Chemical reactions

Life science: ecosystems: interactions, energy, and dynamics

MS-LS2-4: Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations. The DCIs include:

- Engaging in argument from evidence
- Stability and change
- Ecosystem dynamics, functioning, and resilience

MS-LS2-5: Evaluate competing design solutions for maintaining biodiversity and ecosystem services. The DCIs include:

- Influence of science, engineering, and technology on society and the natural world
- Developing possible solutions

Earth science: Earth and human activity

MS-ESS3-3: Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment. The DCIs include:

- Constructing explanations and designing solutions
- Influence of science, engineering, and technology on society and the natural world
- Human impacts on Earth systems

MS-ESS3-4: Construct an argument supported by evidence about how increases in human population and per capita consumption of natural resources impact Earth's systems.
The DCIs include:

- Engaging in argument from evidence
- Human impacts on Earth systems
- Cause and effect

Engineering design

MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

Performance expectations for students include engaging in analyzing and interpreting data, argument from evidence, and use of these practices to demonstrate understandings of core ideas in PS1, LS2, ESS3, and ESS4. These assessments are built into the main module and are included as discussion questions under each section in the student notebook.

3. WHAT THIS MODULE CONTAINS:

Just like all products, lithium-ion batteries follow a supply chain — a series of steps starting with raw materials and resulting in a product delivered to the end user, or you and your students!

Electronic waste (e-waste) is a result of the supply chain moving in one direction from extraction to disposal.

Historically, this sequence has been seen as a chain where each link is connected in a linear order; each step in the chain supplies the next. To understand this sequence, we will explore the following:

BATTERIES AND SAFE CITIES

In this section, we look at why lithium-ion batteries are an important component for powering modern cities, how lithium-ion batteries function, and some of the risks associated with their production, distribution, use and disposal.

RESOURCE EXTRACTION

In this section, we examine the raw materials that are mined to create a lithium-ion battery, including the methods used to extract and refine these resources.

BATTERY PRODUCTION

A battery is defined as one or more cells in an electrical circuit. In this section, explore how lithium-ion battery cells are made and investigate some of the risks involved in this step of the supply chain.

TRANSPORTATION

Once pouch cells are completed, they must be shipped for the next step of the journey — to the factories that make the mobile phones. In this section, discover the challenges for safety scientists, cargo carriers, and manufacturers including the safest way to package and ship lithium-ion batteries.

USE

Mobile phones are built from many individual parts made all over the world. How do mobile phones with their batteries finally come to us at a size that slips into our pockets?

DISPOSAL

More than 2 billion people currently own a smartphone and that number is expected to increase. Those 2 billion smartphone users upgrade to a new phone roughly every 11-24 months. In this section, investigate what happens to all of those used phones.

SOLUTIONS

Lithium-ion batteries power our lives. This dependence will only increase into the future as new technologies often require lightweight, powerful energy supplies. With benefits come challenges. And with challenges come opportunities to engineer solutions. What solutions can be engineered for these challenges? What are the trade-offs for light, powerful, pocket-sized energy?

As you explore the process of extraction to disposal, can you imagine how waste production would be different if we transformed our supply chain from a linear sequence to a circular one? How can we change the ways our urban infrastructures operate in order to affect this system and the ways we use energy now? How can we design our actions as individuals and groups to make these changes?

In this module, you will explore not only how the battery gets into your mobile phone but also why it is important to understand the chain of events and resources, coming from around the world, that make lithium-ion power possible. Equally important are the trade-offs — what are the benefits of lithium-ion power and what are the risks? What are the true costs of batteries as understood by the issue of e-waste?

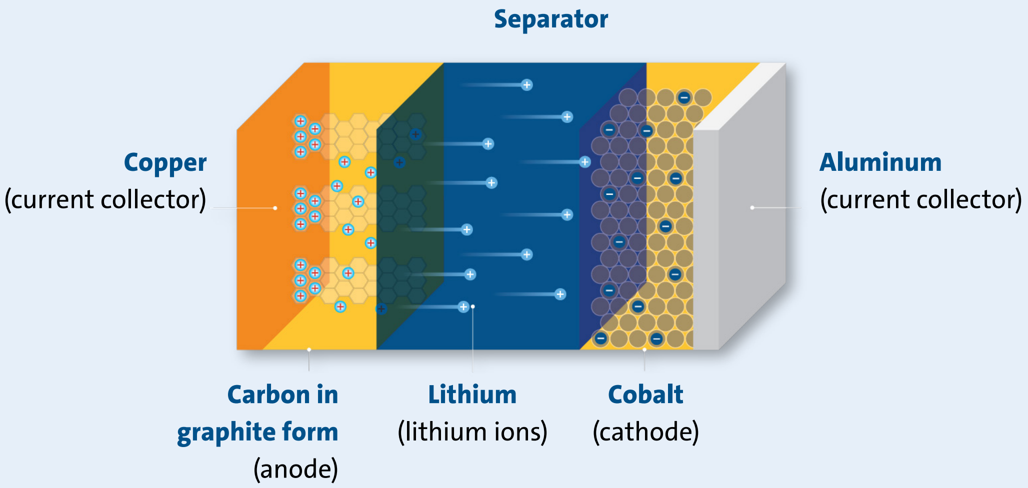
This module will explore:

- Basic lithium-ion power and how lithium-ion batteries work
- The lithium-ion battery supply chain for mobile phones
- The problem of e-waste
- Solutions students can act on
- Solutions being innovated by individuals and organizations around the world

4. BACKGROUND INFORMATION TO EXTEND THE LEARNING

INTRODUCTION — ANATOMY OF A LITHIUM-ION BATTERY

- How a lithium-ion battery works:
  - **a.** Lithium ions (Li+) move between the battery's cathode and anode internally, and electrons move in the opposite direction in the external circuit. This migration is the reason the battery powers the device, because it creates the electrical current.
  - **b.** The movement of the lithium ions creates free electrons in the anode, which creates a charge at the positive current collector. The electrical current then flows from the current collector through the device being powered, like a cellphone or laptop computer, to the negative current collector. The separator facilitates the flow of ions inside the battery.
  - **c.** While the battery is discharging and providing an electric current, the anode releases lithium ions to the cathode, generating a flow of electrons from one side to the other. When the device is plugged into an electrical outlet, the opposite occurs: lithium ions are released by the cathode and received by the anode.
- Components of a lithium-ion battery:
  - **a. Anode:** the negative electrode. Stores lithium while the electrolyte carries lithium ions.
  - **b. Cathode:** the positive electrode. Stores lithium while the electrolyte carries lithium ions.
  - **c. Electrolyte:** Carries positively charged lithium ions from the anode to the cathode and vice versa through the separator. The movement of these lithium ions creates a charge.
  - **d. Separator:** A thin membrane of porous plastic that separates the anode and cathode. It enables and blocks the exchange of electrically charged ions from one side to the other. If the separator is damaged, that can cause an internal short circuit, and eventually thermal runaway.
  - **e. Current collector:** A conductive foil at each electrode of the battery. The current collectors transmit an electric current between the battery, the device, and the energy source that powers the battery.



