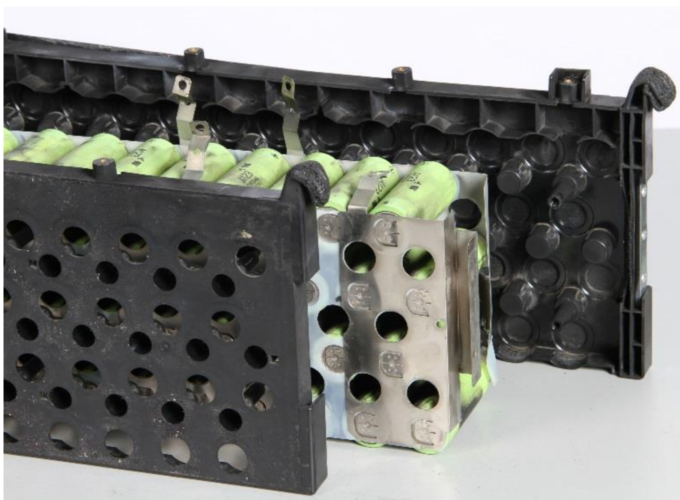
Lithium Ion Batteries

Recycling and Repurposing



Produced by
Charles Ammond, Muskegon Community College
Greg Marczak, Muskegon Community College
Dr. Charles Standridge, Grand Valley State University

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I. Overview

Section A: Batteries

End Goals: This section provides a primer to understanding the structure and chemistry of batteries, with emphasis on Lithium-ion batteries.

To the Student: The focus of this section will be on Lithium Ion types which are typical in most Electric Vehicle and Hybrid Vehicle drive systems. A basic understanding of the chemistry and components within batteries will help you to understand diagnostic and safety issues.

Content Outline:

- Introduction
- Chemistry of Secondary Batteries
- Chemical Considerations for Repurposing or Recycling
- Conclusion

Introduction

Batteries which can be charged electrically fall under a class of batteries called secondary batteries. They include but are not limited to lead-acid batteries (LAB), nickel metal hydride (Ni-Mh), Lithium ion (Li-ion) including variations. The applications for these devices cover a wide range of uses including automobile, hearing aids, alternative energy storage systems, and portable electronic devices, as well as medical and personal health and home care aids.

In this section we will consider the chemistry of these batteries. We will first begin by looking at the basic components of a few select types of batteries, particularly Ni-MH and Li-ion as much of our focus will be on the ability to deliver power for transportation systems. Once the basic systems are described, we will then take a look at methods or justifications for repurposing or recycling batteries based on their chemical constituents.

Chemistry of Secondary Batteries

All batteries, whether or secondary or primary (such as the common non rechargeable AA Alkaline battery) consist of several basic components and several other common components. These include but are not limited to

Anode

Cathode

Electrolyte

Collectors

Circuitry

Separators (or insulators)

In this section, we will confine most of our discussion to the first three, but will occasionally give brief descriptions of the remaining items as we will need to know what to do with these pieces of equipment when it comes to recycling.

The Cathode

The cathode is the material which undergoes the reduction in the oxidation-reduction reaction. Often called a "redox" reaction, this is an electrochemical event where a potential difference exists between two dissimilar materials. This potential difference allows for the transfer of electrons from one material to another, until the potential difference is minimized or matches the potential of surrounding systems. To identify the cathode material in a battery, we have to consider the battery as it is discharging. (Battery designations occur based on the discharge process. Technically, the negative and positive terminals are switched during charging, however, it is not acting as a battery or galvanic cell at this point.) Equation 1 gives the general form for the reduction in a lithium ion battery.

Equation 1

Reduction reaction for a lithium ion cell upon *discharge*

$$Li_{1-x}CoO_2 + nLi^+ + \ ne^- \quad \rightarrow \quad LiCoO_2$$

Where

x = stoichiometric fraction of lithium ions transferred

n = number of electrons transferred

e^- = electron

When given the balanced equation for the discharge, the reduction reaction can be identified by the absence of electrons on the left side of the reaction. For this electrode, electrons are gained by the cathode material because of the lower potential at this electrode. This lower potential is designated with a "+" symbol on the terminal.

In hybrid (HEV) and Plug-in Electric Vehicles (PEV), Nickel Metal Hydride and Lithium Ion batteries are currently the battery of choice. Some common cathode materials from several different types of secondary batteries are indicated below in table 1.

Table 1

Type of Secondary Battery (abbreviation)	Cathode Material (use)
Nickel Cadmium (Ni-Cd)	NiOOH – Nickel oxy hydroxide (hearing aids)
Nickel Metal Hydride (NiMH)	NiOOH – Nickel oxy hydroxide (HEV)
Lithium Cobalt Oxide (LCO)	$LiCoO_2$ - Lithium Cobalt Oxide (Laptop batteries)
Lithium Iron Phosphate (LFP)	$LiFePO_4$ – Lithium Iron Phosphate (EV, Power tools)
Lithium Nickel Cobalt Aluminum Oxide (NCA)	$LiNiCoAlO_2$ – Lithium Nickel Cobalt Aluminum Oxide (PEV)

Both the NiMH and Li-ion have relatively high energy capacity, operate over wide temperature ranges, and have chemical characteristics that are suitable to repeated charging and discharging over an extended period of time. Currently, NiMH is cheaper than lithium ion batteries but the lithium-ion has the advantage of having a higher energy density due to its higher electrochemical potential.

Li-ion electrodes can exist because of the ability of the transition metals to form coordination complexes which layer themselves to allow intercalation of the Lithium ions. This event is quite significant in that upon charging (the reverse of the equation given above), lithium ions are electrochemically stabilized in the structure. In secondary batteries with metal lithium cathodes, repeated charging and discharging can lead to the formation of physical lithium dendrite structures. If large enough, these structures can short circuit the cell (the complete electrochemical cell consisting of all components given above) resulting in a thermal runaway and eventually a catastrophic event.

Additional detail regarding the different lithium ion chemistries and their economic effect on recycling will be given later on in this paper.

The Anode

The anode is the material which undergoes oxidation when the battery discharges. In the case of the lithium ion battery, graphite is a common electrode of choice. The general oxidation reaction is given in equation 2.

Equation 2
Oxidation reaction for a lithium ion cell upon *discharge*

$$Li_yC \rightarrow \quad C + \ nLi^+ + \ \ ne^-$$

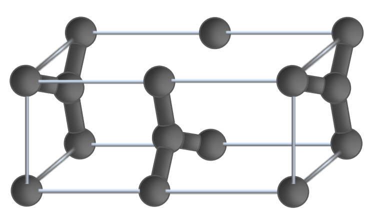
The oxidation reaction can be identified by the presence of the **+ne**$^-$ on the right side of the equation which indicates an abundance of electrons or a higher potential. These electrons are why the electrode terminal is designated as the "-"negative terminal. (Terminals on a battery are designated according to the discharge operation).

Table 2 lists some anode material for secondary batteries.

Table 2

Type of Secondary Battery (abbreviation)	Anode Material (use)
Nickel Cadmium (Ni-Cd)	Cd – Cadmium (hearing aids)
Nickel Metal Hydride (NiMH)	MH - transition metal + hydrogen (HEV)
Lithium Cobalt Oxide (LCO)	LiC_6 – graphite (Laptop batteries)
Lithium Iron Phosphate (LFP)	LiC_6 – graphite (EV, Power tools)
Lithium Nickel Cobalt Aluminum Oxide (NCA)	LiC_6 – graphite (PEV)

Graphite allows for the lithium ion to insert itself between the unit cells. One lithium ion can be intercalated for every six carbons present. This is called stage 1 intercalation. Subsequent stages,2,3,4 occur as the number of intercalated lithium decreases. Weak Vander Wall forces on the carbons allow for this material to become conductive. Additional coating by acetylene black or carbon black allow for conduction between the electrode material and the collectors.



Electrolytes

The electrolytic material allows current to flow between the anode and the cathode. In the NiMH cell, the electrolyte is in a basic medium paste of potassium hydroxide, while the Li-ion electrolytes consist of polymers or organic solvents which can contain ethylene carbonate, dimethyl carbonate, or diethyl carbonate. The carbonate groups allow for charge transfer across the electrolyte. The battery in a lithium battery may also contain a lithium salt.

For the Li-ion cells, the non-aqueous electrolytes provide operating temperatures ranging from -150°C to over 300°C. Depending on the solvent, there may be some concerns associated with the solvent in terms of flammability and compared to aqueous electrolytic solutions a reduced conductivity of solution. An examples of some common solvents found in a lithium ion battery are given in table 3. (Claus Daniel, J.O. Besenhard. *Handbook of Battery Materials*, 2011, 258.)

Table 3.

Solvent	Acronym
Acetonitrile	AN
Diethyl carbonate	DEC
Dimethyl sulfoxide	DMSO
Propylene carbonate	PC

Some commonly used salts are lithium perchlorate ($LiCl_4$), Lithium hexflourophosphate ($LiPF_6$), and Lithium Diflouro(oxalate)borate (LiDFOB), all corresponding the general form of LiX where X is the anion.

Solvent free or "solid" electrolytes are usually thin film polymers which may or may not eliminate the need for a separator. Some materials may appears gel like in nature, but are still considered to fall into the solid category of electrolytes. Just as with non-aqueous solutions, these solid electrolytes often contain an ionic salt to increase conductivity.

Collectors

The collectors in an electrochemical cell may or may not be the same as the oxidation and reduction material. In the Li-ion and the NiMH batteries, they are not. Aluminum and copper are two common materials and are often made up thin sheets which can be rolled or sandwiched in between alternating electrolyte/anode and electrolyte/ cathode materials. As the name implies, collectors must be good conductors of current.

Separators

Some common separators are polymers with pore sizes that allow for the transport of ions but do not allow the anode and cathode to contact each other, thus preventing a short circuit. Separators must be amenable to the types of temperature that will be experienced over the lifetime of the battery. This includes the ability to withstand degradation over time.

Separators are designed to maximize energy and power densities and must have safety characteristics suitable to the system being used. They are usually very thin film membranes (less than 1 mil) made out of polyethylene or polypropylene and they must possess good mechanical strength and dimensional stability. Separators can account for 20% of the battery cost. (Uahn, Liu, Zhang. *Lithium-Ion Batteries Advanced materials and Technologies*, CRC Press, 2011, 19-20)

Circuitry, Thermistors, and Other Internal Controls

Circuitry and other controls will be discussed in the electrical section of this paper.

The Battery

The above components all fit together to make a cell. The combination of individual cells is then connected in series to increase the voltage or in parallel to increase the energy capacity. When more than one cell is connected, the resulting system is called the battery.

Repurposing and Recycling

Repurposing or recycling batteries is dependent on the physical and chemical characteristics of a battery, the economies associated with tearing apart and putting back together, and the regulatory practices dictated by government agencies. Lead battery recycling which is estimated to be around 80% or more per year, is driven by all these factors. Fairly simple in design, these batteries can be economically destroyed with the resulting product yielding enough lead to make it economically feasible to put into a new battery. Lithium ion batteries on the other hand require extensive processing and the resulting high value components have been reported to at best, yield enough to match the same economies as procuring from new material.

This section will consider the current methods for battery reclamation or recycling in regards to the chemistry of the battery. What is apparent from reviewing sources for this paper, is that good opportunities still exist for finding ways to maximize the recovery or reuse of these materials. Later sections will briefly discuss the regulatory aspects of battery recovery and recycling, but it cannot be underemphasized that the practices deemed necessary by regulatory agencies have a large impact on the cost associated with recycling and repurposing.

Physical methods

A major recycler of battery materials is Toxoco located in Ohio. A visit to their site will quickly reveal that the battery recovery process requires a lot of physical and brute strength. When one considers just the amount of primary batteries such as the AA or AAA Alkaline batteries used in a single household in a year, the task of sorting, breaking, processing, and recovering material from these batteries becomes quite enormous.

Batteries are segregated according to type. Typically, Li-ion and NiMH batteries are being sent back to the manufacturer. There are two reasons for this. One is that the vehicle manufacturers want to maintain intellectual control over their proprietary processes used in developing these batteries and the other is that they are concerned with “cradle to grave” environmental aspects of this material. Because of this, it is not unusual to find that trying to obtain batteries for research or physical examination is not as easy as one might think.

Methods of destruction literally include using saws, hammers, screwdrivers, metal cutters, and anything which will separate the battery into individual cells. Covered elsewhere in this manual are important safety considerations that deal with the discharge of the battery prior to touching it with any tool. Please read those safety considerations before attempting any disassembly of a battery.

Chemical Recovery

Within the NiMH battery, the primary constituent for recovery is the nickel. The high nickel content makes it attractive for steel alloys. The presence of cobalt or cadmium in these batteries can make recovery more difficult, as they are not necessarily suited for these types of steel alloys.

The specific morphology and crystallinity required of the cathode materials (such as $LiMn_2O_4$, $LiCoO_2$, $LiFePO_4$, etc...) so that intercalation of the lithium ions may occur does not lend itself well to thermo-metallurgy processes in terms of reuse. Instead, many processes focus on recovering the elements lithium and cobalt for the raw material used in a new battery.

In order to economically justify recovering the raw elements, the destruction of the battery pack must be taken as a whole. For example, consider a pyro-metallurgical process where the battery pack is fed into a smelter. The organics such as the electrolytes, the separators, and case can be incinerated in this process and recovered through use of an electric arc furnace to control/eliminate emissions. (Claus Daniel, J.O. Besenhard. *Handbook of Battery Materials*, 2011, 190). The lithium and transition metals can be converted to slag through the formation of oxides which can then go through additional processing to separate out the individual elements.

Driving this however, is the concentration and commodity price of the raw material. In a battery where the major component of the cathode is $LiCoO_2$, the percentage of cobalt may be large enough to justify its recovery. However, as battery manufacturers use other metals such as aluminum, iron, or nickel to build the layered intercalation structure while lowering cost, the concentration of cobalt becomes diluted thereby lowering the benefit of salvaging or recovering the cobalt as an individual element. Therefore, opportunities do exist to consider new methods which are less energy intensive to remove and separate those high value components from the rest of the battery components.

As might be expected, alternative methods exist whereby the materials are processed using dissolution and separation techniques based on the solubility of the newly formed transition metal complexes. Depending on the initial amount of manual labor used to remove circuitry and easily accessible high value components such as copper, batteries can often be shredded and then dissolved in strong acids or bases. The transition metal complexes can be effectively separated from the plastics while dissolved and then can be selectively precipitated using carbonates or hydroxides, standard techniques taught in any second semester general chemistry course. For the precipitates with similar solubility's, electroplating may be used to separate the individual elements. Again, the heavy processing comes at a cost and is currently not economically viable for the replacement of using raw mined material, although regulations could dictate that such processes be used if burial of the battery materials is not allowed.

As the ability of the lithium ions to insert and extract themselves from the anode and cathode materials starts to degrade, the electron transfer process which is crucial to maintaining the energy capacity and specific energy of the battery. Some pilot studies have indicated the "soft processing may be able to increase the amount of lithium back into these layered structures to achieve the appropriate energy capacity levels as the original cell. (Claus Daniel, J.O. Besenhard. *Handbook of Battery Materials*, 2011, 193) However, these processes occur at elevated temperatures greater than 850° and battery disassembly and material segregation/disposal must occur with the remaining components. Again, a labor intensive process.

Toxicity

In any disassembly or reprocessing, the toxicity effects of the components must be considered. As dictated by OSHA and other federal regulating agencies, companies are subject to monitoring their employees' exposure through urine or blood testing a regular basis. To prevent contamination, workers are often dressed in full hazard suits and wear regulators. To prevent contamination from leaving the work space, regular safety meetings are required to train employees how to undress and showers are required before they go home. Special "sticky" mats are used to prevent contamination picked up on shoes from entering office spaces.

Thorough inventories of substances must be kept and maintained. Battery recyclers such as Toxoco understand that the physical aspects of battery recycling or material reuse can easily be replicated by any person who can meet the physical demands of the job. However, the compliance side of handling these battery materials is what they really sell. Batteries are not allowed to be stored for long periods of time and must be processed within a limited time frame, often as short as six months.

The level of Cobalt in an adult human is around 1 to 1.5mg and is often obtained from vitamin B12. (Jurgen Garch, Chris Dyer, et al. *Encyclopedia of Electrochemical Power Sources*, v4, 2009, 236). Cobalt may lead to problems with the thyroid or heart problems. Cobalt has been reported to be a sensitizer for both dermal and pulmonary systems. In processing or recovery materials, a large amount of small particles can expose a human to these sensitizers in the form of dust. Thus, the primary focus on eliminating problems with exposure to cobalt will involve appropriate respiratory and dermal protection as well as constant blood or urine monitoring.

Excessive exposure to lithium may result in blurred vision, kidney toxicity, and dehydration. However, these effects were mostly noted with pharmacologic use of lithium compounds used in psychological disorders. Such concentrations are not expected to be obtained in a production facility where appropriate personal protective equipment is used. One must be careful to distinguish between the lithium ion and the lithium metal. Lithium metal is extremely reactive with air and can cause an explosion in the presence of oxygen and any humidity. Lithium ion on the other hand usually exists as a solid salt when dry or as an aqueous solution when dissolved. Currently, no carcinogenic effects have lithium compounds has been noted.