- **Benefits** of lithium-ion batteries:
  - **a.** Lithium-ion batteries have the capacity to be small and powerful; they have a great energy density.
  - **b.** Lithium-ion batteries empower us to be flexible with energy storage. They make it easier to have on-the-go energy in portable products. They also enable us to store more energy from renewable sources, including wind and solar power.
- Where lithium-ion batteries are in our communities:
  - **a.** Lithium-ion batteries are prevalent. In the module cityscape, we examine electric vehicles, drones, public transit, headphones, hoverboards, power tools, power banks, satellites, laptops, wearable tech, solar panels, medical devices, and mobile phones… each powered by lithium-ion batteries.
- **Risks** associated with lithium-ion batteries:
  - **a.** Throughout the lithium-ion battery supply chain, there are risks and trade-offs.
  - **b.** One of the primary risks related to lithium-ion batteries is thermal runaway. Thermal runaway is an exothermic reaction that can occur as a result of damage within the battery like an internal short circuit, caused when the separator of the battery is damaged and the anode and cathode make contact with one another.

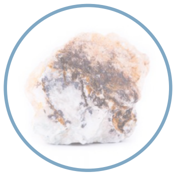
Only when the cell is/cells are installed inside the device (phone, tablet or laptop) along with its protective circuit board, it is referred to as a battery. Before that, it is referred to as a cell.

Once a cell is manufactured, it is sent to the battery manufacturer. The battery manufacturer can be the same as the cell manufacturer or someone in another city or country in the world. The cells are then assembled into batteries that also have a protective circuit board.

> *Lithium-ion batteries can contain single cells and a protective circuit board or multiple cells and a protective circuit board.*
>
> *— Dr. Judy Jeevarajan*
> *Research Director, Electrochemical Safety,*
> *Underwriters Laboratories*

RESOURCE EXTRACTION

- Resources are used to make a lithium-ion battery:
  - **a.** Different kinds of devices use different kinds and chemistries of lithium-ion batteries, depending on requirements for power, capacity, and size.
    - **i.** The kind of lithium-ion battery commonly used in mobile phones has a lithium cobalt oxide chemistry, also known as $LiCoO_2$ or “LCO.”



b. In this module, we are examining five of the materials used in this kind of lithium-ion battery:

  - **i. Aluminum:** used as a current collector at the cathode of the battery
  - **ii. Cobalt:** used in the cathode of the battery
  - **iii. Copper:** used as a current collector at the anode of the battery
  - **iv. Carbon** in the form of **graphite:** used in the anode of the battery
  - **v. Lithium:**
    - Lithium in the form of **lithium ions (Li+)** moves between electrodes. Li+ ions move between the battery's cathode and anode internally, and electrons move in the opposite direction in the external circuit. This migration is the reason the battery powers the device, because it creates the electrical current.
    - Lithium in the form of an **oxide ($LiCoO_2$ or Lithium cobalt oxide)** is used as the active component of the cathode.

c. Specific elements in mobile phone:

  - **i.** Aluminum
  - **ii.** Cobalt
  - **iii.** Copper
  - **iv.** Graphite/Carbon
  - **v.** Lithium

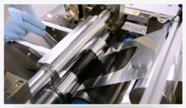
- Processes of extracting these resources:
  - **a. Open-pit mining:** Open-pit mining uses a descending set of ledges dug into the ground. Borers drill holes into the rock. Explosives are inserted into these holes to break the rock into boulders, which are then hauled away to be processed (aluminum, cobalt, copper, and natural graphite).
  - **b. Brine extraction:** Brine extraction is a method in which miners pump groundwater to the surface that collects into ponds. Here, they wait for the water to evaporate under the sun's heat. Left behind is a sludge brine residue, which contains the desired mineral (lithium).
- Environmental and health **risks** related to extracting these resources:
  - **a. Open-pit mining** impacts the environment, and impacts people too. First, in order to make way for an open pit, vegetation must be cleared away. Then, a deep pit is dug. Together, these factors create conditions for erosion. Mining can create toxic soils and dust with high concentrations of heavy metals like copper and nickel. These dusts are carried by wind into water supplies, crops, and the air. Breathing in, eating food, or drinking water with this contamination puts people and animals at a higher risk of illness.
  - **b. Brine extraction** impacts the environment, and impacts people too. Brine extraction drains water from natural underground reserves of drinking water. This water is depleted from the ecosystem more quickly than it can be replaced through the water cycle. Brine extraction requires toxic chemicals to process lithium. Release of these chemicals harms air, soil, and water quality.

BATTERY PRODUCTION

- Mobile phones use a format of lithium-ion battery known as a **pouch cell**. Pouch cell lithium-ion batteries are used for their relative flexibility.
- Process of producing a lithium-ion pouch cell:

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

1. Powders containing the active materials in electrodes are mixed in a big bowl with binding materials, which act like a glue to create what scientists call a slurry, or a paste.
    - **i.** This paste will become the electrode — the anode or cathode — of the battery.
    - **ii.** In your mobile phone battery, the electrode active materials are likely lithium cobalt oxide and carbon at the cathode, and graphite at the anode.



VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

2. The slurry is then spread out onto a very long piece of foil, which slowly rolls through high heat. This heat (up to 300 degrees Fahrenheit; 149 degrees Celsius) bakes the electrode into a solid and sticks the paste to the foil. The foil becomes a current collector attached to the electrode paste.
    - **i.** In your mobile phone battery, the foil is made of aluminum at the cathode and copper at the anode.

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

3. The baked electrode roll is cut into smaller pieces, which are placed under a super-sharp, rectangular die. With a sudden movement, the die quickly pushes down on the electrode sheet and cuts out an individual electrode battery piece.

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

4. An automated machine uses suction to pick up and release sheets of cut-out electrode material and wrap an insulating layer in between each sheet. The result is a credit card-sized electrode stack, which is spit out of the machine with the turn of a metal arm.
    - **i.** Several configurations are available for battery assembly.
    - **ii.** In this configuration for a pouch cell battery, layers are stacked like a cake: anode, separator, cathode, another separator.
    - **iii.** In another configuration, layers may be rolled rather than stacked. The foils are wound into a “jelly roll” of alternating layers: again, anode, separator, cathode, separator.

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

5. A special plastic, moisture-resistant barrier material is pressed to create rectangular pouches. The electrode stack is inserted into the resulting pouch to create a pouch cell.
    - **i.** This pouch is made of aluminized plastic.

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

6. The pouch is injected with a liquid electrolyte.
    - **i.** The electrolyte allows the continuous movement of lithium ions (Li+) during cell operation.
    - **ii.** In your mobile phone battery, the electrolyte is made of organic carbonates and a salt.

BATTERY PRODUCTION CONTINUED

VIDEO PROVIDED COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

7. The electrolyte-soaked battery pouch is heat-sealed and placed in a vacuum chamber, which removes gases from inside the pouch.
8. Throughout the process and after sealing, the battery is subject to testing for safety and performance.
   i. These tests are detailed below, under “precautions against these risks.”

- **Risks** involved with producing a lithium-ion battery:
  a. **Internal short-circuiting:** During the manufacturing process of a lithium-ion battery pouch cell, internal short-circuiting may occur. This can be caused by a multitude of factors including: too much moisture in the room; burrs; weld splatter; iron particles from the mixer entering slurry; etc. Internal short-circuiting leads to performance issues, overheating, fires, and sometimes thermal runaway.
  b. **Contamination:** If contaminants – including water – enter the pouch cell during manufacturing, it is possible that there will be performance issues and/or safety issues with the battery. Some potential outcomes are swelling and short circuits. During the manufacturing process attention is focused on a latent or hidden defect that could be formed in the cell. This hidden defect can gradually create an internal short circuit while the battery is in use. These defects are often contaminants like water or iron flakes from manufacturing machinery.
  c. **Lithium dendrites:** Dendrites of lithium metal naturally form within pouch batteries as a byproduct of aging. A strong exothermic reaction could result if these dendrites puncture the separator or come into contact with water.
  d. **Burrs:** If material is cut with a dull blade, “burrs” – jagged edges – can result. If these burrs puncture the separator, a strong exothermic reaction will occur.
  e. **Swelling:** Pouch batteries are prone to a bit of natural swelling, but sometimes they will overswell upon excessive heat or contamination. Swelling is primarily a performance issue based on faulty manufacturing and can have safety ramifications. A punctured swelled pouch battery will release flammable gases. A swelling battery is indicative of internal short-circuiting and overheating.
  f. **Thinning separator and insulation:** The separator acts as an insulator between the cathode and anode, but it is porous enough to let ions flow through. Under heat, the pores close up and ions stop migrating. This is known as “shutdown.” This insulation helps prevent thermal runaway. As devices become thinner and demand increasingly powerful batteries, battery separators and other internal insulators are becoming thinner as well.
     i. The utility of this thinness is twofold: it accommodates device size constraints and allows room for more active material within the battery, which increases the battery’s power capacity. Unfortunately, a thinner separator reduces insulation for the battery, reducing its safety, too.
  g. **Fires:** Fires are a risk at battery manufacturing facilities due to the high concentration of flammable materials stored at the facilities and the kind of abuse testing performed on the batteries.
  h. **Nanomaterials:** Nanomaterials are extremely fine particles of material. Some lithium-ion battery manufacturers are using nanomaterials as manufacturing materials to help bolster

the battery's performance. The concern comes from the risk to people working in manufacturing facilities. There is little knowledge of the extent of nanomaterials' potential human and environmental health risks other than they can be easily inhaled or ingested through the skin.

- Precautions against these risks:
    a. **Maintain clean facilities and equipment:** Maintaining clean facilities and equipment helps prevent contamination of pouch cells and in turn prevents swelling and short-circuiting. Part of the manufacturing process takes place in a special low-humidity room.
    b. **Automation:** Automation removes some of the human error from the manufacturing process and helps standardize production. It also helps protect people from contact with nanomaterials and other hazardous materials exposed during battery manufacturing.
    c. **Integrity testing:** During the process of winding or stacking cell layers, a short-circuit detector is used.
    d. **Production line sample testing:** Throughout the manufacturing process, battery cell samples are pulled out of the production line, examined, and subjected to testing. Testing ranges from abuse tests to measuring the battery's weight and dimensions; manufacturers also look for signs of electrolyte leakage. After formation and sorting (see below), tear down analysis (also below) is performed as part of this sampling procedure.
    e. **X-ray pouch materials:** After placing rolled electrode layers in the unsealed pouch, manufacturers X-ray the pouch materials to ensure that each component is assembled correctly and that the layers are rolled to the proper tension. (If the roll is too loose, the layers can become mashed and bent. If too tight, tension can cause damage.)
    f. **Formation testing:** This test is done after the pouch is sealed. "Formation" is the process of testing a cell's capacity and performance, it is the first charging and discharging of the battery cell. During formation, lithium ions are embedded in the crystal structure of the graphite on the anode side, causing the solid electrolyte interface (SEI) to form, which creates an interface layer between the electrolyte and the electrode.
    g. **Impedance performance cycle analysis:** If the resistance is low within the circuit, then the current can cause a short circuit, resulting in thermal damage to the battery pouch. During this analysis, the battery is tested for its internal resistance to a current.
    h. **Sorting or aging:** Aging is the final step in the manufacturing process. This step is done to sort out the weaker cells and is used for quality assurance. During the process, the battery is monitored by regularly measuring the open circuit voltage (OCV) for up to three weeks. If the voltage drops over that time, or the capacity is not where it should be, this could be a sign of internal shorting or other problems. No significant change in the battery cell properties means the battery is fully functional and can be delivered to the customer.
    i. **Tear down analysis:** Cells that are rejected as part of the formation and sorting process are torn down and analyzed. They are extensively screened for visual, physical, and other defects to determine internal problems like poor coating coverage. These problems are then acted upon.

TRANSPORTATION

- **Risks** involved with transporting a lithium-ion battery:
    - **a.** When a lithium-ion battery is not designed or handled the right way, the battery can undergo thermal runaway. In this state, the lithium-ion battery can smoke, catch fire, or explode. If that battery is in the cargo hold of a plane, the fire is difficult to reach. If that battery is near other lithium-ion powered devices or dangerous goods, it is a more difficult problem to solve.
    - **b.** Mislabeled and unlabeled boxes are dangerous because they may not be packaged or handled properly.
- Precautions against these risks:
    - **a.** **International Civil Aviation Organization (ICAO)** is a United Nations specialized agency. ICAO designates lithium-ion batteries as a Dangerous Good, which is defined as articles or substances that are capable of posing a risk to health, safety, property or the environment; and can pose a safety risk if not prepared and shipped in compliance with international transport regulations.
    - **b.** To address the safety and performance of the batteries before they can be transported, batteries are put through rigorous safety tests including: crush tests, altitude simulations, nail tests, short circuit simulations, projectile tests, thermal, vibration, shock, impact and overcharge tests, and a forced discharge test.
    - **c.** Additionally, they must meet the following criteria when being packaged and shipped:
        - **i.** Lithium-ion batteries must be at no more than a 30% state of charge when shipped. (This does not include batteries that are installed inside a device.)
        - **ii.** Packages must be secured to protect batteries from shifting, short-circuiting, activating, and being damaged by other package contents
        - **iii.** Packages that contain lithium-ion batteries must be clearly marked.