Nickel has been noted for some time to have some toxicity based on the type of nickel compound and its solubility. Nickel itself does not demonstrate much toxicity, but as an ion (such as those found when dissolved in aqueous solution) has been demonstrated to show toxicity in animals. Insoluble nickel compounds have been classified as Group 1 carcinogens by the International Agency for Research on Cancer. This was based on workers exposed through chronic inhalation in the processing and refining of ores.

As might be expected, the alkaline based potassium hydroxide is corrosive to human skin, respiratory, and eyes and must be considered upon any disassembly of a NiMH pack. Non-aqueous electrolytes can be highly flammable and may result in the formation of hydrogen fluoride and phosphorous oxide gases at high temperatures from the salt in those electrolytes. One must also be concerned with the trace metals that accompany any of the refined metals or salts used in the process. Mixing of different types of battery materials is not recommended for this reason.

1. Overview
   Section A: Batteries

Lab 1 – Building a voltaic cell

End Goals: This activity is meant to provide a refresher on the basic chemical principles and components of an electrochemical cell.

Pre-Requisites: Students should be familiar with the following principles prior to starting

- Student should be able to write a balanced oxidation-reduction reaction.
- Students should be able to determine which species are oxidized or reduced in an electrochemical reaction.
- Students should be able to use a table of electrochemical reduction potentials to determine the predicted voltage of a cell.

Materials

- Pennies (2000 or later) 12 per student *or* 12 copper and 12 zinc washers per student.
- Sand paper, file, or Dremmel tool with sander.
- Filter paper or similar water adsorbent material
- Solder kit (optional)
- 12 Gauge copper wire red (color type is optional), 1 foot per student, ends stripped.
- 12 Gauge copper wire black (color type is optional), 1 foot per student, ends stripped.
- A pencil or nonconducting rod. (optional)
- Voltmeter with leads
- Alligator clips preferred but optional

Purpose: While simple, this activity is meant to familiarize the student with the basic cell and battery potentials of two dissimilar metals. In addition, the recognition of potential and the relationship to the ground of a meter are considered.

Safety

- If using the Dremmel bit to sand one side of a penny, an appropriate clamp must be used to keep the penny in place and to keep the sanding bit of the Dremmel away from fingers.
- Safety glasses should be worn when using the Dremmel or solder kit.
- Students may choose to solder the wire to work pieces under appropriate supervision. NEVER touch the heating element or tip on the soldering iron.

Activity

1. In order to perform this activity, obtain two dissimilar metals. This may be done as follows:
   a. If using pennies: Using a file, sand paper, or Dremmel bit with a sanding tip, put a penny in a clamp or vise grip and sand one side of the penny until a silvery finish is seen.
   b. If using washers, make sure the metal type of each washer is clearly identified by some physical characteristic or notation.
2. Set up the voltmeter to perform a voltage measurement. Make it clear in your notes, which lead is attached to the voltage input and which lead is attached to the common or ground input. (While newer voltmeters have circuit protection, the meter should be set at the highest DC voltage range and then lowered until a reading can be achieved.)
3. The hardest part of this experiment is placing the pennies or washers between the leads of the voltmeter. Your instructor may ask you to solder a 12 inch wire on one of the work pieces of one metal type, and another 12 inch wire on one of the work pieces of the other metal type. The pencil may be used with the washers to allow the pennies to stand on end, which makes measurement much easier.
4. Start with one combination or the two dissimilar metals.
   a. For the pennies, this would be just one penny. Place the positive lead of the voltmeter on the copper and the common ground of the voltmeter on the zinc (shiny end).
   b. For the washers, place a piece of filter paper soaked in an electrolyte solution such as NaCl or KNO_3 between the two dissimilar metals. Ensure that they are touching.
5. Measure the voltage and record.
6. Reverse the leads of the voltmeter and measure the voltage and record.
7. Repeat steps 4 through 6 after adding another penny or set of washers. Continue repeating until a minimum of 6 pennies or 6 sets of washers have been used. (Note, you may want to continue building until you equal the standard voltage of a AA battery which is 1.5 Volts).

Effect on reversal of cells

8. Using the very last combination from step 7 above, reverse one of the pennies or sets of washers and record the new voltage. In this case, set the leads so that only a positive voltage is obtained.
9. Predict what would happen if half the cells were reversed. Then measure the voltage to confirm your hypothesis.
10. Answer the questions at the end of the data sheet.

Data Sheet for Lab 1 – Activity 1

Type of metal(s) used		
Lead Configuration	Positive on : Negative on:	Positive on: Negative on:
Voltage of 1 penny or 1 set of dissimilar metals		
Voltage of 2 pennies or 2 sets of dissimilar metals		
Voltage of 3 pennies or 3 sets of dissimilar metals		
Voltage of 4 pennies or 4 sets of dissimilar metals		
Voltage of 5 pennies or 5 sets of dissimilar metals		
Voltage of 6 pennies or 6 sets of dissimilar metals		
Voltage of 6 pennies or 6 sets of dissimilar metals when one cell is reversed		
Voltage of 6 pennies or 6 sets of dissimilar metals when three cells are reversed		

Analysis (Questions)

The voltage of any cell can be determined by use of standard reduction potentials. Standard refers to a given temperature at which these values were determined. To compare the actual voltage of a cell to the theoretical voltage of a cell, one must determine which substance is being oxidized and which substance is being reduced.

1. Using the voltage readings and configuration of the leads as your reference point, explain how one can determine which substance is being oxidized and which substance is being reduced.
2. Based on your answer for the previous question, how should the voltage on a battery be measured? (i.e. which terminal gets connected to the positive terminal and which terminal gets connected to the negative terminal.) Why?
3. Write the oxidation half-cell reaction and reduction half-cell reaction below. This can be easily looked up in a reference book or on the internet.
4. Using a table of standard reduction potentials, determine the potential of each half reaction. Note, if using a table of standard reduction potentials, you will need to reverse the sign for the voltage for the oxidation reaction.

Reduction Reaction (as written)	**Standard Reduction Potential**
$NO_3^-(aq) + 4\ H^+(aq) + 3\ e^- \rightarrow NO_{(g)} + 2\ H_2O$	0.96 V
Ag+(aq) + 1e- → Ag(s)	0.80 V
$2MnO_2(s) + 2\ e^- + 2NH_4Cl(aq) \rightarrow Mn_2O_3(s) + 2NH_3(aq) + H_2O(aq) + 2\ Cl^-$	0.50V
$Cu^{2+}(aq) + 2e^- \rightarrow Cu\ (s)$	0.34 V
$Pb^{2+}(aq) + 2e^- \rightarrow Pb(s)$	-0.13 V
$Zn^{2+}(aq) + 2e^- \rightarrow Zn(s)$	-0.76 V
$K^+(aq) + 1e^- \rightarrow K(s)$	-2.93V

5. To determine the predicted voltage of one cell, use the following formula.

$$E^o_{cell} = E^o_{ox} + E^o_{red}$$

where
E^ocell = theoretical standard voltage of the cell
E^oox = standard oxidation potential
E^ored = standard reduction potential

6. Compare your theoretical voltage to the voltage determined in the activity. Determine the percent error. For errors greater than 10%, discuss what may be causing that error.

% error = $\frac{|Actual\ Voltage - Theoretical\ Voltage|}{Theoretical\ Voltage}\ x\ 100\%$

7. If the meter isn't connected to each end of the pile, does a potential difference still exist between the metals?

For the instructor (not to be printed with the student lab)

While simple, the purpose of this lab is to reacquaint the student with some basic electrochemical concepts that they may have had in previous classes. Students should be introduced to an oxidation and reduction reaction. In this case, we are using the half-cell reaction…

$Zn \rightarrow Zn^{2+} + 2e^-$ Oxidation half-cell reaction

$Cu^{2+} + 2e \rightarrow Cu$ Reduction half-cell reaction

The reaction can be combined by adding together.

$$Zn + Cu^{2+} \rightarrow Zn^{2+} + Cu$$

In theory, this reaction should produce a voltage close to the standard cell potential (E^ocell) which is based on standard half-cell potentials which can found in reference books. The degree sign indicates that values have been measured under specific conditions. (See table above in the activity).

In this case the reduction half-cell potentials are…

Reduction Reaction (as written)	**Standard Reduction Potential**
$Cu^{2+} + 2e^- \rightarrow Cu$	0.34 V
$Zn^{2+} + 2e^- \rightarrow Zn$	-0.76 V

In our example above, we must change the sign on the reaction for the Zn, because this substance is being oxidized.

Reaction as it occurs in the cell	**Potentials as written for the oxidation and reduction**
$Cu^{2+} + 2e^- \rightarrow Cu$ (E^ored)	0.34 V
$Zn \rightarrow Zn^{2+} + 2e^-$ (E^oox)	0.76 V

The standard cell potential can now be determined.

$$E^{o}_{cell} = E^{o}_{ox} + E^{o}_{red}$$

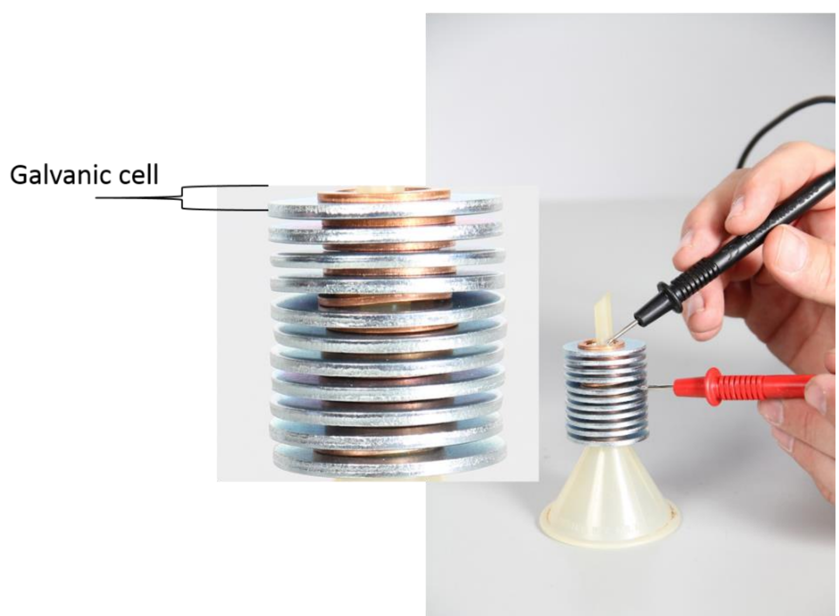
$$E^{o}_{cell} = 0.76V + 0.34V$$

$$E^{o}_{cell} = 1.10V$$

Many students using a multimeter will connect the wires so that a positive voltage is obtained. Batteries often make it easy for a student to identify which wire to connect by the "+" and "-" markings. In the experiment above, the cells are treated as if the positive and negative ends of the cell are unknown. Thus, a student that connects the hot wire to the oxidation and a common wire to the reduction, will obtain a negative value. Since batteries are designated with the negative terminal as the oxidation reaction (this the anode) and the positive terminal as the reduction reaction (this is the cathode) the student should be able to deduce which end is positive and which end is negative, even if markings are not present.

The purpose of reversing cells is to show how a change in potential affects the overall voltage of cell. Each cell should produce the same voltage. When combined in series, the voltages are additive. However, when one of the cells is reversed, this negates the potential of another cell. But other cells that have not been negated will still add to the voltage. (If you had a fire hose pushing up on a waterfall, it would stop some of the waterfall, but not all of it. Thus the overall voltage would be less but not zero, unless your fire hose was as powerful and wide as the waterfall itself).

Galvanic Battery



I. Overview

Section A: Batteries

Lab 2 – Building an electrochemical cell

End Goals: This activity is meant to demonstrate the electrochemical potential based on cell configuration and to identify components of a cell.

Pre-Requisites: Students should be familiar with the following principles prior to starting

- Student should be able to write a balanced oxidation-reduction reaction.
- Students should be able to determine which species are oxidized or reduced in an electrochemical reaction.
- Students should be able to use a table of electrochemical reduction potentials to determine the predicted voltage of a cell.
- Ideally, a student will have had a minimum of one semester of college chemistry.

Materials (per student)

- Six, 10mL or 25mL beaker (10mL preferred)
- Filter paper or similar water adsorbent material cut into approximately 4" L x 0.25" wide".
- 100mLs of 0.10M potassium nitrate
- 100mLs of 0.10M Copper (II) Nitrate
- 100mLs of 0.10M silver nitrate
- 100mLs of 0.10M lead (II) nitrate
- 100mLs of 0.10M aluminum nitrate
- 100mLs of 0.10M iron (II) nitrate
- 100mLs of 0.10M magnesium nitrate
- 100mLs of 0.10M Tin (II) nitrate
- 100mLs of 0.10M zinc nitrate
- 100mLs of 0.10M unknown electrolyte
- Charcoal or carbon black
- 10 Piece Electrode Set (0.75"W x 5"l x 0.25"thick)
- D Cell battery with battery holder
- Voltmeter (Multimeter) with leads
- Alligator clips preferred but optional

Purpose: To identify the half cell reactions of an electrochemical reaction and the effect of contaminants in the electrolyte material.

Safety

- Solutions should be disposed in to an appropriate waste container as identified by your instructor. Electrodes are to be returned to the instructor.
- Safety glasses should be worn during the experiment.
- To prevent beakers from tipping, caution must be taken when working with the electrodes and the solutions in the beaker.

Activity

Reduction Reaction (as written)	**Standard Reduction Potential**
$NO_3^-(aq) + 4 H^+(aq) + 3 e^- \rightarrow NO_{(g)} + 2 H_2O$	0.96 V
$Ag+(aq) + 1e- \rightarrow Ag(s)$	0.80 V
$2MnO_2(s) + 2 e^- + 2NH_4Cl(aq) \rightarrow Mn_2O_3(s) + 2NH_3(aq) + H_2O(aq) + 2 Cl^-$	0.50V
$Cu^{2+}(aq) + 2e- \rightarrow Cu (s)$	0.34 V
$Pb^{2+}(aq) + 2e- \rightarrow Pb(s)$	-0.13 V
$Zn^{2+}(aq) + 2e- \rightarrow Zn(s)$	-0.76 V
$K^+(aq) + 1e- \rightarrow K(s)$	-2.93V

<u>Activity 1: Building an electrochemical cell</u>

1. Before constructing your cell, calculate the E^ocell for a copper/zinc electrochemical cell using the potentials given above.
2. Fill one beaker ¾ full with zinc nitrate solution.
3. Fill one beaker ¾ full with copper (II) nitrate solution.
4. Place a Zinc electrode in the Zinc solution.
5. Place a copper electrode in the copper solution.
6. Connect a meter to the electrodes and measure the voltage. Discuss the voltage results. (i.e. do they correspond to the prediction of the E^ocell?)

7. Add a salt bridge: Place your filter paper in a dry beaker. Saturate the filter paper with potassium nitrate solution. Allow the filter paper to sit in the beaker for a minimum of two minutes.
8. Remove the filter paper and place one end in the beaker with the zinc solution and the other end in the beaker with the copper solution.
9. Record the voltage of the cell and compare to E^ocell for this system.
10. Move the hot lead to the Amperage input of the voltmeter. Record the current. Be sure to report units.
11. Continue to keep the voltmeter (or ammeter) leads connected for 5 minutes. Make visual observations of what is happening in the solution and on the electrodes.

<u>Activity 2 - Building an electrochemical battery</u>

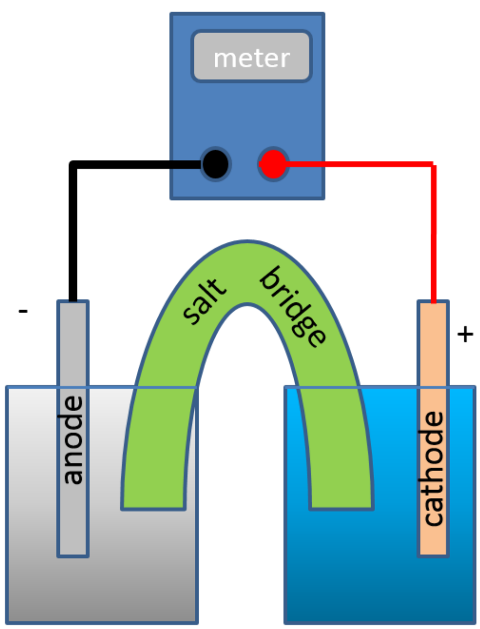
1. Build a battery by connecting three cells in series. When connected in series, the total voltage should be equal to the sum of the cell voltages. Measure and compare your voltage to the theoretical voltage expected for the battery.
2. Illustrate your battery, in the data table provided. Also indicate the following on your illustration:
    A. Anode
    B. Cathode
    C. Electrodes
    D. Electrolyte
    E. Separators
    F. Conductors
    G. Current flow direction

<u>Activity 3 -Effect of contamination.</u>

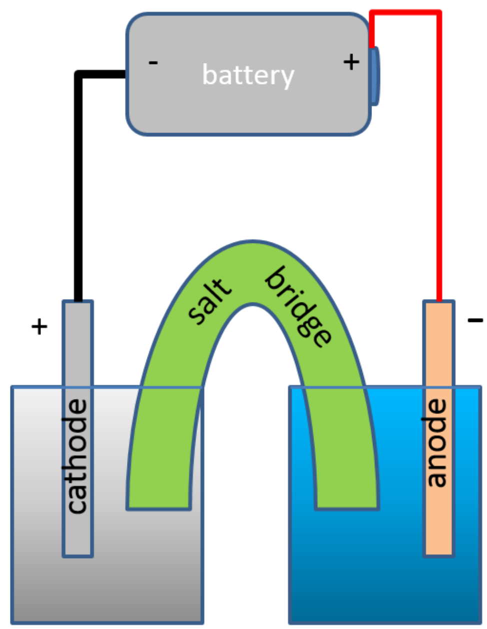
1. Using only one of the electrochemical cells as prepared previously, contaminate the zinc nitrate solution by adding several drops of copper nitrate solution. Record the voltage and current.
2. Again, contaminate the zinc nitrate solution, but this time add 3 to 5 mLs of copper nitrate solution. (Note, you may have to remove some zinc nitrate prior to doing this step to prevent overflow). Record the voltage and current and be sure to make visual observations. Give a reason as for any visual observations or changes in voltages compared to the original cell.
3. Using a different electrochemical cell as prepared in the initial battery configuration, contaminate it by adding some charcoal or carbon black. Record the voltage and current and report any visual observations or changes in voltages compared to the original cell.
4. Using the third cell from the battery preparation above, insure that the beakers are touching before measuring the voltage. What happens to the voltage and current? Give an explanation. What does this say about materials of construction?