USE

- Throughout this module, we have been examining the supply chain of a lithium-ion battery inside a mobile phone. It is important to note that mobile phones consist of a multitude of components, each of which has a supply chain of its own. The supply chain of a mobile phone is complex.
- Mobile phone design and manufacturing:
    - **a.** Mobile phones are becoming smaller, thinner, and more powerful. Because of this, they require batteries that are also smaller, thinner, and more powerful.
    - **b.** Manufacturers sometimes make sacrifices to fit batteries into the phones and to keep them in place. These trade-offs, like gluing and fusing pieces of the phone together, make it more difficult to repair and recycle the phones.
- Mobile phone use:
    - **a.** The way that we use our mobile phones has implications for how long the mobile phones, and the batteries inside them, will be able to last.

b. When devices are dropped, crushed, and exposed to extreme conditions, the batteries inside of them face an increased risk of thermal runaway.

c. Taking good care of mobile phones can extend the life of many of the components inside.

DISPOSAL

- E-waste:

    a. **E-waste**, or electronic waste, is a term that refers to any electronic device that has been disposed of. This includes mobile phones.

- **Improper disposal:**

    a. The things we place in the mainstream waste and recycling program can be damaged. In garbage trucks and waste facilities, discarded items including mobile phones are dropped, crushed, scraped, and punctured during the disposal process. This kind of damage may not sound like much, but it could be disastrous when the discarded item contains a lithium-ion battery.

    b. Dropping, crushing, scraping, and puncturing a battery can damage a battery's separator and allow the chemicals inside to mix in an uncontrolled way: an internal short circuit. This causes the battery to heat up and undergo thermal runaway. It can trigger a fire or even an explosion at waste and recycling facilities, and in vehicles.

- **Risks** from burning e-waste:

    a. Burning e-waste, especially in the open air, presents health effects. One prevalent health effect related to burning e-waste is respiratory illness. This comes as a result of inhaling the fumes of burning e-waste and related dusts.

    b. Additionally, these fumes are toxic. Electronic devices contain toxic materials like heavy metals. For instance, arsenic, mercury and lead can all be found in mobile phone components.

        i. Children living in e-waste recycling communities such as Guiyu, China, have been found to have significantly higher levels of lead in their blood than children living elsewhere, which stunts development, causes illness, and can be fatal.

        ii. It is not just the toxic metals that present a problem. Burning waste plastic materials releases highly toxic particulates, too.

    c. Why would crops grown near these areas be of concern? (Answer: they store contaminants.)

        i. Near e-waste burn sites, there is relatively heavy soil contamination that surpasses European Union (EU) and United States Environmental Protection Agency (U.S. EPA) regulatory limits on copper/lead in soils. Rainwater leaches these heavy metals into surface waters used for domestic purposes. There is subsequent contamination of plants that reside in these soils. Crops that are farmed near polluted areas absorb pollutants. Ingestion of these fruits and vegetables contributes to significant lead intake.

- **Proper disposal:**

    a. The U.S. EPA recommends that instead of throwing away mobile phones, we should trade them in or take them to an electronics retail store that then sends them to a specific, professional recycler who handles e-waste safely and sustainably.

    b. Before recycling your electronics, make sure that you have completely removed your personal information from the device. This is more complicated than just deleting files; check out the guides in the appendix for more information.

5. APPENDIX OF RESOURCES

WHAT'S IN THE APPENDIX:

5A. PROMPTS FOR STUDENT DISCUSSIONS

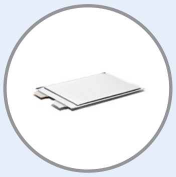
These questions are posed throughout the Student Guide. They can be used to prompt reflection and discussion between students. They may also be extended to create classroom or individual investigations. Here, the questions are listed under the Student Guide section where they can be found.

00 Introduction: Anatomy of a lithium-ion battery

- Name two devices that use lithium-ion batteries.
- How would you define thermal runaway?
- What are the benefits of lithium-ion batteries?
- What are the risks of lithium-ion batteries?

01 Resource extraction: Where the supply chain begins

- How would you compare open pit mining and brine extraction mining methods? (Set up as t-chart or open response)
- What impacts on the land did you observe at the open-pit mines over time? What year did the changes increase? What else was happening at that time?



02 From raw materials to battery cells

- Describe how a pouch cell battery is made?
- What is an exothermic reaction?
- What are the defects that can cause a short circuit?
- How would this be a problem later on in the supply chain or when the device is in your hands?

03 Shipping and transporting batteries to assemble your mobile phone

- Why is it necessary for shippers to follow specific rules when it comes to shipping lithium-ion batteries?

04 The mobile phone has finally arrived

- What is the first thing people commonly do when they get a new phone?
- What are some ways that short-circuiting and thermal runaway can be triggered?
- How can you use your mobile phone to avoid these risks?
- Based on what you have seen so far throughout the supply chain, what are some unintended consequences that come with getting a new phone?

05 What happens to batteries and our devices when we no longer use them?

- Check out the map of global e-waste flows. How much e-waste does your country generate every year? Where does this e-waste end up?
- Investigate the photo of Utah, United States. E-waste is not just limited to phones but includes all electronics like large ones such as televisions, computers and car parts. This is an image from the United States. What do you see? What is the main electronic in this burned e-waste? What do you think are the health impacts?
- Investigate the photo of Lagos, Nigeria. E-waste is sometimes piled up with other trash. What are the electronics? What other trash do you see? Without judgment of the people who live there, make some predictions about the environmental and health impacts of this scenario.
- As we have seen, e-waste is a major problem now, and it is only expected to get worse. As we go from producing 50 million metric tons a year to 120 million metric tons in the next 30 years, what will the impacts be? Are there ways to reduce the amount of e-waste we produce? Are there better approaches to the extraction, manufacturing, transportation, use, and disposal of our mobile devices and other electronics that can make a difference?
- Based on your observations of the battery supply chain, which part of that chain do you think requires the most urgent or immediate attention?
    - Resource extraction
    - Battery manufacturing
    - Transport
    - Disposal
- Why? Explain your answer.
- See how these issues are being solved right now! (Click through to solutions page)

Solutions

- After watching the videos, what are some actions you can take to help solve the problem of e-waste?
- What solutions are others working on that inspire you? What do you find interesting? What do you still have questions about?

5B. GLOSSARY OF TERMS

Anode: The negative electrode of a battery.

Battery: One or more cells in an electrical circuit.

Cathode: The positive electrode of a battery.

Current collector: A conductive foil at each electrode of the battery. The current collectors transmit an electric current between the battery, the device, and the energy source that powers the battery.

Delivery: The stage of the supply chain when the product reaches the end user.

E-waste: Electronic waste; any electronic device (powered by a battery or cord) that has been disposed of.

Electrode: The positively or negatively charged end of a battery. Attached to a current collector that transmits the current to the device.

Electrolyte: A liquid or gel that conducts electricity. The electrolyte allows the continuous movement of lithium ions (Li+) during cell operation.

Exothermic reaction: A type of chemical reaction that releases heat.

Extraction: The process of removing raw materials from the Earth to create a product.

Internal short circuit: When the anode and cathode of the battery cell come into contact with each other.

Lithium-ion battery: A type of battery that is powered by the movement of lithium ions between electrodes. Lithium-ion batteries have many uses, one of which is powering our mobile phones.

Manufacturing: The process of creating a product.

Separator: A porous plastic film that “separates” the electrodes while enabling the exchange of lithium ions from one side to the other.

Supply chain: The series of steps a product goes through to reach an end user.

Thermal runaway: A rapid, uncontrolled increase in temperature causing additional increases in temperature, usually resulting in a hazardous situation.

Transportation: The process of moving a product from one place to another.

Tonne: A metric ton equal to 1,000 kilograms.

5C. UL'S ON THE MARK STUDENT READINGS

On the Mark is a publication created to explore the intersection of safety science and technology. This rich resource offers students nonfiction readings to extend their learning. The Lithium-ion Battery Issue of On the Mark, published in Fall 2018, can be downloaded as a PDF from the homepage of this module or here.

(Sorted by reference order in the teacher guide)

- On the Mark: "Take a Look Inside," pp. 8-9
  Describes the current applications and advantages of lithium-ion technology
- On the Mark: "Lithium-ion Batteries by the Numbers," pp. 11-13
  Facts and figures related to lithium and lithium-ion batteries
- On the Mark: "Lithium-Ion Timeline," pp. 14-19
  A timeline of developments in lithium-ion battery design and a profile of the Nobel Laureate "father of lithium-ion batteries" John Goodenough
- On the Mark: "Rays of Light," pp. 29-30
  Describes the relationship between lithium-ion batteries and solar power
- On the Mark: "On the Road," pp. 31-35
  Discusses how lithium-ion batteries, by storing portable power, make travel more convenient and feasible
- On the Mark: "It's a Lithium World," pp. 4-7
  Describes the current applications and advantages of lithium-ion technology
- On the Mark: "Towers of Power," pp. 26-28
  Discusses the costs, benefits, and other factors that should be considered when planning to incorporate lithium-ion batteries into our lives
- On the Mark: "Lithium-Ion Issues," pp. 36-37
  Describes risks and issues associated with lithium-ion batteries
- On the Mark: "The Mark of Safety," pp. 38-41
  Describes how UL sets Standards and tests lithium-ion batteries for safety
- On the Mark: "Getting on the Grid," pp. 20-25
  Describes lithium-ion microgrids and how they contribute to resilience in the face of an emergency such as a natural disaster

(Sorted by order in On the Mark (OTM))

- On the Mark: "It's a Lithium World," pp. 4-7
  Describes the current applications and advantages of lithium-ion technology
- On the Mark: "Take a Look Inside," pp. 8-9
  Describes how lithium-ion batteries work. Illustrates each component of the battery during charge and discharge.
- On the Mark: "Lithium-Ion Batteries by the Numbers," pp. 11-13
  Facts and figures related to lithium and lithium-ion batteries

- On the Mark: “Lithium-Ion Timeline,” pp. 14-19

  A timeline of developments in lithium-ion battery design and a profile of the Nobel Laureate “father of lithium-ion batteries” John Goodenough
- On the Mark: “Getting on the Grid,” pp. 20-25

  Describes lithium-ion microgrids and how they contribute to resilience in the face of an emergency such as a natural disaster
- On the Mark: “Towers of Power,” pp. 26-28

  Discusses the costs, benefits, and other factors that should be considered when planning to incorporate lithium-ion batteries into our lives
- On the Mark: “Rays of Light,” pp. 29-30

  Describes the relationship between lithium-ion batteries and solar power
- On the Mark: “On the Road,” pp. 31-35

  Discusses how lithium-ion batteries, by storing portable power, make travel more convenient and feasible
- On the Mark: “Lithium-Ion Issues,” pp. 36-37

  Describes risks and issues associated with lithium-ion batteries
- On the Mark: “The Mark of Safety,” pp. 38-41

  Describes how UL sets Standards and tests lithium-ion batteries for safety
- On the Mark: “The Green Scene,” pp. 42-47

  Describes the environmental risks of lithium mining

5D. EXTERNAL RESOURCES: (SORTED BY REFERENCE ORDER IN TEACHER GUIDE)

INTRODUCTION

- External resource: United Nations, “Goal 11: Sustainable Cities and Communities”

  Explains the reasoning behind UN Sustainable Development Goal (SDG) 11, highlights relevant statistics, and lists the goal targets. Links to case studies that describe SDG 11 in action
- External resource: UL Xplorlabs: Portable Electrical Power

  This UL Xplorlabs module encourages students to use scientific inquiry to engage with portable electrical power, teaching them how batteries convert energy and introducing the phenomenon of thermal runaway.

EXTRACTION

- External resource: National Museums Scotland, “From Minerals to your Mobile”

  Uses the periodic table to show which elements and minerals are used in each component of a mobile phone

- Wikimedia Commons, Periodic Table of the Elements.
- Specific elements in mobile phone:
  - Aluminum
    - External resource: USGS, "Aluminum (Mineral Commodities Survey)" (2019)
      Summary of aluminum production trends in the year 2018
  - Cobalt
    - External resource: USGS, "Cobalt (Mineral Commodities Survey)" (2019)
      Summary of cobalt production trends in the year 2018
    - External resource: USGS, "Cobalt: For Strength and Color" (2011)
      Brief fact sheet that describes how and why cobalt is used; where cobalt comes from; and supply and demand trends for cobalt
    - External resource: USGS, "Cobalt" (2017)
      Extensive guide to cobalt: cobalt's uses, geology, production, and relevant environmental considerations
  - Copper
    - External resource: USGS, "Copper (Mineral Commodities Survey)" (2019)
      Summary of copper production trends in the year 2018
    - External resource: USGS, "Copper: A Metal for the Ages" (2009)
      Brief fact sheet that describes how and why copper is used; where copper comes from; and supply and demand trends for copper
  - Graphite/Carbon
    - External resource: USGS, "Graphite (Natural) (Mineral Commodities Survey)" (2019)
      Summary of natural graphite production trends in the year 2018
    - External resource: USGS, "Graphite" (2017)
      Extensive guide to graphite: graphite's uses, geology, production, and relevant environmental considerations
  - Lithium
    - External resource: USGS, "Lithium (Mineral Commodities Survey)" (2019)
      Summary of lithium production trends in the year 2018
    - External resource: USGS, "Lithium Use in Batteries" (2012)
      Extensive guide to lithium: why it is used in batteries, effects on supply and demand, summaries of lithium production and recycling, and types of lithium-ion batteries and their applications
    - External resource: USGS, "Lithium: For Harnessing Renewable Energy" (2014)
      Brief fact sheet that describes how and why lithium is used; where lithium comes from; and supply and demand trends for lithium
    - External resource: USGS, "Lithium" (2017)
      Extensive guide to lithium: lithium's uses, geology, production, and relevant environmental considerations
- External resource: USGS, "The Life Cycle of a Mineral Deposit: A Teacher's Guide for Hands-On Mineral Education Activities" (2005)
  An introduction to mineral deposits. 10 hands-on investigative activities aimed at students in grades 5-8