Activity 4 -New Cell, Electrolytic conditions (Note: although we are not charging in this system, electrolytic conditions are the same type of conditions that exist under charging conditions of a battery).

1. Prepare a new cell using any of the electrodes or solutions which have not been used yet.
2. Predict the E°cell for this reaction.
3. Measure the voltage and current of your cell. Compare this to the theoretical E°cell.
4. Draw a picture of your new cell in the data table and indicate the anode and cathode by the appropriate symbol.
5. Note the voltage on a D cell battery. To create an electrolytic cell, the voltage (potential) of the D cell battery must be higher than the voltage of your cell. If the D cell voltage is not higher than the voltage of your cell, connect D cell batteries in series until this condition is met.
6. To create an electrolytic cell, you will need to have the potential configured so that it is opposite of your electrochemical cell so that the current will be reversed.



Galvanic Cell



Electrolytic Cell

see text for anode/cathode designations for batteries

7. Once connected, make visual observations. Be particularly attentive to the color and any reactions around the electrodes and in the solution.

Data Sheet for Lab 1

Activity 1 -Building an electrochemical cell

Draw your cell here.

Voltage without salt bridge (no filter paper)	
Voltage with salt bridge (filter paper)	
Current with salt bridge:	
E^ocell predicted	
% difference	
Reason for % difference	

Activity 2 - Building a battery

Draw your battery here. Be sure to label all components as specified in the lab directions.

Voltage of battery (3 cells)	
Current of battery (3 cells)	
Predicted battery voltage	
% difference	
Reason for % difference	

Activity 3 -Effect of contamination

Cell 1 contaminated with copper nitrate Voltage and current with 3 drops Voltage and current with 2 to 5 mLs	
Explanation	
Cell 2 contaminated with charcoal or carbon black Voltage and current	
Explanation	
Cell 3 beakers touching Voltage and current	
Explanation	

Activity 4 - New cell, electrolytic conditions

Draw a picture of your new cell, being sure to label all parts.

1. Write the half-cell oxidation reaction and indicate it's half-cell standard oxidation potential.

2. Write the half-cell reduction reaction and it's half-cell standard reduction potential.

3. Write the overall electrochemical reaction and calculate the E^ocell.

4. Compare your cell voltage _______________ to the E^ocell ____________ by calculating the % difference.

5. What is the voltage of a D cell battery?

6. How many D cell batteries did it take to create an electrolytic cell for your reaction?

7. List visual observations for your electrolytic cell.

8. What are the reasons for the visual observations seen while reversing the current flow in your cell?


Lab 2 *Building an Electrochemical Cell* supplies
FISHERbrand
Filter Paper
P5
Electrode set – Carolina.com, #757487


Creating a simple salt bridge
from filter paper.

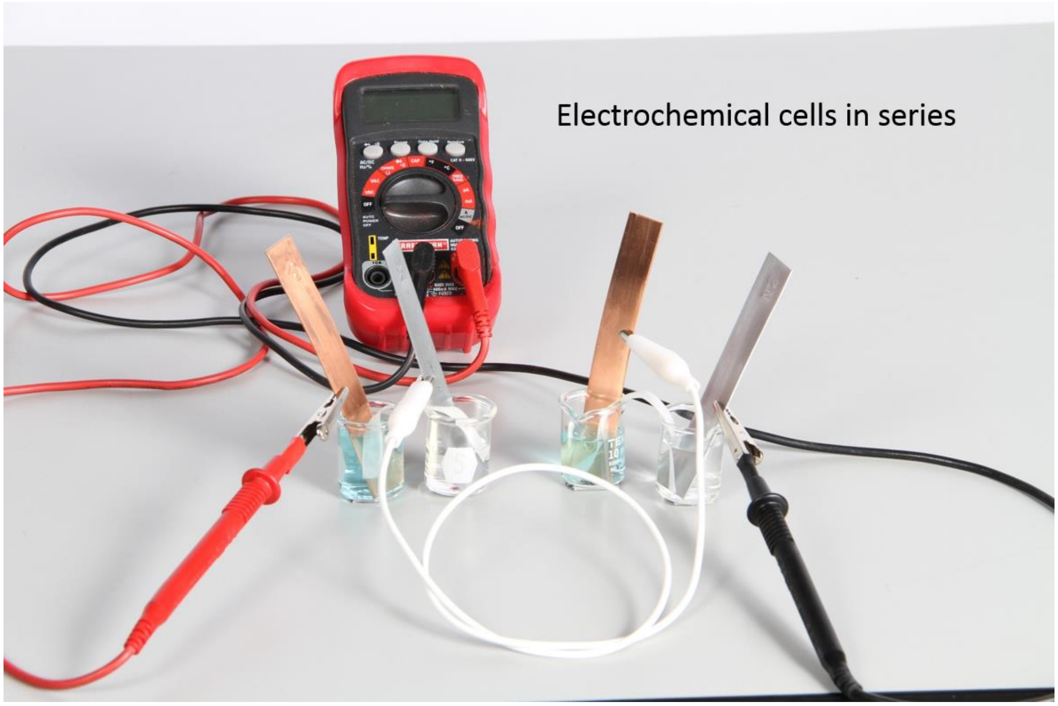
Ground on Anode

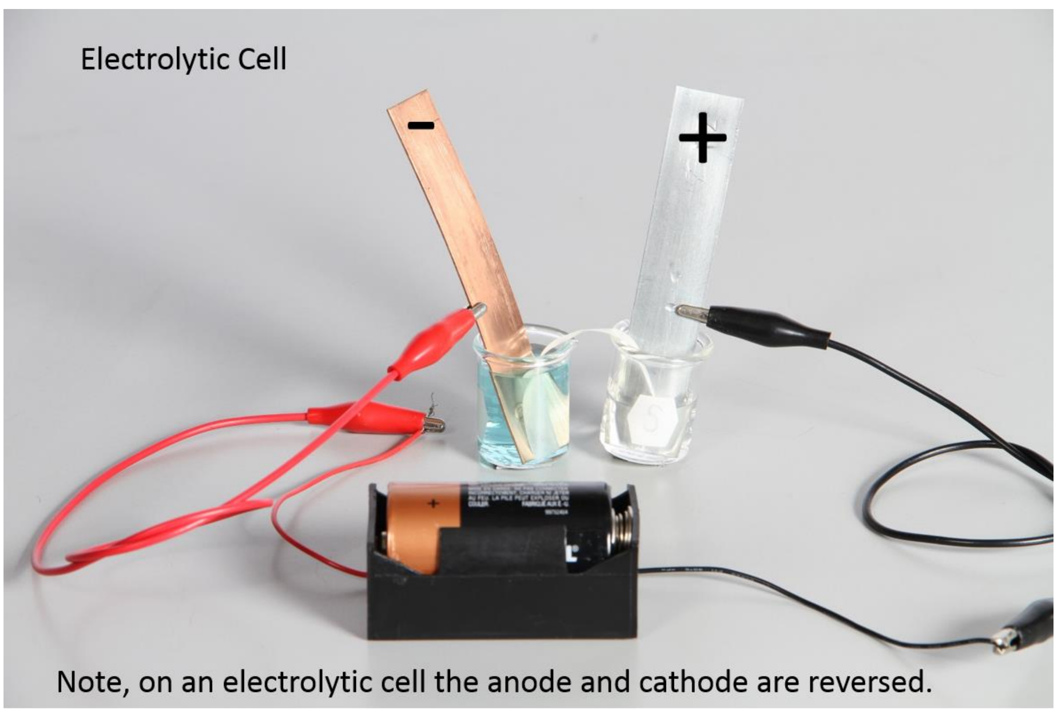
Glass beakers may conduct slightly resulting in voltage error if touching.

Alternative electrochemical cell setup
Carolina.com, #757586A

Cathode solution

Anode solution


Electrochemical cells in series


Electrolytic Cell
−
+
Note, on an electrolytic cell the anode and cathode are reversed.

Section B: Battery Packs

End Goals: This section describes the structure, interconnection, and components of common battery packs found in automobiles.

To the Student: The focus of this section will be to understand the battery packs that are used in Hybrid and Plug-in Electric Vehicles. Components, electronics, cooling, and attachment will be covered.

Content Outline:

- Major Components
- Outer Shell
- Electronics
- Cooling
- Attachment

Body of Knowledge:

1 **Overview of the structure of the battery packs**

a **Major components**

The battery packs contain three major components: the outer shell, the battery cells, and the mechanical and electrical connection points. These components can be separated from each other to be dealt with individually. The outer shell will need to be opened or removed to access the battery cells, which can then be dealt with individually.

The outer shell will also contain the wiring and connectors that will provide terminals for tying into the car's electrical system as well as interconnection terminals for the individual battery cells. There may also be some electronics on circuit boards relevant to the charging or discharging operation of the battery pack.

i **Outer shell**

The outer shell provides a physical barrier for the battery cells and the electronics contained for interconnection and charge controls. It also has the form for integrating with the car's physical structure ensuring a secure containment. Because of the uniqueness of the cars' shapes and sizes, there is likely to be little inter-vehicle standardization with the shape and size of the complete battery bank. Many times the outer shell will have the electronics and cooling channels integrated into its structure.

ii **Electronics**

The primary function of the electronics outside of the battery cells is to provide interconnection means within the battery pack as well as connection terminals for integration with the car's electrical system. The circuitry and functionality will vary between battery packs for different vehicles. A primary function that will be tested is the integrity of the conduction paths and the connection points.

iii **Cooling**

Lithium-ion batteries can generate substantial heat during the charging and discharging processes. Because heat affects battery performance and capacity, a cooling system will be integrated into the battery pack. This cooling will affect the overall performance of the system, but also is intended to keep all of the individual cells in a similar condition so their performance is consistent throughout the pack. Evaluation and performance verification with the cooling system will be very important.

iv **Attachment**

An important feature of the battery pack deals with its attachment to the vehicle. Assessing integrity and proper elements to the attachment system is important to the safety and performance of the battery pack. As with other elements, the attachment methods and devices are likely to vary between brands and car varieties. Only attempt to detach the battery pack from the vehicle after switching off the disconnect, waiting at least ten minutes, and disconnect external connections from the pack.

2 **Safe Handling**

A. **PPE**

Lithium-ion batteries can be volatile when exposed to certain conditions, and the elements contained are not generally safe for direct human contact. Although the intention of this instruction module is to avoid direct contact with any harmful substances, including airborne particles, protection against accidental exposure or broken containers is necessary. The elements within the batteries' electrodes and plates, the electrolyte, and the electrical potential energy pose great possible danger to someone unprotected. A full face shield, chemical and electrical resistant gloves, and a splash apron are all required for proper protection.

B. **Electrical Safety**

Due to the large energy capacity of the batteries within the system, extra care with electrical safety is necessary. Besides the personal protective equipment discussed above, it is essential to have a non-conductive work surface in case of contact with exposed terminals. If possible, remove jewelry from hands to protect against accidental shorting with a low-resistance material. A volt-meter to check the state-of-charge is a good tool for determining the potential energy present in a cell or system. Depending on the type of terminals present on the individual battery cells, connectors can be made to securely attach to the cells for voltage testing, charging, and discharging. Whenever discharging the battery system, bleed resistors will be used to insure current limiting so the batteries can safely discharge with less risk of thermal runaway and over-stressing the batteries' capabilities.

C. **Organization of the workspace.**

The layout of the work area will facilitate safe and efficient evaluation of the battery systems. For physical protection, assuring that batteries cannot fall among each other (and potentially have contact between terminals) and cannot fall to the floor, fixtures and curbs may work the best. For electrical safety and efficiency of testing, have a charger, meter, bleed resistor, temperature probes, timer, and data entry device mounted and conveniently located. Fitting the test leads with terminals that will mate securely with the batteries and battery pack will provide a safe and reliable connection. A properly rated DC switch for the bleed resistor will help with accurate time measurements and prolong the life of the connection terminals. Have a Class ABC fire extinguisher mounted to the workstation to assure easy access and the ability to safely fight various causes of fire.

D. **Disassembly**

Care must be taken when disassembling the battery pack to avoid forcing, cutting, or breaking the outer case. Assess the pack for tools needed to open and remove various parts from within. If the pack is riveted or bonded by adhesive or plastic welds, a means to break the bond without damaging the internal cells will need to be employed. Ideally, the outer shell can be re-used.

2 **Techniques for diagnosis**

a **Disassembly**

Discharging the pack as a whole using a bleed resistor will be the safest first step in the disassembly process. Getting the energy level as low as possible before extensive handling will minimize the risk of injury. The next step will be to split the outer case. When the case is able to open, check for all electrical connections that are between the case and the internal components, disconnect them if disassembly is restricted by their connection. Photographing the disassembly process will give a good record for re-assembly, if needed. Also, labeling wires, connectors and their mates, and assemblies will be useful for re-assembly. Place the disassembled parts securely in the work-space for further assessment.

b **Physical Assessment**

Look over all components of the assembly for physical imperfections such as: cracks, corrosion, white powder around vent, chafing, broken wires, discoloration, restricted air or water channels, and liquid or debris. Also make note of all labeling including manufacturers, model numbers, serial numbers, and ratings.

c **Battery Charging**

The first electrical assessments will involve charging the individual modules and testing their voltage at different intervals of time. Then there will be tests involving charging and assessing the battery response to different rates of discharge. Having the charging circuit properly configured and wired will be essential for the electrical testing.

The voltage, current rates, and charging control must be specifically for Lithium-ion cells. The charging current should be at 0.3xIt(A) [Amp-Hour rating / 1 Hour] amps for cylindrical cells and 0.7xIt(A) amps for prismatic (rectangular) cells allowing the voltage to rise to a maximum of 4.2 volts. When the maximum voltage is reached, allow the current to drop below its set point. Charge is complete.

d **Electrical tests and procedures**

i Self-Discharge

Fully charge the battery and disconnect terminals from all associated circuitry. At time intervals of: 1 hour, 4 hours, 24 hours, and 48 hours, note the voltage of the battery. The rate of self-discharge will give an indication of the battery's state of health.

ii Controlled-Discharge

Fully charge the battery. Connect the proper discharge resistor to the battery terminals, connect the resistor load by closing the disconnect switch, record the voltage of the battery and the time. Using the It(A) rating [Amp-Hour rating / 1 Hour] At one minute time intervals, note the voltage of the battery. If the cell voltage gets below 2.5 volts/cell, stop the test.

iii Diagnostic Tools

There are commercially available diagnostic tools for Lithium Ion batteries. One such unit is from Automotive Research and Design in Sterling Heights, Michigan. Their unit, BDUGENII, is powered from 12VDC and creates a database to log the results of each test.

3 **Post Diagnosis**

Sorting

i Categories

For all of the modules that have been tested, sort them by test results into multiple categories. There will be multiple categories within the acceptable range, unacceptable modules can be put together.

ii Acceptable Modules

For modules within the acceptable category, separate them into sub-categories which span ranges of discharge times, energy capacity, and power capacity – as found in previously described tests.

iii Unacceptable Modules

Any modules that are physically damaged, leaking, or fail the electrical testing are to be considered unacceptable. Because of the toxicity and

Lithium-Ion Battery Assessment

Terms and definitions

Battery Pack
The complete integrated unit that includes the outer shell, the battery cells, the electronic controls, and the mechanical and electrical connections

C/x Discharge
The current limit for a particular battery or pack. C is the capacity in Amp-Hours, x is the time in Hours.

State-of-Health (SOH)
The designation of the battery's overall condition and ability to deliver the rated capacity.

State of Charge (SOC)
The amount of charge that the battery shows, as indicated by its open-circuit voltage.

Degree of Discharge (DOD)
100% minus the State of Charge

Self Discharge
Reduction in the State of Charge with no electrical connection to the battery.

Maximum Operating Voltage
A limit set by the battery manufacturer to prevent an overcharging condition.

Minimum Operating Voltage
A limit set by the battery manufacturer to indicate the designation of an over-discharge condition

Open Circuit Voltage
A voltage measurement on the battery terminals with no electrical connection to the battery.

Overview
Section B – Battery Packs

Lab 3 –Battery Pack Configurations

End Goals: This lab is designed to give the student an understanding of how the voltage and current capacities are affected by the parallel and series connection of power supplies in a circuit. They will use batteries in different configurations and measure the resultant signals to quantify the effect.