- External resource: MIT, “Environmental Risks of Mining” (2012)
  Describes environmental hazards associated with different forms of mining and resource extraction
- External resource: WEF, “A New Circular Vision for Electronics” (2019)
  Includes infographics and text detailing the environmental risks associated with mining, mapping e-waste flows, describing impacts of e-waste, and mapping a circular economy

BATTERY PRODUCTION

- External resource: PNNL/DOE, “How to Make a Battery in 7 Steps” (2016)
  This is the source of the video and some text that we use during the Battery Manufacturing stage of the module. Details the process — with video and text — of manufacturing a lithium-ion pouch cell battery
- External resource: NIH NIEHS, “Nanomaterials” (2019)
  Explains nanomaterials, a type of material used in mobile phones and other electronics
- External resource: MEL Science, “Properties of Lithium, and the Reactions of Water and Certain Acids with Lithium”
  Describes chemical and physical properties of lithium. Lists chemical reactions between lithium and various acids, and reaction between lithium and water (including video)

TRANSPORTATION

- External Link: PHMSA, “Transporting Lithium Batteries” (2019)
  Brief page explaining why lithium-ion battery transportation is regulated, with links to resources for shippers, manufacturers, airline passengers, and general consumer product safety, including battery recycling
- External Link: PHMSA: “Shipping Batteries Safely by Air: What You Need to Know” (2018)
  Thorough, illustrated guide about battery transportation. Details why batteries are regulated, examples and classifications of different lithium-ion batteries, and the requirements that apply to each type of battery

USE

- External resource: National Museums Scotland, “From Minerals to your Mobile”
  Uses the periodic table to show which elements and minerals are used in each component of a mobile phone
- External resource: The New York Times, “An iPhone’s Journey, From the Factory Floor to the Retail Store” (2016)
  Briefly describes the supply chain of a mobile phone from component sourcing to shipping

DISPOSAL

- External resource: BBC, “Your Old Phone is Full of Untapped Precious Metals” (2016)
  Discusses the precious materials inside a mobile phone, common methods of extracting these materials, and the global rate at which mobile phones are becoming e-waste.
- External resource: WEF, “A New Circular Vision for Electronics” (2019)
  Includes infographics and text detailing the environmental risks associated with mining, mapping e-waste flows, describing impacts of e-waste, and mapping a circular economy
- External resource: Reviews on Environmental Health, “Prevention-Intervention Strategies to Reduce Exposure to E-Waste” (2018)
  Several case studies of e-waste and informal recycling; includes site descriptions, accounts of human health and environmental impacts, and applied intervention approaches
- External resource: Citylab, “The Toxic Effects of Electronic Waste in Accra, Ghana” (2019)
  Describes the effects of e-waste and informal recycling on a site in Accra, Ghana, where much e-waste is dumped
- External resource: The Guardian, “Toxic ‘E-Waste’ Dumped in Poor Nations, Says United Nations” (2013)
  Describes the global e-waste industry and some of the relevant harms
- External resource: Panda Security, “The Complete Guide to Recycling Electronics” (2019)
  Includes infographics about e-waste and disposing of a mobile phone. Also provides a step-by-step guide to donating, reselling, or otherwise disposing of your devices and list of services that accept reused mobile phones
- External resource: U.S. EPA, “The Secret Life of a Cell Phone” (2017)
  Infographic about considerations to take when purchasing, donating, reselling, or otherwise disposing of a mobile phone
- External resource: Consumer Reports, “How to Recycle Old Electronics” (2018)
  Explains different options for donating, reselling, or otherwise disposing of your devices
- External resource: Consumer Reports, “Wiping Clean Personal Data off Your Devices” (2015)
  Explains how to erase data from a device with cybersecurity in mind before donating, reselling, or otherwise disposing of the device

The Periodic Table of the Elements

by Robert Campion version 1.4

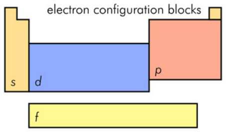
atomic mass or most stable mass number	55.845
1st ionization energy in kJ/mol	762.5
electronegativity	1.83
atomic number	26
chemical symbol	Fe
name	Iron
electron configuration	[Ar] $3d^6 4s^2$
oxidation states most common are bold	+6 +5 +4 **+3** **+2** +1 −1 −2

- 🟧 alkali metals
- 🟧 alkaline metals
- 🟨 other metals
- 🟨 transition metals
- 🟩 lanthanoids
- 🟩 actinoids
- 🟩 metalloids
- 🟪 nonmetals
- 🟪 halogens
- 🟦 noble gases
- ⬜ unknown elements
- ☢ radioactive elements have masses in parenthesis