Pre-Requisites:

- A basic understanding of simple electrical connections
- The ability to perform algebraic calculations on a scientific calculator
- Knowledge of Ohm's laws formulas

Materials

- Four D-cell batteries
- Holders for batteries with pig-tail wires
- Resistors: Three 5Ω 5 Watt
- Jumper wire
- Terminal strip
- Multi-meter
- Scientific calculator

Purpose: This lab demonstrates principles of voltage and current values related to parallel and series connections on the generation side of circuits.

Safety

Even with simple, low power circuits, it is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present

Activities

1. Activity 1 – Voltage sources, series and parallel
    a. Setup
        i. Assemble batteries on the lab bench.
        ii. Get the interconnection wire, a terminal strip and a multi-meter ready for use.
    b. Steps
        i. Connect four batteries to a terminal strip, one lead on each terminal.
        ii. Using a multi-meter, measure the voltage of each battery using the DC Voltage setting.
        iii. Interconnect the (-) terminal from battery 1 to the (+) terminal of battery 2, the (-) terminal of battery 2 to the (+) terminal of battery 3, and the (-) terminal of battery 3 to the (+) terminal of battery 4.
        iv. Using a multi-meter, measure the voltage of the battery bank by connecting the meter's red lead to the (+) terminal from battery 1 and the (-) terminal from battery 2.
        v. Disconnect the interconnection wires.
        vi. Interconnect all of the (-) terminals from the batteries together. Interconnect all of the (+) terminals from the batteries together.
        vii. Using a multi-meter, measure the voltage of the battery bank by connecting the meter's red lead to the (+) terminal connection and the meter's black lead to the (-) terminal connection.
        viii. Disconnect the interconnection wires.

2. Activity 2 – Loaded voltage sources, current and power
    a. Setup
        i. Assemble batteries and resistors on the lab bench.
        ii. Get the interconnection wire, a terminal strip and a multi-meter ready for use.
    b. Steps
        i. Connect one battery to a terminal strip, one lead on each terminal.
        ii. Using a multi-meter, measure the voltage of the battery using the DC Voltage setting.
        iii. Connect 10Ω of resistance across the leads of the battery.
        iv. Record the voltage of the series voltage circuit.
        v. Disconnect the + lead from the series resistive circuit.
        vi. Changing the multi-meter to "current" mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
        vii. Disconnect the circuits.
        viii. Connect 5Ω of resistance across the leads of the battery.
        ix. Record the voltage of the series voltage circuit.
        x. Disconnect the + lead from the series resistive circuit.

xi. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
xii. Disconnect the circuits.
xiii. Connect 2.5Ω of resistance across the leads of the battery.
xiv. Record the voltage of the series voltage circuit.
xv. Disconnect the + lead from the series resistive circuit.
xvi. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
xvii. Disconnect the circuits.

3. Activity 3 – Increasing the source capacity
   a. Setup
      i. Keep the same setup as in Activity 2
   b. Steps
      i. Connect one battery to a terminal strip, one lead on each terminal.
      ii. Using a multi-meter, measure the voltage of the battery using the DC Voltage setting.
      iii. Connect 5Ω of resistance across the leads of the battery.
      iv. Record the voltage of the series voltage circuit.
      v. Disconnect the + lead from the series resistive circuit.
      vi. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
      vii. Connect a second battery in parallel.
      viii. Record the voltage of the series voltage circuit.
      ix. Disconnect the + lead from the series resistive circuit.
      x. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
      xi. Connect a third battery in parallel.
      xii. Record the voltage of the series voltage circuit.
      xiii. Disconnect the + lead from the series resistive circuit.
      xiv. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
      xv. Connect a fourth battery in parallel.
      xvi. Record the voltage of the series voltage circuit.
      xvii. Disconnect the + lead from the series resistive circuit.
      xviii. Changing the multi-meter to “current” mode, put the multi-meter leads in series with the + lead and the resistive circuit. Record the current of the series circuit
      xix. For each circuit, calculate the power produced with this resistive load.

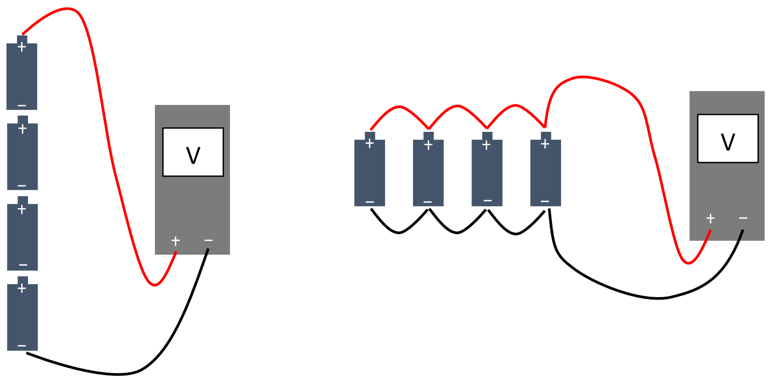
Data Sheet for Module 1 – Section 2

Activity 1 – Voltage Sources		
Component	Measured Voltage	
Battery 1		
Battery 2		
Battery 3		
Battery 4		
Battery Bank (series)		
Battery Bank (parallel)		

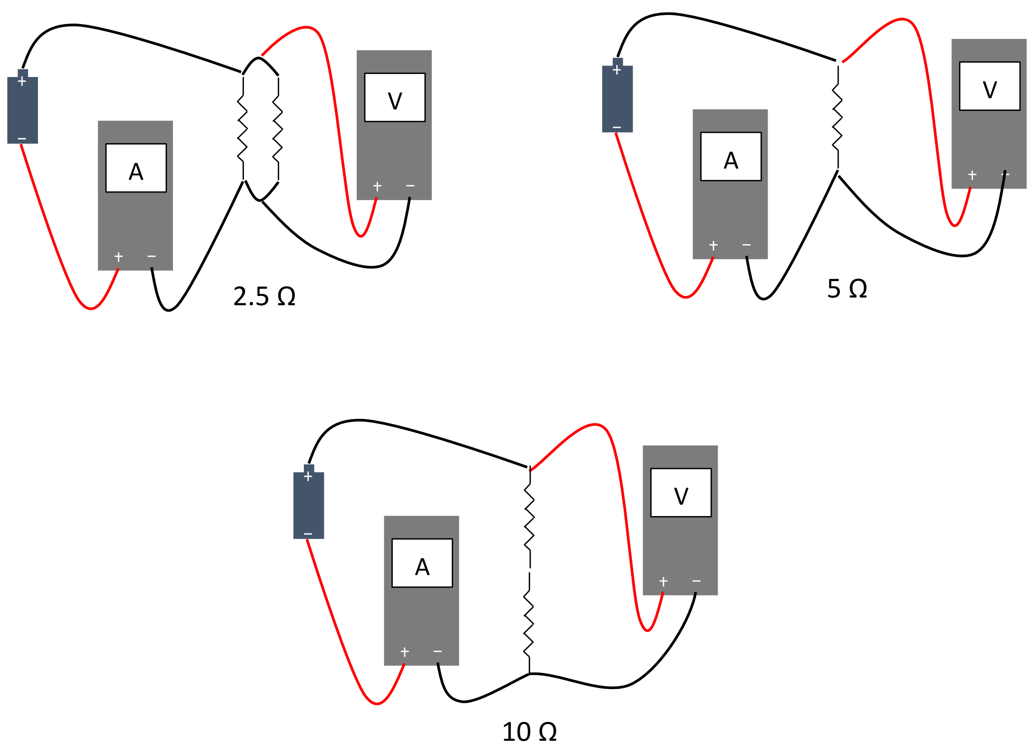
Activity 2 – Loaded Voltage Sources		
Component	Measured or Calculated Value	Units
Battery Bank (source)		Volts
Load Resistor 1	2.5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts
Battery Bank (source)		Volts
Load Resistor 2	5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts

Component	Measured or Calculated Value	Units
Battery Bank (source)		Volts
Load Resistor 3	10	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts

Activity 1

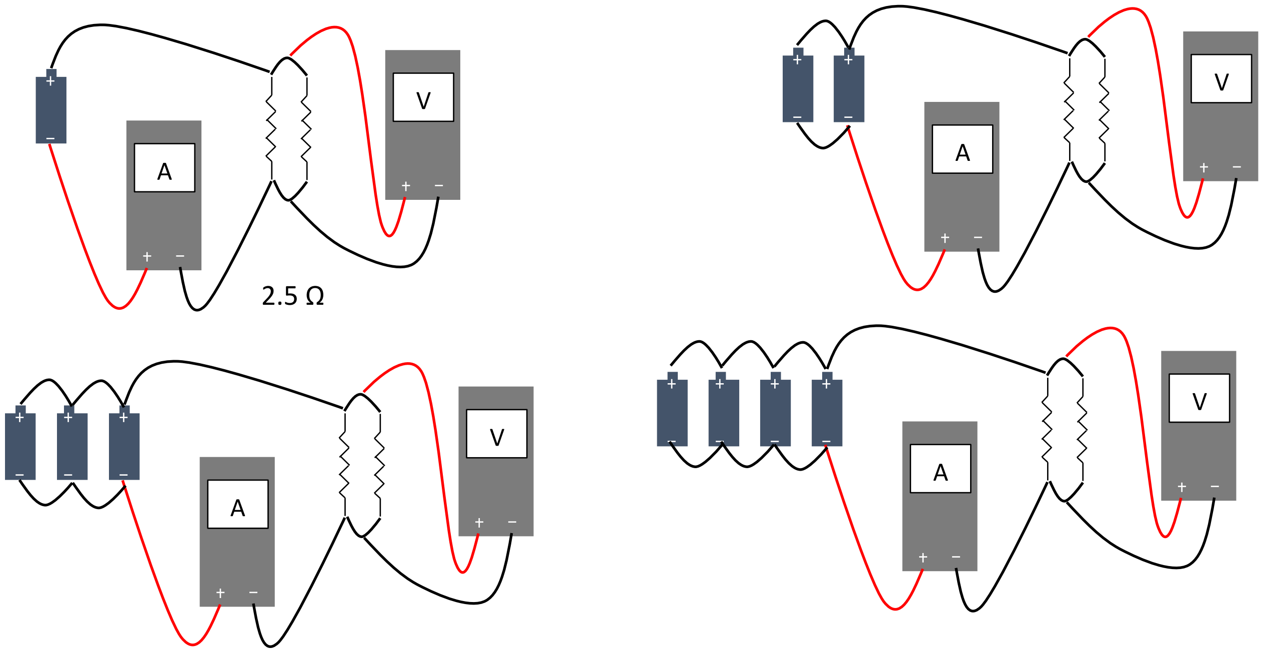


Activity 2



Activity 3 – Increasing Source Capacity		
Component	**Measured or Calculated Value**	**Units**
Batteries in Parallel	1	Each
Load Resistor	2.5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts
Batteries in Parallel	2	Each
Load Resistor	2.5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts
Batteries in Parallel	3	Each
Load Resistor	2.5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts
Batteries in Parallel	4	Each
Load Resistor	2.5	Ohms
Resistor (load)		Volts
Circuit Current		Amps
Circuit Power		Watts

Activity 3

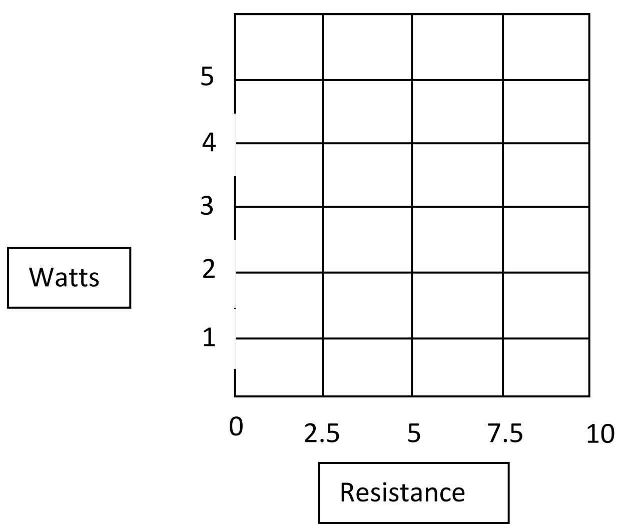


Analysis (Questions)

a. From Activity 1, what is the formula for calculating total open-circuit voltage of sources in series?

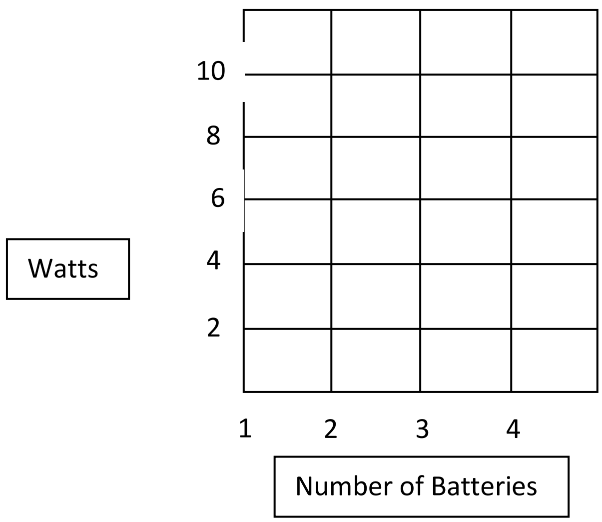
b. Activity 2, did the voltage of the circuit change when a resistive load was introduced? Why do you think this is?

c. Activity 2, plot the power for each circuit tested using "resistance" on the X axis and "watts" on the Y axis. What is the trend?



a. Activity 3, did the voltage of the circuit change when different numbers of source power supplies were introduced? In what way?

b. Activity 3, plot the power for each circuit tested using "number of batteries" on the X axis and "watts" on the Y axis. What is the trend?



c. If the open-circuit battery voltage is the same with any number of batteries in parallel and the load resistance is the same – why would the power of the circuit change with more supply capacity?

For the instructor (not to be printed with the student lab)

This lab demonstrates source circuit voltages based on series and parallel configurations. It also shows differences in circuit response because of power supply capacity and loads.

Answers to the questions:

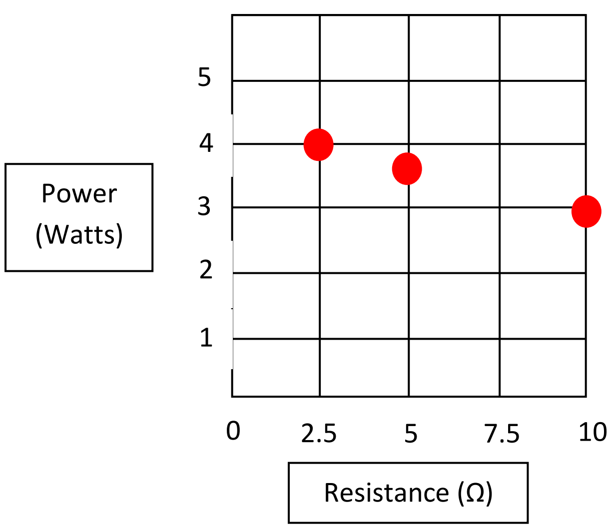
Analysis and graphs

a. From Activity 1, what is the formula for calculating total open-circuit voltage of sources in series? $V_T = V_1 + V_2 + V_3 + V_4$

b. Activity 2, did the voltage of the circuit change when a resistive load was introduced? Yes, it became lower.

   Why do you think this is? When there is a load on a power supply, the internal resistance becomes part of the circuit. The voltage at the load will equal the open-circuit voltage minus the voltage loss due to the internal resistance of the battery.