period	group 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1.00794 1 1312.0 2.20 H Hydrogen $1s^1$ **+1** **−1**																	4.002602 2 2372.3 He Helium $1s^2$
2	6.941 3 520.2 0.98 Li Lithium $1s^2 2s^1$ **+1** −1	9.012182 4 899.5 1.57 Be Beryllium $1s^2 2s^2$ **+2**											10.811 5 800.6 2.04 B Boron $1s^2 2s^2 2p^1$ **+3** +2 +1	12.0107 6 1086.5 2.55 C Carbon $1s^2 2s^2 2p^2$ **+4** +3 +2 +1 −1 −2 −3 **−4**	14.0067 7 1402.3 3.04 N Nitrogen $1s^2 2s^2 2p^3$ **+5** +4 +3 +2 +1 −1 −2 **−3**	15.9994 8 1313.9 3.44 O Oxygen $1s^2 2s^2 2p^4$ +2 +1 −1 **−2**	18.998403 9 1681.0 3.98 F Fluorine $1s^2 2s^2 2p^5$ **−1**	20.1797 10 2080.7 Ne Neon $1s^2 2s^2 2p^6$
3	22.98976 11 495.8 0.93 Na Sodium [Ne] $3s^1$ **+1** −1	24.3050 12 737.7 1.31 Mg Magnesium [Ne] $3s^2$ **+2** +1											26.98153 13 577.5 1.61 Al Aluminium [Ne] $3s^2 3p^1$ **+3** +1	28.0855 14 786.5 1.90 Si Silicon [Ne] $3s^2 3p^2$ **+4** +3 +2 +1 −1 −2 −3 **−4**	30.97696 15 1011.8 2.19 P Phosphorus [Ne] $3s^2 3p^3$ **+5** +4 **+3** +2 +1 −1 −2 **−3**	32.065 16 999.6 2.58 S Sulfer [Ne] $3s^2 3p^4$ **+6** +5 **+4** +3 **+2** +1 −1 **−2**	35.453 17 1251.2 3.16 Cl Chlorine [Ne] $3s^2 3p^5$ **+7** +6 **+5** +4 **+3** +2 **+1** **−1**	39.948 18 1520.6 Ar Argon [Ne] $3s^2 3p^6$
4	39.0983 19 418.8 0.82 K Potassium [Ar] $4s^1$ **+1**	40.078 20 589.8 1.00 Ca Calcium [Ar] $4s^2$ **+2**	44.95591 21 633.1 1.36 Sc Scandium [Ar] $3d^1 4s^2$ **+3** +2 +1	47.867 22 658.8 1.54 Ti Titanium [Ar] $3d^2 4s^2$ **+4** +3 +2 +1 −1	50.9415 23 650.9 1.63 V Vanadium [Ar] $3d^3 4s^2$ **+5** +4 +3 +2 +1 −1	51.9962 24 652.9 1.66 Cr Chromium [Ar] $3d^5 4s^1$ **+6** +5 +4 **+3** +2 +1 −1 −2	54.93804 25 717.3 1.55 Mn Manganese [Ar] $3d^5 4s^2$ **+7** +6 +5 **+4** +3 **+2** +1 … −3	55.845 26 762.5 1.83 Fe Iron [Ar] $3d^6 4s^2$ +6 +5 +4 **+3** **+2** +1 −1 −2	58.93319 27 760.4 1.91 Co Cobalt [Ar] $3d^7 4s^2$ +5 +4 **+3** **+2** +1 −1 −2	58.6934 28 737.1 1.88 Ni Nickel [Ar] $3d^8 4s^2$ +4 +3 **+2** +1 −1	63.546 29 745.5 1.90 Cu Copper [Ar] $3d^{10} 4s^1$ +4 +3 **+2** +1	65.38 30 906.4 1.65 Zn Zinc [Ar] $3d^{10} 4s^2$ **+2**	69.723 31 578.8 1.81 Ga Gallium [Ar] $3d^{10} 4s^2 4p^1$ **+3** +2 +1	72.64 32 762.0 2.01 Ge Germanium [Ar] $3d^{10} 4s^2 4p^2$ **+4** +3 **+2** +1 **−4**	74.92160 33 947.0 2.18 As Arsenic [Ar] $3d^{10} 4s^2 4p^3$ **+5** **+3** +2 **−3**	78.96 34 941.0 2.55 Se Selenium [Ar] $3d^{10} 4s^2 4p^4$ **+6** **+4** **+2** **−2**	79.904 35 1139.9 2.96 Br Bromine [Ar] $3d^{10} 4s^2 4p^5$ **+7** **+5** +4 **+3** **+1** **−1**	83.798 36 1350.8 3.00 Kr Krypton [Ar] $3d^{10} 4s^2 4p^6$ **+2**
5	85.4678 37 403.0 0.82 Rb Rubidium [Kr] $5s^1$ **+1**	87.62 38 549.5 0.95 Sr Strontium [Kr] $5s^2$ **+2**	88.90585 39 600.0 1.22 Y Yttrium [Kr] $4d^1 5s^2$ **+3** +2 +1	91.224 40 640.1 1.33 Zr Zirconium [Kr] $4d^2 5s^2$ **+4** +3 +2 +1	92.90638 41 652.1 1.60 Nb Niobium [Kr] $4d^4 5s^1$ **+5** +4 +3 +2 −1	95.96 42 684.3 2.16 Mo Molybdenum [Kr] $4d^5 5s^1$ **+6** +5 **+4** +3 +2 +1 −1 −2	(98) 43 702.0 1.90 Tc Technetium [Kr] $4d^5 5s^2$ **+7** +6 +5 **+4** +3 +2 +1 −1 −3	101.07 44 710.2 2.20 Ru Ruthenium [Kr] $4d^7 5s^1$ +8 +7 +6 +5 **+4** **+3** +2 +1 −2	102.9055 45 719.7 2.28 Rh Rhodium [Kr] $4d^8 5s^1$ +6 +5 +4 **+3** +2 +1 −1	106.42 46 804.4 2.20 Pd Palladium [Kr] $4d^{10}$ **+4** **+2**	107.8682 47 731.0 1.93 Ag Silver [Kr] $4d^{10} 5s^1$ +3 +2 **+1**	112.441 48 867.8 1.69 Cd Cadmium [Kr] $4d^{10} 5s^2$ **+2**	114.818 49 558.3 1.78 In Indium [Kr] $4d^{10} 5s^2 5p^1$ **+3** +2 +1	118.710 50 708.6 1.96 Sn Tin [Kr] $4d^{10} 5s^2 5p^2$ **+4** **+2** **−4**	121.760 51 834.0 2.05 Sb Antimony [Kr] $4d^{10} 5s^2 5p^3$ **+5** **+3** **−3**	127.60 52 869.3 2.10 Te Tellurium [Kr] $4d^{10} 5s^2 5p^4$ **+6** +5 **+4** **+2** **−2**	126.9044 53 1008.4 2.66 I Iodine [Kr] $4d^{10} 5s^2 5p^5$ **+7** **+5** **+3** **+1** **−1**	131.293 54 1170.4 2.60 Xe Xenon [Kr] $4d^{10} 5s^2 5p^6$ +8 **+6** **+4** **+2**
6	132.9054 55 375.7 0.79 Cs Cæsium [Xe] $6s^1$ **+1**	137.327 56 502.9 0.89 Ba Barium [Xe] $6s^2$ **+2**	174.9668 71 523.5 1.27 Lu Lutetium [Xe] $4f^{14} 5d^1 6s^2$ **+3**	178.49 72 658.5 1.30 Hf Hafnium [Xe] $4f^{14} 5d^2 6s^2$ **+4** +3 +2	180.9478 73 761.0 1.50 Ta Tantalum [Xe] $4f^{14} 5d^3 6s^2$ **+5** +4 +3 +2 −1	183.84 74 770.0 2.36 W Tungsten [Xe] $4f^{14} 5d^4 6s^2$ **+6** +5 **+4** +3 +2 +1 −1 −2	186.207 75 760.0 1.90 Re Rhenium [Xe] $4f^{14} 5d^5 6s^2$ +7 +6 +5 **+4** +3 +2 +1 −1 −3	190.23 76 840.0 2.20 Os Osmium [Xe] $4f^{14} 5d^6 6s^2$ +8 +7 +6 +5 **+4** +3 +2 +1 −2	192.217 77 880.0 2.20 Ir Iridium [Xe] $4f^{14} 5d^7 6s^2$ +6 +5 **+4** **+3** +2 +1 −1 −3	195.084 78 870.0 2.28 Pt Platinum [Xe] $4f^{14} 5d^9 6s^1$ +6 +5 **+4** **+2**	196.9665 79 890.1 2.54 Au Gold [Xe] $4f^{14} 5d^{10} 6s^1$ +5 **+3** +2 +1 −1	200.59 80 1007.1 2.00 Hg Mercury [Xe] $4f^{14} 5d^{10} 6s^2$ +4 **+2** **+1**	204.3833 81 589.4 1.62 Tl Thallium [Xe] $4f^{14} 5d^{10} 6s^2 6p^1$ **+3** **+1**	207.2 82 715.6 2.33 Pb Lead [Xe] $4f^{14} 5d^{10} 6s^2 6p^2$ **+4** **+2** −4	208.9804 83 703.0 2.02 Bi Bismuth [Xe] $4f^{14} 5d^{10} 6s^2 6p^3$ +5 **+3** −3	(210) 84 812.1 2.00 Po Polonium [Xe] $4f^{14} 5d^{10} 6s^2 6p^4$ +6 **+4** **+2** **−2**	(210) 85 890.0 2.20 At Astatine [Xe] $4f^{14} 5d^{10} 6s^2 6p^5$ **+1** −1	(220) 86 1037.0 Rn Radon [Xe] $4f^{14} 5d^{10} 6s^2 6p^6$
7	(223) 87 380.0 0.70 Fr Francium [Rn] $7s^1$ **+1**	(226) 88 509.3 0.90 Ra Radium [Rn] $7s^2$ **+2**	(262) 103 470.0 Lr Lawrencium [Rn] $5f^{14} 7s^2 7p^1$ **+3**	(261) 104 580.0 Rf Rutherfordium [Rn] $5f^{14} 6d^2 7s^2$ **+4**	(262) 105 Db Dubnium **+5**	(266) 106 Sg Seaborgium **+6**	(264) 107 Bh Bohrium **+7**	(277) 108 Hs Hassium **+8**	(268) 109 Mt Meitnerium	(271) 110 Ds Darmstadium	(272) 111 Rg Roentgenium	(285) 112 Cn Copernicium	(284) 113 Uut Ununtrium	(289) 114 Uuq Ununquadium	(288) 115 Uup Ununpentium	(292) 116 Uuh Ununhexium	117 Uus Ununseptium	(294) 118 Uuo Ununoctium