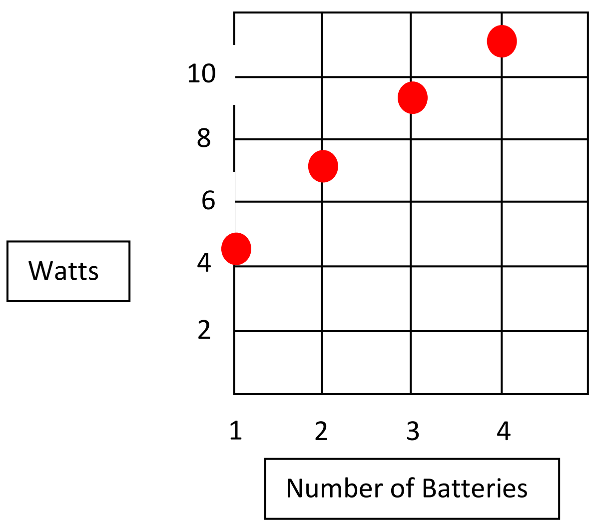
c. Activity 2, plot the power for each circuit tested using "resistance" on the X axis and "watts" on the Y axis. What is the trend? Higher power with lower resistance, due to the voltage being mostly constant using the formula:
   $P = V^2 / R$



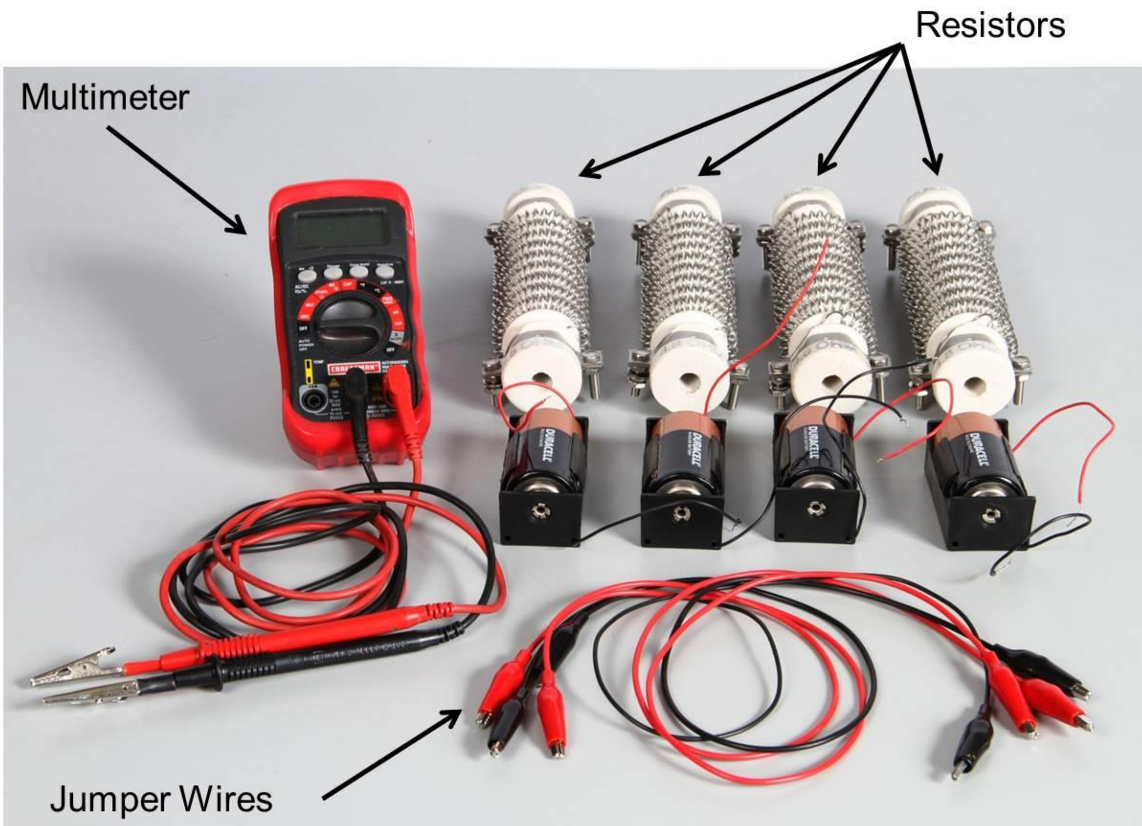
d. Activity 3, did the voltage of the circuit change when different numbers of source power supplies were introduced? Yes

e. In what way? It increases closer to the open-circuit voltage with an increased capacity source.

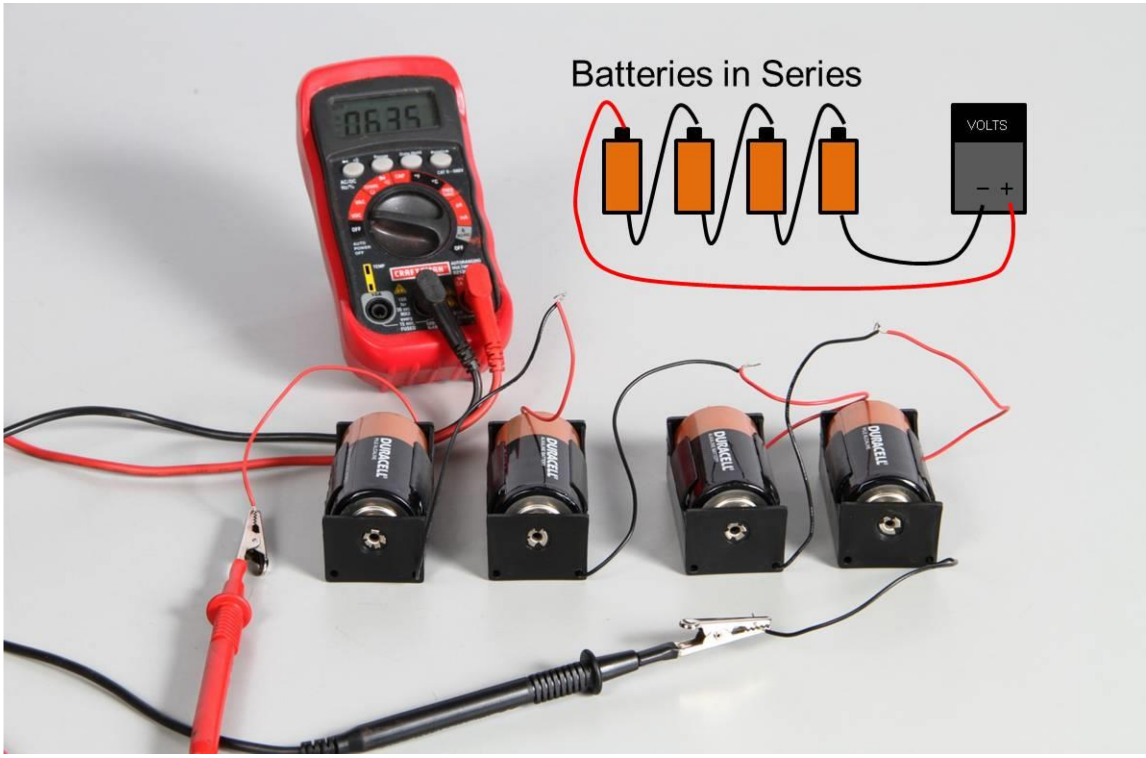
f. Activity 3, plot the power for each circuit tested using "number of batteries" on the X axis and "watts" on the Y axis. What is the trend?

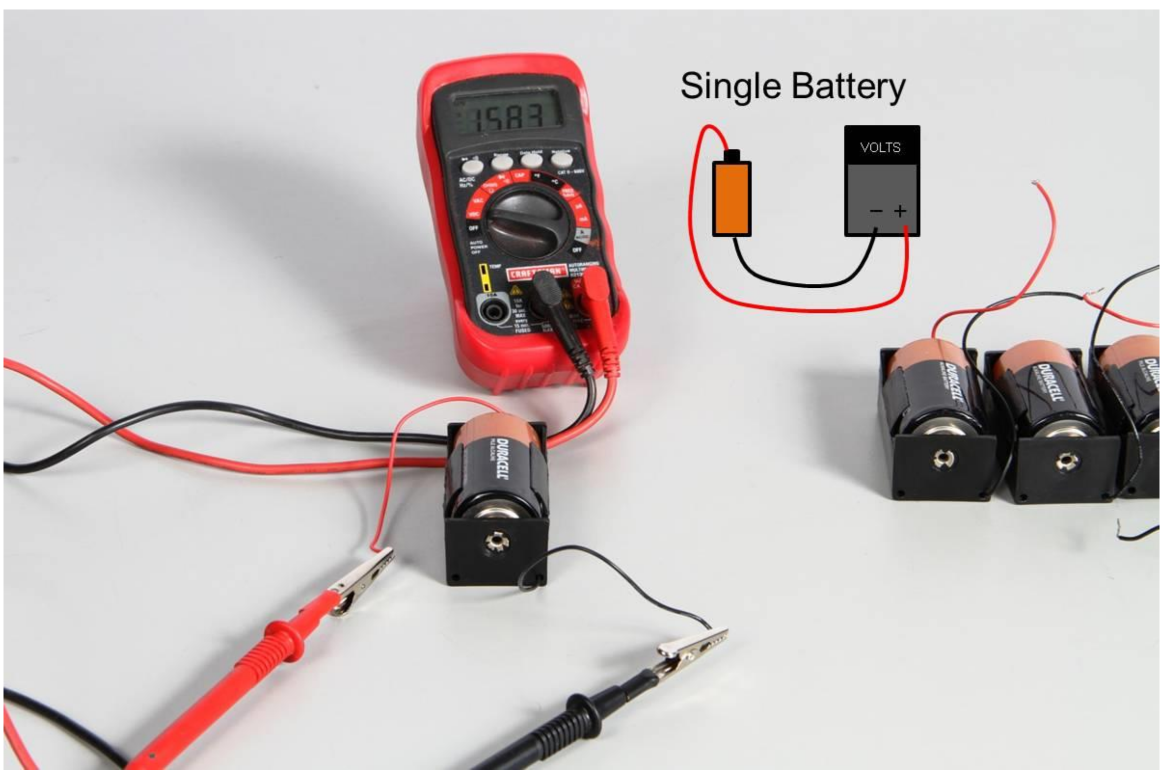


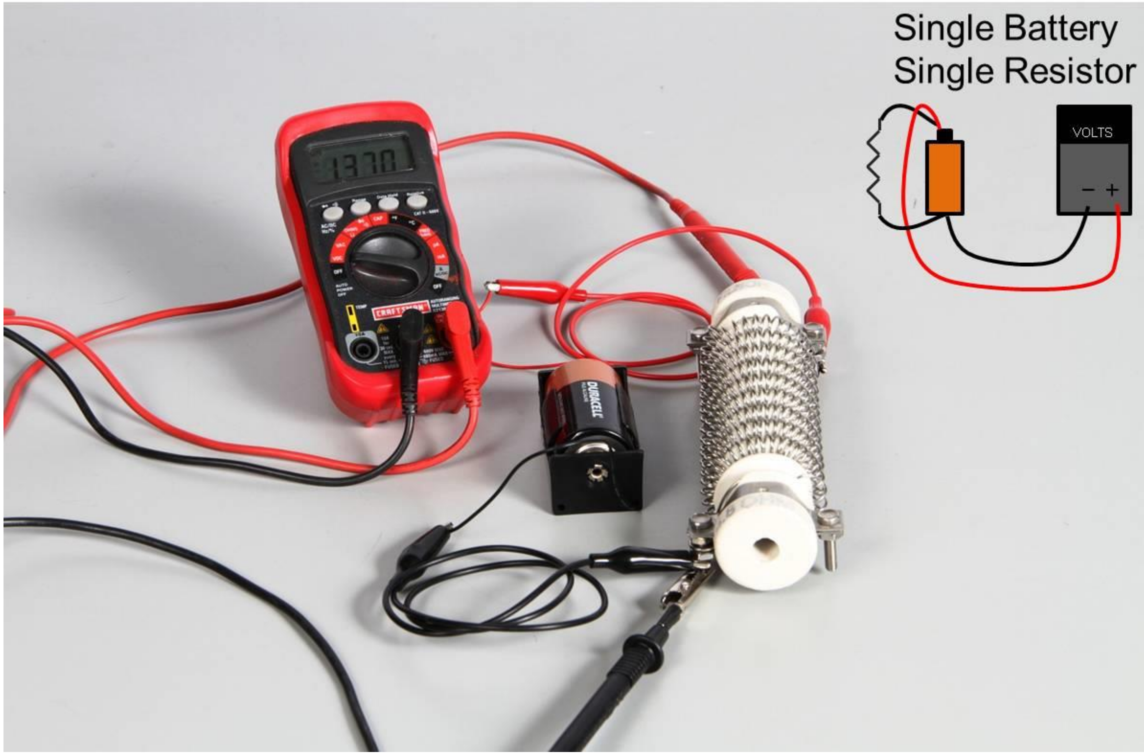
g. If the open-circuit battery voltage is the same with any number of batteries in parallel and the load resistance is the same – why would the power of the circuit change with more supply capacity? The ability to deliver more current to the load without as much stress on the voltage source. It can be related to the internal resistance of the batteries, which are calculated as parallel resistances therefore lower as battery quantities increase.

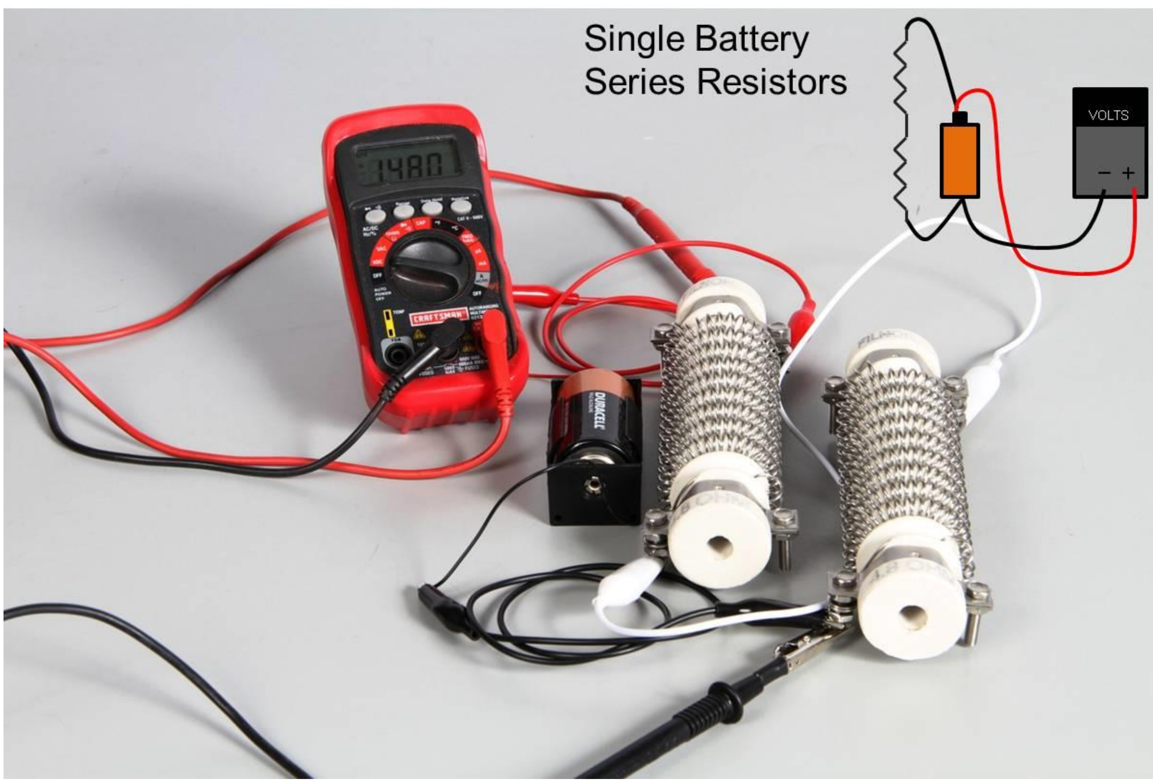


Supplies

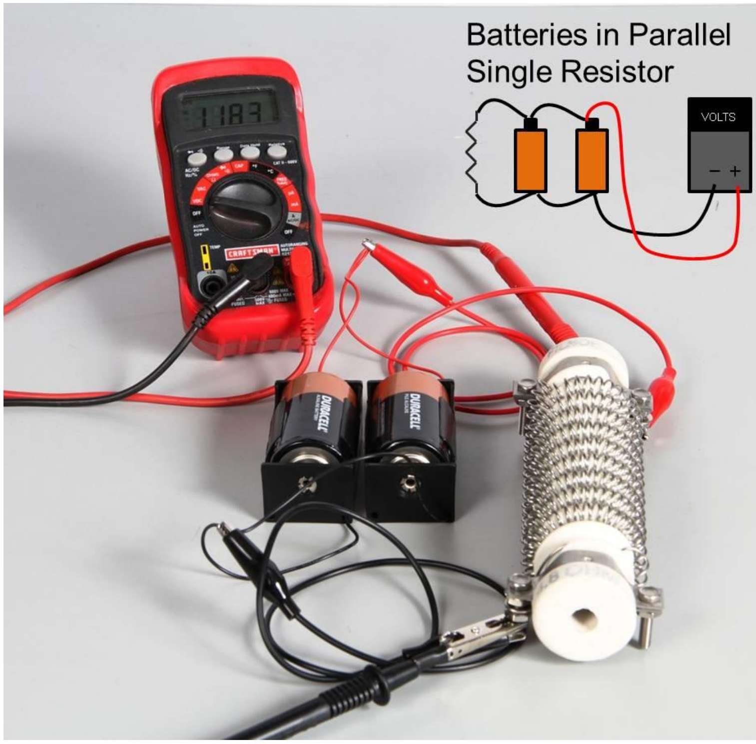

Batteries in Series
VOLTS
– +
0635
DURACELL


Single Battery
VOLTS
– +
1583
DURACELL

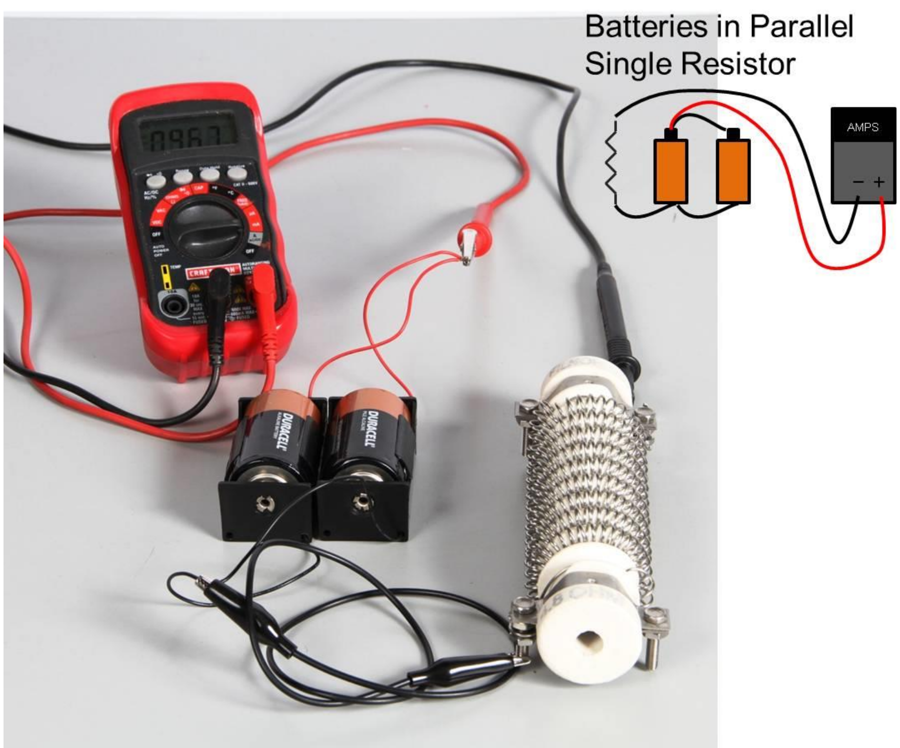




Wiring configurations



Voltage Measurement



Current Measurement

Section A: Disassembly

End Goals: This section describes the disassembly of battery packs. It includes safety as well as organization issues.

To the Student: The focus of this section will be to safely disassemble battery packs prior to assessment. Safe handling, workspace organization, documentation, and techniques will be covered.

Content Outline:

- Safety
- Workspace
- Methods
- Documentation

Body of Knowledge:

1 Safety, Handling

Lithium Ion batteries are safe to handle when they are properly sealed, are prevented from making an electrical connection, and are safely contained to not pose the possibility of falling or being dropped.

a. Properly sealed

Lithium Ion batteries have the possibility to be reactive when exposed to oxygen, both in the air and in water. Assuring the case is intact and not damaged is essential. Keeping the electrolyte contained is important, it should not be allowed to spill on your clothing or have any contact with your skin.

b. Prevention of making an electrical connection

These batteries, as with any batteries, are able to store great amounts of energy. Releasing this energy through inadvertent connection of the terminals can be dangerous and damaging. Keep all conductive materials away from the battery cells while working on them, including the bench-top, personal jewelry, and other conductive parts in the workspace. Not knowing the state of charge, you must assume that it is high and very dangerous. The result can be arcing, welding, thermal runaway, explosion, and a break in the case.

c. Falling or dropped batteries

A battery being dropped or falling from the workspace can result in the case being broken and spillage of the electrolyte as well as exposure to oxygen. To prevent this, be sure to have a workspace that can properly contain the battery cells from sliding or rolling off.

2 Workspace

Besides the safety aspects of the workspace, as defined above, layout of the space will help with the organization of the assessment in an efficient manner.

The battery pack will require an adequate amount of space to segregate the various sub-assemblies contained in the pack. Depending on the manufacturer and the application, these assemblies may be separate or combined.

The outer shell needs to be removed to expose the battery frame, electronic controls, and interconnection wiring. There should be room to set this aside apart from the rest of the pack. The electronic controls section may be removable; this too will need space to be set aside. All of the removed parts will require adequate bench top space to be placed during the disassembly.

Eventually, the battery cells will be items that will be assessed, so leaving room for them at the easiest accessed spot on the work surface will make a comfortable working environment. There also will need to be room for the testing and charging equipment which will include, at a minimum, a multi-meter, charger(s), and resistor banks.

If there is a damaged cell, with a broken shell or otherwise exposed internal component, it should be placed in a separate container for recycling. Make sure the container is in a stable and convenient location and is dry.

3 Methods

The end goal of the disassembly process is to separate the individual battery cells for evaluation and sorting. It is recommended to take photos of the battery pack at each step during the disassembly process as a record, which may be helpful if the same assembly is re-built.

Using common tools, the outer shell should first be removed to expose the inner components to be disassembled. It is preferable to use insulated handles on the tools in case there is an accidental electrical connection. Following the shell removal, disconnect any of the electrical connections that are exposed. It will be helpful to label the wires and terminals, on both sides of the connection, to assure re-connection to the same point.

Remove any sub-assemblies that have exposed fasteners. Putting the fasteners back into the framework after disassembly will keep them organized. There are likely to be busbars or interconnection cables that interconnect the individual battery cells that will need to be removed.

Remove the individual battery cells and organize them neatly so they can be tested individually. If each cell does not have a unique serial number or marking, make your own mark to identify each one for record keeping purposes.

4 Documentation

The documentation process will be to fill out an assessment sheet that will identify each individual battery cell and fill in information as it is evaluated. The documentation will be used to identify the state-of-health of each battery cell which will eventually be used to sort them into categories related to this state-of-health for re-use or to justify their end-of-life recycling. The assessment sheets may be filled out by hand during the evaluation, but should eventually be entered as an electronic record for easier archiving as well as sorting and other automated data handling.

II. Assessment
Section A. Disassembly

Lab 4 – Battery Pack Examination and Identification of Components

End Goals: This lab is designed to give the student hands-on experience with locating and identifying the elements that make up a battery pack.

Pre-Requisites:

- A basic understanding of simple electrical connections
- A basic understanding of simple mechanical connections
- Understanding of the use of basic hand tools

Materials

- Manufacturer's data
- Labels
- Marker
- Camera

Purpose: This lab is a guide to the identification of the various components within a battery pack.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

Battery Pack Components

a. Setup
    i. Place a complete battery pack on a lab bench.
    ii. Assemble the manufacturer's data, labels, marker, and worksheets on the bench.
b. Activity
    i. On the identification form, document the following data found on the battery pack:
        1. Model #
        2. Serial #
        3. Date code
        4. Voltage
        5. A-H capacity
        6. Manufacturer
    ii. Using the worksheets, identify the various components and sub-assemblies of the unit.
    iii. Make labels to adhere to the battery pack that include:
        7. Outer shell
        8. Bus bar or cable
        9. Battery cell
        10. Control electronics
        11. Main electrical terminals
        12. Tabs for securing into vehicle
        13. Structural framework
    iv. In the manufacturer's data, find the following:
        14. Limits on battery voltage, maximum and minimum
        15. Charging procedure recommendations
        16. Temperature limits

Data Sheet for Lab 4

Activity 1 – Battery Pack Nameplate Data		
Item	**Data**	**Notes**
Model #		
Serial #		
Date code		
Voltage		
Amp-Hour capacity		
Manufacturer		

Activity ii – Identification of Components		
Component	Quantity	Comments
Outer shell		
Bus bars or cables		
Battery cells		
Control electronics		
Main electrical terminals		
Tabs for securing into vehicle		
Structural framework		
Nameplate		
List other components:		

Activity iv – Manufacturer's data		
Item	Data	Notes
Battery Vmax		
Battery Vmin		
Charging Procedure		
Temperature High Limit		
Temperature Low Limit		
List other specifications:		

Analysis (Questions)

d. Following the bus bar or cables, what is the configuration of the battery pack in terms of batteries in series and parallel?

e. From the information in (a), what is the expected voltage and current capacity of each individual cell?

f. What is the overall energy capacity of the battery pack?

For the instructor (not to be printed with the student lab)

This lab has the student identify the various components in a battery pack, without disassembly. This will help them to understand the name of the sub-assemblies and look for important data specifications.

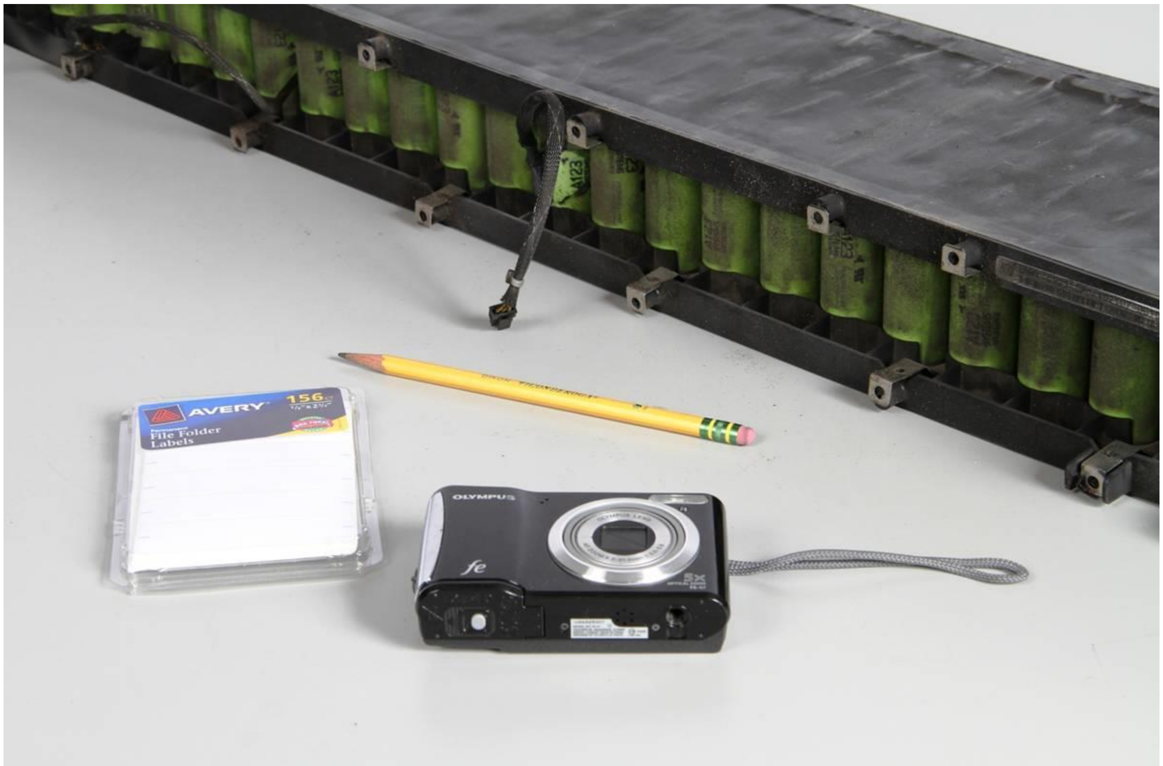
Answers to the questions:

Analysis

a. Following the bus bar or cables, what is the configuration of the battery pack in terms of batteries in series and parallel? The student will need to trace the connections between the (+) terminals and (-) terminals of the batteries to find how many are in each stack and how many stacks are wired in parallel. The nominal voltage of many Li-Ion batteries is around 3.7 volts, so a 42 volt pack would have 12 batteries in series.

b. From the information in (a), what is the expected voltage and current capacity of each individual cell? Dividing the battery pack voltage by the number of batteries in each stack will give the individual cell voltage. Dividing the A-H of the battery pack by the number of parallel stacks will give the individual cell A-H rating.

c. What is the overall energy capacity of the battery pack? This can be calculated by multiplying the battery pack voltage by its current capacity. The units will be Volts x Amp-Hours which will give Watt-Hours.



Supplies

II. Assessment

Section A Disassembly

Lab 5 – Workspace Organization

End Goals: This lab is designed to guide the student through the organization and set-up of a safe and effective workspace that will be used for battery pack disassembly and battery cell evaluation.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Ruler or tape measure
- Multi-meter
- Power-supply
- Battery recycling container
- Labels
- Marker
- Camera

Purpose: This lab will be used to organize the workspace to be used for battery pack evaluation.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

1. Finding dimensions needed in workspace
    a. Setup
        i. Start with an empty workspace.
        ii. Have a battery pack, tools, measurement instruments, and a power supply available on another lab bench close by.
        iii. Assemble labels and tape to mark the intended reserved areas.
    b. Activities
        i. Measure the following sub-assemblies on the battery pack to get the footprint dimensions
            1. Outer shell
            2. Electronics/control unit
            3. Electrical connectors
            4. Battery cells
            5. Workspace for evaluating individual cells
        ii. Measure the following to note the footprint needed for:
            1. Tools
            2. Measurement instruments
            3. Power supply
            4. Notebook
            5. Battery recycling container
        iii. Use tape or cutout templates to mark areas in the workspace that are reserved for the above elements.
            1. Be sure to reserve the best working area for the Workspace for evaluating individual cells with the other items in step ii conveniently located for effective and safe assessment.
            2. If the lab bench is not of adequate size, designate another bench for items 1-3 in step i and items 1 and 5 in step ii.
        iv. If the individual cells are cylindrical, create a curb around area reserved for Battery cells and the Workspace for evaluating individual cells

Analysis (Questions)

a. Draw the layout of the lab bench or benches with the designated areas labeled, including dimensions.

b. Why is a curb recommended around the battery cell areas?

c. Are there other suggestions for safety or efficiency?

For the instructor (not to be printed with the student lab)

This section will also get the students familiar with the disassembly of battery pack itself, in a safe and organized manner. Having the correct tools and workspace layout are stressed for a safe and efficient procedure.

Answers to the questions:

Analysis and drawings:

a. Draw the layout of the lab bench or benches with the designated areas labeled, including dimensions.
The student will have a drawing with all of the elements designated and dimensioned.

b. Why is a curb recommended around the battery cell areas?
To prevent them from rolling onto the floor.

c. Are there other suggestions for safety or efficiency?
Any suggestions that the students will have that will make for a safer or more efficient work environment.

Assembled Battery Pack

Supplies

Tools

II Assessment

Section A. Disassembly

Lab 6 – Disassembly

End Goals: This lab is designed to guide the student through the disassembly of a battery pack to prepare for assessment and diagnosis.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Battery recycling container
- Insulated tools including:
  - Screwdrivers
  - Sockets and ratchet
  - Open-end wrenches
  - Pliers
- Dust mask
- Soft cloth
- Labels
- Marker
- Camera
- Manufacturer's data

Purpose: This lab will be used to organize the workspace to be used for battery pack evaluation.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

1. Activity 1 – Disassembly of a Battery Pack
    a. Setup
        i. Start with the designated workspace.
        ii. Have a battery pack ready for disassembly.
        iii. Assemble tools and labeling items.
    b. Activities
        i. Document any data from the battery pack on the appropriate form.
        ii. Disassemble the battery pack by removing the most convenient components and sub-assemblies first
        iii. Label the parts, return fasteners to their original location where possible, and take photos of the various states of disassembly.
        iv. Place the removed parts in the designated areas
        v. Wipe off any loose dust or dirt with a soft cloth. Wear a dust mask if the dirt or dust is likely to become airborne.
        vi. Finally, make sure the individual battery cells are assembled in a safe and organized manor in the designated area.

Analysis (Questions)

Data Sheet for lab 6

Activity 1 – Battery Pack Nameplate Data		
Item	**Data**	**Notes**
Model #		
Serial #		
Date code		
Voltage		
Amp-Hour capacity		
Manufacturer		

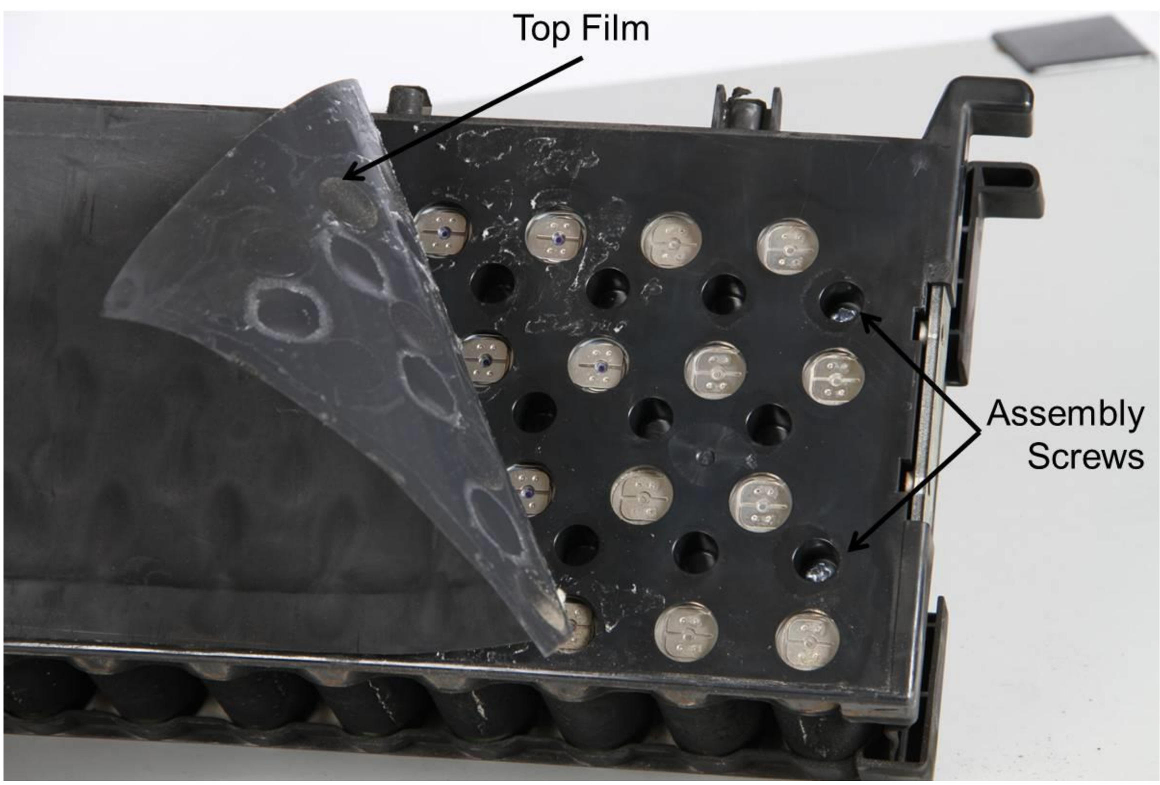
Activity 1 – Manufacturer's data		
Item	**Data**	**Notes**
Battery Vmax		
Battery Vmin		
Charging Procedure		
Temperature High Limit		
Temperature Low Limit		
List other specifications:		

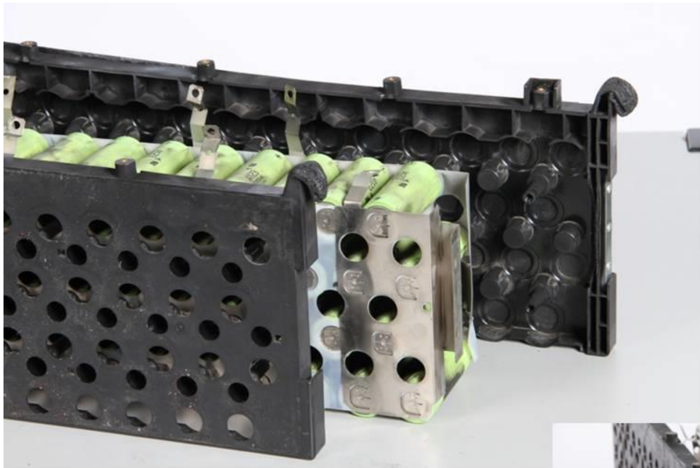
For the instructor (not to be printed with the student lab)

This section will also get the students familiar with the disassembly of battery pack itself, in a safe and organized manner. Having the correct tools and workspace layout are stressed for a safe and efficient procedure. It will also include the documentation of data found on the battery pack as well in the manufacturer's literature.