138.9054 57 538.1 1.10 La Lanthanum [Xe] $5d^1 6s^2$ **+3** +2	140.116 58 534.4 1.12 Ce Cerium [Xe] $4f^1 5d^1 6s^2$ **+4** **+3** +2	140.9076 59 527.0 1.13 Pr Praseodymium [Xe] $4f^3 6s^2$ +4 **+3** +2	144.242 60 533.1 1.14 Nd Neodymium [Xe] $4f^4 6s^2$ **+3** +2	(145) 61 540.0 Pm Promethium [Xe] $4f^5 6s^2$ **+3**	150.36 62 544.5 1.17 Sm Samarium [Xe] $4f^6 6s^2$ **+3** +2	151.964 63 547.1 Eu Europium [Xe] $4f^7 6s^2$ **+3** **+2**	157.25 64 593.4 1.20 Gd Gadolinium [Xe] $4f^7 5d^1 6s^2$ **+3** +2 +1	158.9253 65 565.8 Tb Terbium [Xe] $4f^9 6s^2$ +4 **+3** +1	162.500 66 573.0 1.22 Dy Dysprosium [Xe] $4f^{10} 6s^2$ **+3** +2	164.9303 67 581.0 1.23 Ho Holmium [Xe] $4f^{11} 6s^2$ **+3**	167.259 68 589.3 1.24 Er Erbium [Xe] $4f^{12} 6s^2$ **+3**	168.9342 69 596.7 1.25 Tm Thulium [Xe] $4f^{13} 6s^2$ **+3** +2	173.054 70 603.4 Yb Ytterbium [Xe] $4f^{14} 6s^2$ **+3** +2
(227) 89 499.0 1.10 Ac Actinium [Rn] $6d^1 7s^2$ **+3**	232.0380 90 587.0 1.30 Th Thorium [Rn] $6d^2 7s^2$ **+4** +3 +2	231.0358 91 568.0 1.50 Pa Protactinium [Rn] $5f^2 6d^1 7s^2$ **+5** +4 +3	238.0289 92 597.6 1.38 U Uranium [Rn] $5f^3 6d^1 7s^2$ **+6** +5 +4 +3	(237) 93 604.5 1.36 Np Neptunium [Rn] $5f^4 6d^1 7s^2$ +7 +6 **+5** +4 +3	(244) 94 584.7 1.28 Pu Plutonium [Rn] $5f^6 7s^2$ +7 +6 +5 **+4** +3	(243) 95 578.0 1.30 Am Americium [Rn] $5f^7 7s^2$ +6 +5 +4 **+3** +2	(247) 96 581.0 1.30 Cm Curium [Rn] $5f^7 6d^1 7s^2$ +4 **+3**	(247) 97 601.0 1.30 Bk Berkelium [Rn] $5f^9 7s^2$ +4 **+3**	(251) 98 608.0 1.30 Cf Californium [Rn] $5f^{10} 7s^2$ +4 **+3** +1	(252) 99 619.0 1.30 Es Einsteinium [Rn] $5f^{11} 6s^2$ **+3** +2	(257) 100 627.0 1.30 Fm Fermium [Rn] $5f^{12} 7s^2$ **+3** +2	(258) 101 635.0 1.30 Md Mendelevium [Rn] $5f^{13} 7s^2$ **+3** +2	(259) 102 642.0 1.30 No Nobelium [Rn] $5f^{14} 7s^2$ **+3** +2

electron configuration blocks



notes

- as of yet, elements 113-118 have no official name designated by the IUPAC.
- 1 kJ/mol ≈ 96.485 eV.
- all elements are implied to have an oxidation state of zero.

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