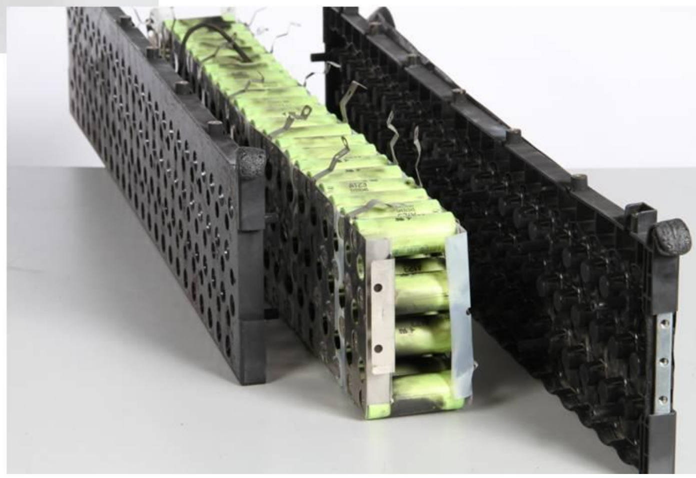
Standard Tools with Insulated Tools in Foreground

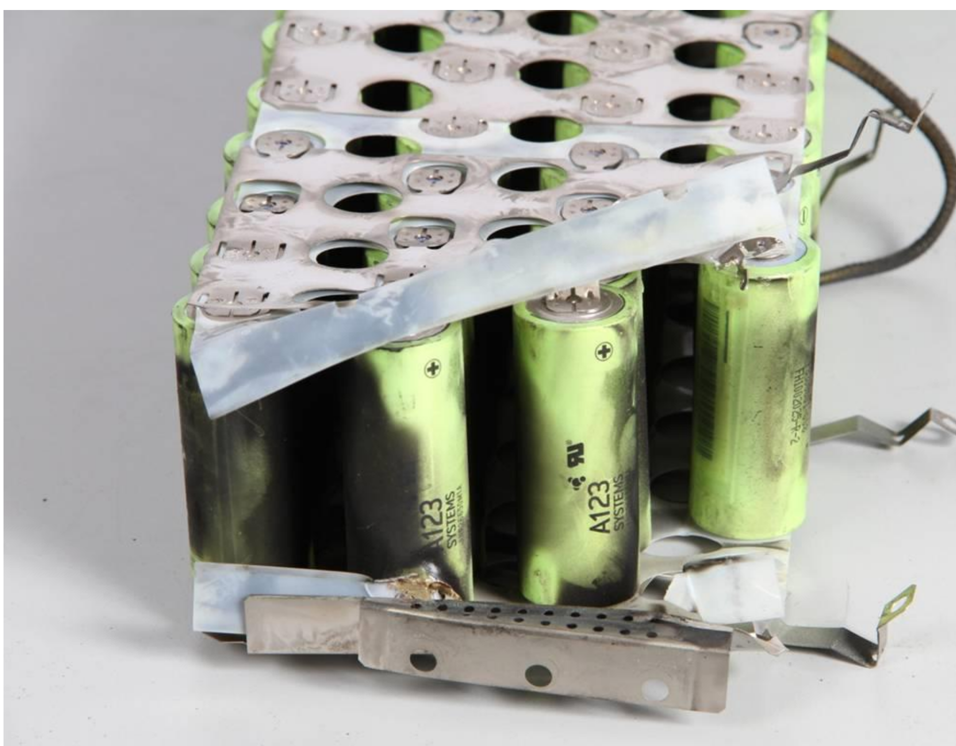

Assembled Battery Pack

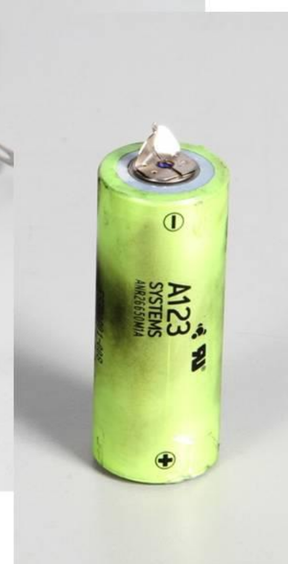

Top Film
Assembly
Screws



Disassembled Battery Pack







Cell removed, cut free or un-soldered

Section B: Physical assessment

B. **End Goals:** This section describes the physical assessment of the battery pack components. It includes safety as well as identification issues.

C. **To the Student:** The focus of this section will be to safely perform a physical assessment on the components within a battery pack. Safe handling and identification of potential problems will be covered.

D. **Content Outline:**

- Safety
- Outer shell
- Electrical connections
- Structure

E. **Body of Knowledge:**

1. Safety

   When the individual components are segregated from the others, assessment of all sides will be possible without hidden areas. With the potential of chemical and electrical exposure, be sure to use proper personal protective equipment (PPE) which includes gloves, safety glasses, no exposed jewelry, and an apron. Have a container available that will be used to contain damaged cells for recycling.

2. Battery cells

   The outer shell of the batteries is essential to inspect, as it can lead to an early rejection of a cell that may cause chemical damage potentially a reaction due to exposure. Carefully look at all sides of the cell and wipe it clean with a soft, dry, cloth. Look for cracks, evidence of chemical contamination, and evidence of overheating. If any of these flaws are present, put it in the container for damaged cells.

3. Electrical connections

   The electrical connections are essential for assuring maximum efficiency and effectiveness of the complete pack. Look for any rust or other corrosion at all connection points, both on the terminals and on the conductors.

   Examine the conductor paths, whether a bus-bar or cable, for any damage or corrosion along its length. Look for evidence of overheating. This will show up as a discoloration to the conductor or melted insulation or support structure. Resistance readings between terminal points can be made if there is a questionable appearance to any of the conductors. The resistance should be very low ($<1\Omega$).

   The electrical connections on the cells need to be inspected for any corrosion as well as the mechanical fastening ability of the terminal screw. Look for discoloration of the metal as well. With any of these indicated as problems, discard into the container for damaged cells.

4. Outer shell

   The outer shell should be inspected for any cracks and damage to fastening devices. Look for any corrosion of metallic parts as well. There will be tabs or other mating means where the battery pack is attached to the automobile when in service, these need to be inspected for structural integrity as well.
   When the shell is removed from the rest of the pack, flexing it will help to identify any cracks or other hidden flaws. Clean it off using a soft cloth to expose all of the surface without it being hidden by dust or dirt.

5. Structure

   The structural pieces that hold the battery pack together can be inspected for cracks, heat damage, discolored metal pieces, and failed fasteners.

F. **Materials Needed:** Insulated tools including:

- Battery pack
- Screwdrivers
- Sockets and ratchet
- Open-end wrenches
- Pliers
- Labels
- Marker

G. **Activities:** Disassemble battery pack as outlined in the previous module. Log the conditions found in your physical assessment of the following components.

- Outer shell
- Battery modules
- Structure
- Conductors

II. Assessment

Section B. Physical Assessment

Lab 7 – Physical Assessment

End Goals: This lab is designed to guide the student through the physical assessment of individual battery cells as well as battery pack components.

Pre-Requisites:

- Ability to use basic hand tools
- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Insulated tools including:
  - Screwdrivers
  - Sockets and ratchet
  - Open-end wrenches
  - Pliers
- Battery recycling container
- Labels
- Marker
- Camera

Purpose: This lab will be used to perform the first step in assessment of batteries and other components prior to the electrical testing.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

4. Physical Assessment
    a. Setup
        i. Have the batteries and battery pack disassembled and organized on the lab bench.
    b. Activities
        i. Assessment of battery cells
            1. Inspect the shell of the battery cell for cracks, chemical contamination, and evidence of overheating.
            2. Inspect the electrical terminals for corrosion, broken pieces, and other damage
            3. Inspect the seams for a good seal, corrosion, and chemical contamination
        ii. Assessment of conductors
            1. Corrosion
            2. Damage
            3. Evidence of overheating
                a. Discoloration
                b. Melted insulation or support structure
        iii. Assessment of outer shell of battery pack
            1. Cracks
            2. Chemical contamination
            3. Corrosion
        iv. Assessment of structural components of battery pack
            1. Cracks
            2. Damage
            3. Discolored metal pieces
            4. Failed fasteners

Analysis (Questions)

Data Sheet for lab 7

Activity i – Battery Cell Physical Assessment	Serial #	
Condition	**Acceptable/Unacceptable**	**Notes**
Shell - Cracks		
Shell - Chemical contamination		
Shell – Overheating evidence		
Shell - Other		
Terminals – Corrosion		
Terminals – Broken pieces		
Terminals - other		
Seams – Seal condition		
Seams – Corrosion		
Seams – Chemical contamination		

Activity ii – Conductors Physical Assessment		
Condition	**Acceptable/Unacceptable**	**Notes**
Corrosion		
Damage		
Overheating evidence		

Activity iii – Outer Shell Physical Assessment		
Condition	Acceptable/Unacceptable	Notes
Cracks		
Chemical contamination		
Corrosion		

Activity iv – Structural Components Physical Assessment		
Condition	Acceptable/Unacceptable	Notes
Cracks		
Damage		
Discolored metal pieces		
Failed fasteners		

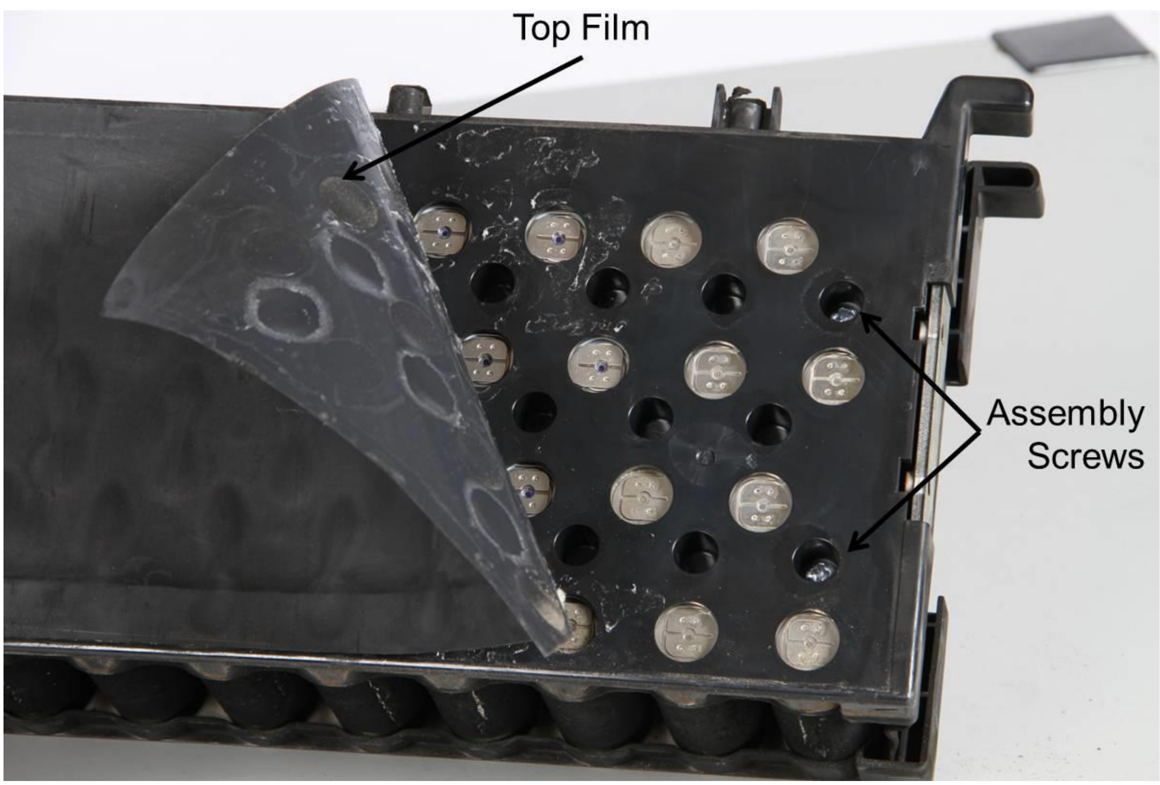
For the instructor (not to be printed with the student lab)

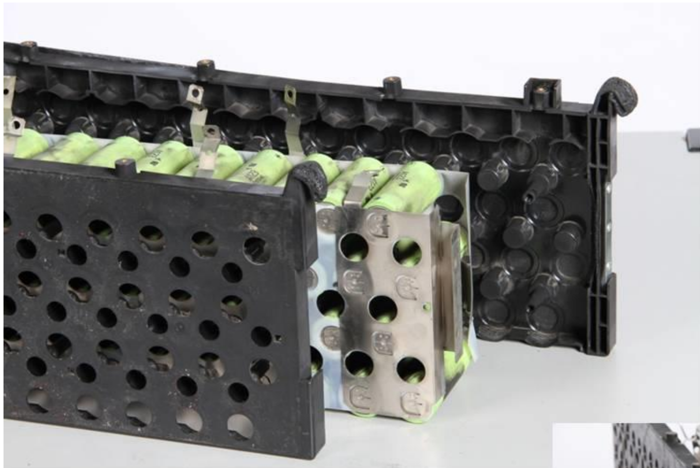
This section will get the students familiar with the physical inspection of each component of the battery pack. Early rejection of unsafe cells is stressed to avoid contamination of persons or other objects in the lab. This will prepare the student for the electrical assessment with a clean and safe group of batteries.

Tools

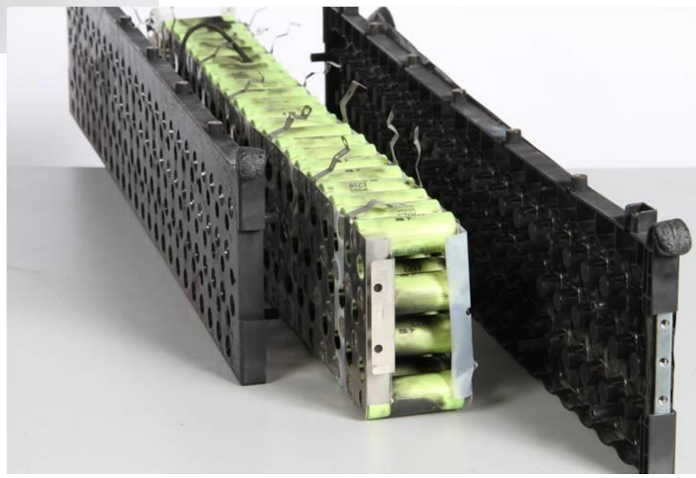
Insulated Tools

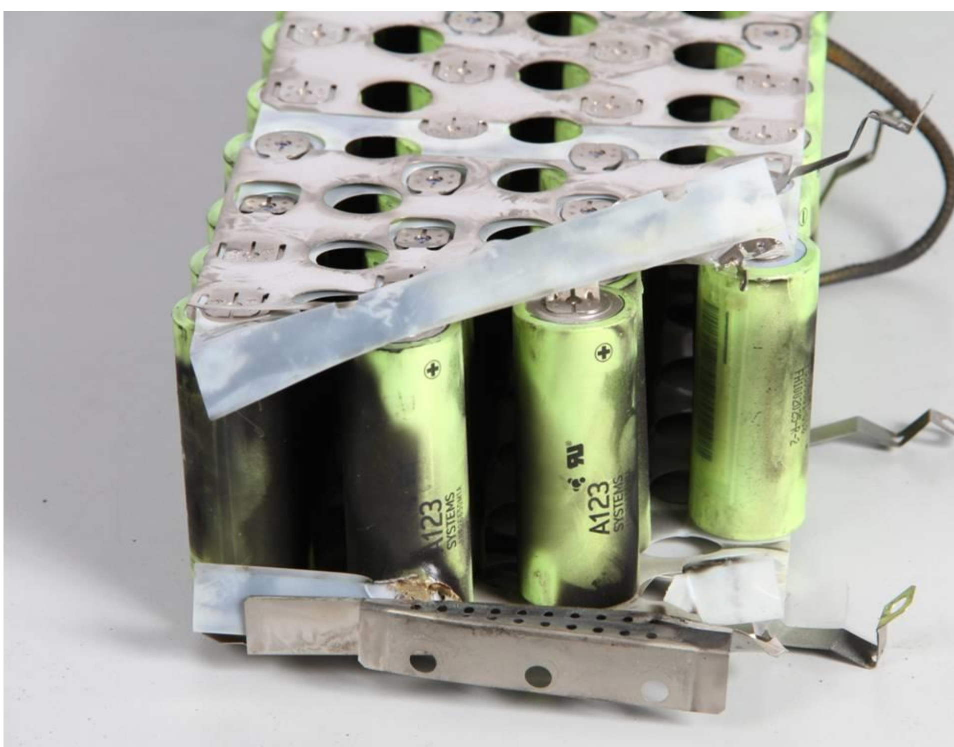

Assembled Battery Pack


Top Film
Assembly
Screws



Disassembled Battery Pack





Cell removed, cut free or un-soldered

Section C: Charging

A. **End Goals:** This section describes the procedure for charging the individual battery cells. For all of the electrical diagnosis of the cells, proper and consistent charging is essential for safety and evaluation.

B. **To the Student:** The focus of this section will be to perform the proper charging of the batteries. Knowledge of multi-meters and power supplies will be necessary.

C. **Content Outline:**
- Safety
- Charging
- Data collection and recording

D. **Body of Knowledge:**

1. Safety

   When the individual batteries are tested for State of Health, there will be electrical connections and the batteries themselves have a lot of potential energy. Careful handling includes avoiding shorting the battery terminals and keeping the batteries contained so as not to drop to the floor. With the potential of chemical and electrical exposure, be sure to use proper personal protective equipment (PPE) which includes gloves, safety glasses, no exposed jewelry, and an apron. Have a container available that will be used to contain damaged cells for recycling.

2. Charging

   Charging a battery is performed in distinct stages. The first is used to recover from a deep discharge only. It is a constant current charge known as the Bulk charging stage. The second, known as the absorption stage, is a constant voltage charge. The current will be limited by the internal resistance of the battery which increases as the state-of-charge increases. There is a third stage, which is used to maintain a battery at 100% state-of-charge, is called the Float charging stage. This is a constant voltage charge, but at a lower value than the absorption stage. This is only used for batteries in the field to compensate for self-discharge and will not be used for diagnostic testing.

   For the diagnostic tests, the beginning condition of the battery will be charging it completely. If available, use the manufacturer's recommended procedure for fully charging the battery. If the manufacturer's information is not available, use the following procedure to charge, which is listed below. Care must be taken to follow the instructions precisely to avoid overcharge and damage to the cell or power supply. The nominal voltage of a typical LiIon cell is 3.6V or 3.7V. The charging voltage should go no higher than 4.2V.

- If the battery voltage is 2.9V or less, limit the charging current to 0.1/H * the A-H capacity of the battery. Charge with a 4.0V power supply.
- For a voltage of greater than 2.9V, set the charging voltage at 4.0V with a reference charge current of 0.7/H * the A-H capacity of the battery.
- Keeping a constant voltage, monitor the charging current which will steadily fall as the battery reaches a higher state of charge. When it reaches between 0.1/H and 0.07/H * the A-H capacity of the battery, terminate the charging.
- If the battery voltage gets above 4.2V, terminate the charging.
- If either the charging of the <2.9V battery or >2.9V battery procedures take greater than 120 minutes, terminate the charging and reject the battery.

3. Data Collection and Recording

Information regarding the charging process needs to be documented for each individual cell. This can be used in the determination of the state of health of the battery. Keeping track of the temperature during the charging process will also help define the health of the battery.

II. – Assessment

Section C – Charging of Batteries

Lab 8 Charging Batteries

End Goals: This lab is designed to guide the student through the charging of individual batteries.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Infrared thermometer
- Stopwatch
- Multi-meter
- Power-supply
- Battery recycling container
- Labels
- Marker
- Camera

Purpose: This lab will be used to organize the workspace to be used for battery pack evaluation.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

5. Activity 1 – Charging the batteries
    a. Setup
        i. Have a battery in a convenient location on the lab bench.
        ii. Assemble the power supply and measurement instruments close by.
        iii. Have your notebook and battery analysis form ready.
    b. Activity
        i. Check the initial, open circuit, voltage of the battery. If it is below the manufacturer's Vmin or 2.9V, it will need to go through the Bulk Charging stage
            1. Limit the charging current to 0.1/H * the A-H capacity of the battery.
            2. Charge the battery with a 4.0 V power supply keeping the current limit in place.
            3. Constantly monitor the temperature of the battery with an infrared thermometer or a thermocouple adhered to the battery shell. If it rises over the Tmax of the battery, terminate the charging and reject the battery.
            4. When the battery reaches a voltage of greater than 2.9 V it can be charged with an Absorption Charging stage.
        ii. If the battery's open circuit voltage is above 2.9 V, it will be charged through an Absorption Charging stage
            1. Set the charging voltage on the power supply at 4.0 V with a limit on the charge current at 0.7/H * the A-H capacity of the battery.
            2. Constantly monitor the temperature of the battery with an infrared thermometer or a thermocouple adhered to the battery shell. If it rises over the Tmax of the battery, terminate the charging and reject the battery.
            3. When the battery reaches a charging current of 0.1/H *the A-H capacity of the battery or lower, the Absorption Charging stage is over and the diagnostic procedure can begin.
            4. All diagnostic procedures require a one-hour resting period for the battery after charging to cool down and stabilize before testing.
        iii. If the combination of the Bulk stage and Absorption stage take more than a 120 minute length of time, terminate the charging and reject the battery.

Analysis (Questions)

Data Sheet for Module 2 – Section 5

Activity i – Battery Cell Nameplate Data		
Item	Data	Notes
Model #		
Serial #		
Date code		
Voltage		
Amp-Hour capacity		
Manufacturer		

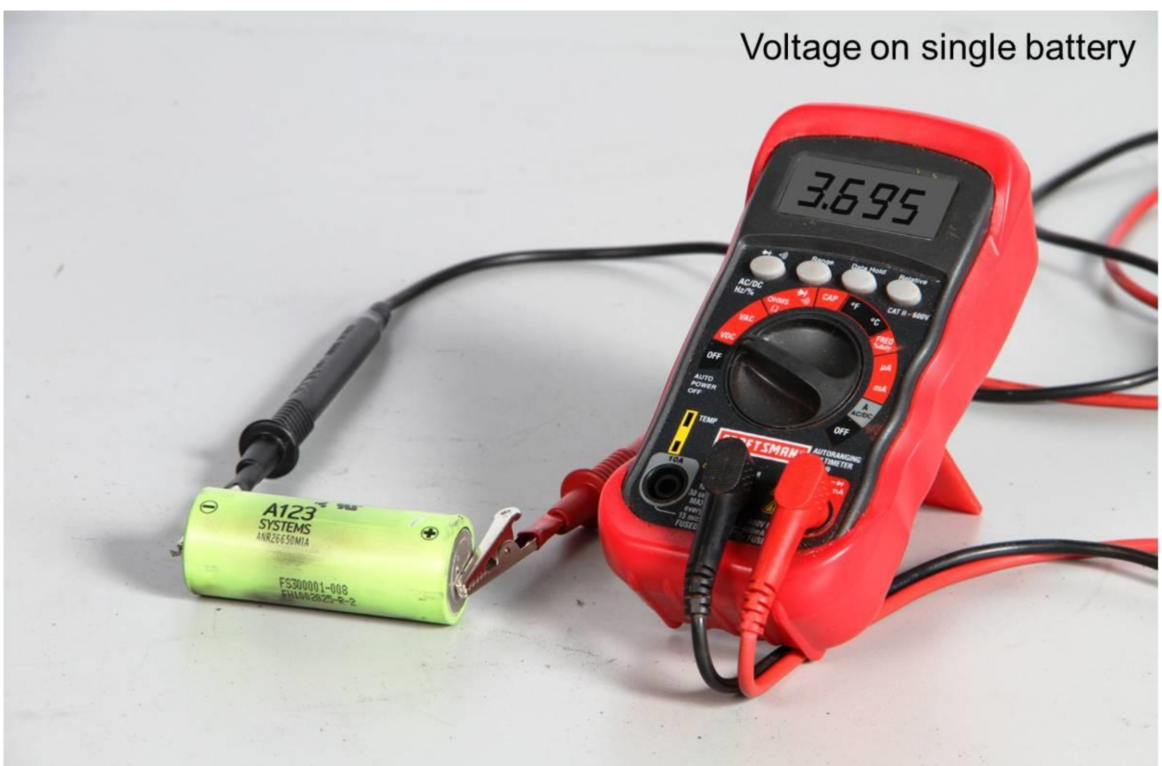
Activity ii – Manufacturer's data		
Item	Data	Notes
Battery Vmax		
Battery Vmin		
Charging Procedure		
Temperature High Limit		
Temperature Low Limit		
List other specifications:		

Activity iii – Charging documented		
Item	Data	Notes
Initial battery voltage		
Time for Constant Current Charging (Bulk stage)		
Maximum Temperature reached (Bulk stage)		
Ambient Temperature (Bulk stage)		
Time for Constant Voltage Charging (Absorption stage)		
Maximum Temperature reached (Absorption stage)		
Ambient Temperature (Absorption stage)		
Charging within specification?		

For the instructor (not to be printed with the student lab)

This section will take the students through the charging process. Check their documentation form for completeness and be sure to make sure the batteries are rejected if the total charging process takes more than two hours or if a high temperature is reached.

Supplies for Charging




Temperature measurement
during charging and
discharge testing
°C/°F
CAUTION
A123
SYSTEMS

Section D: Diagnosis

A. **End Goals:** This section describes the electrical diagnostic process for the battery cells. This will define the State of Health (SOH) of each battery and will be used to sort them into categories of like cells.

B. To the Student: The focus of this section will be to perform an electrical assessment on the individual batteries. Knowledge of multi-meters and power supplies will be necessary.

C. Content Outline:

- Safety
- Tests
- Data collection and recording

D. Body of Knowledge:

6. Safety

When the individual batteries are tested for State of Health, there will be electrical connections and the batteries themselves have a lot of potential energy. Careful handling includes avoiding shorting the battery terminals and keeping the batteries contained so as not to drop to the floor. With the potential of chemical and electrical exposure, be sure to use proper personal protective equipment (PPE) which includes gloves, safety glasses, no exposed jewelry, and an apron. Have a container available that will be used to contain damaged cells for recycling.

7. Tests

The end-of-life of a battery is defined by the results of the diagnostic testing. If the net delivered capacity of a battery is less than 80% of its rated capacity, it is considered at the end of its life. Peak power capability it measured at an 80% Depth of Discharge. If it delivers less than 80% of rated power, it is not acceptable for its given task.

Other tests are performed on the batteries to allow them to be sorted into categories with batteries of similar states of health. Keeping similar batteries together will not compromise the performance available in a battery bank due to one weak cell. The current capacity of a battery bank is limited by the lowest performing cell in each stack. The voltage capacity of a battery bank is limited by the voltage of the lowest performing stack.

a. Self-discharge
   1. After fully charging the battery, measure the open circuit voltage. Make note of the voltage at increments of time up to 48 hours.

b. Controlled discharge

1. c/3 discharge
    a. Discharge the battery through a resistor which will give a full discharge over a 3 hour period. This can be calculated using the formula $R = V/I_d$ where V is the nominal voltage of the battery and I_d is found by: 1/3H * A-H capacity of the battery. Be sure that the resistor is rated for at least double the power output which will be $P_d = (I_d)^2 * R$. Terminate the test when the manufacturer's minimum voltage is reached.

2. c/2 discharge
    a. Discharge the battery through a resistor which will give a full discharge over a 2 hour period. This can be calculated using the formula $R = V/I_d$ where V is the nominal voltage of the battery and I_d is found by: 1/2H * A-H capacity of the battery. Be sure that the resistor is rated for at least double the power output which will be $P_d = (I_d)^2 * R$. Terminate the test when the manufacturer's minimum voltage is reached.

3. c/1 discharge
    a. Discharge the battery through a resistor which will give a full discharge over a 1 hour period. This can be calculated using the formula $R = V/I_d$ where V is the nominal voltage of the battery and I_d is found by: 1/1H * A-H capacity of the battery. Be sure that the resistor is rated for at least double the power output which will be $P_d = (I_d)^2 * R$. Terminate the test when the manufacturer's minimum voltage is reached.

c. Partial discharge

1. c/3 discharge rate
    a. Discharge the battery through a resistor which will give a full discharge over a 3 hour period. Terminate the test after 1-1/2 hours and check the voltage of the battery.

d. Open circuit voltage vs state-of-charge

1. c/1 discharge rate
    a. Charge the battery to 100% state-of-charge
    b. Rest for 1 hour
    c. Discharge the battery through a resistor which will give a full discharge over a 1 hour period. Terminate the test after three minutes.
    d. Rest for 1 hour
    e. Check the voltage of the battery.
    f. Repeat steps c – e until the manufacturer's minimum voltage is reached.

e. Capacity verification

1. c/1 discharge rate
    a. Charge the battery to 100% state-of-charge
    b. Rest for 1 hour
    c. Discharge the battery through a resistor which will give a full discharge over a 1 hour period until the manufacturer's minimum voltage is reached.
    d. Document the time for discharge.
    e. Repeat the test until three successive tests are within 2% of each other.

8. Data collection and reporting

The data collection can take place in a logbook; ultimately the data should be put into an electronic spreadsheet. Having it in an electronic format allows for easy duplication for security and makes it convenient for sorting and performing mathematical analysis.

II – Assessment

Section D – Diagnosis

Lab 9 Diagnosis

End Goals: This lab is designed to guide the student through the diagnosis procedures to be performed on the individual battery cells.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Infrared thermometer
- Stopwatch
- Multi-meter
- Power-supply
- Battery recycling container
- Labels
- Marker
- Camera

Purpose: This lab will be used to organize the workspace to be used for battery pack evaluation.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

6. Finding dimensions needed in workspace
    a. Setup
        i. Have a battery, fully charged, in a convenient location on the lab bench.
        ii. Assemble the power supply and measurement instruments close by.
        iii. Have your notebook and battery analysis form ready.
    b. Activities
        i. Self-discharge test
            1. Be sure that the battery has had an hour to rest after charging
            2. Measure the open-circuit voltage and note the time
            3. Measure the open-circuit voltage and time at least each hour for a period of 48 hours.
            4. An acceptable value is < 15% discharge in a 48 hour period.
        ii. Controlled discharge, c/3 rate
            1. Be sure that the battery has had an hour to rest after charging
            2. Measure the open-circuit voltage and note the time
            3. Discharge the battery through a resistor which will set the current for a 3-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/3H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
            4. Terminate the test when the V_{min} is reached.
        iii. Controlled discharge, c/2 rate
            1. Be sure that the battery has had an hour to rest after charging
            2. Measure the open-circuit voltage and note the time
            3. Discharge the battery through a resistor which will set the current for a 2-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/2H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
            4. Terminate the test when the V_{min} is reached.
        iv. Controlled discharge, c/1 rate
            1. Be sure that the battery has had an hour to rest after charging
            2. Measure the open-circuit voltage and note the time
            3. Discharge the battery through a resistor which will set the current for a 1-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/1H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
            4. Terminate the test when the V_{min} is reached.
        v. Partial discharge, c/3 rate
            1. Be sure that the battery has had an hour to rest after charging

2. Measure the open-circuit voltage and note the time
3. Discharge the battery through a resistor which will set the current for a 3-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/3H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
4. Terminate the test after 1-1/2 hours.
5. Measure the open-circuit voltage and note the temperature of the battery.

vi. Open circuit voltage vs state-of-charge

1. Be sure that the battery has had an hour to rest after charging
2. Measure the open-circuit voltage and note the time
3. Discharge the battery through a resistor which will set the current for a 1-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/1H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
4. Discharge the battery for three minutes.
5. Allow the battery to rest for one hour.
6. Measure the open-circuit voltage
7. Discharge the battery for another three minutes.
8. Allow the battery to rest for one hour.
9. Measure the open-circuit voltage
10. Repeat steps 7 – 9 until V_{min} is reached

vii. Capacity verification.

1. Be sure that the battery has had an hour to rest after charging
2. Measure the open-circuit voltage and note the time
3. Discharge the battery through a resistor which will set the current for a 1-hour discharge. This is calculated using $R = V/I_d$, where V is the nominal voltage and I_d is found by I_d = 1/1H * the A-H capacity of the battery. Be sure the resistor is rated for at least double the power rating of $P_d = (I_d)^2 * R$.
4. Discharge the battery until V_{min} is reached.
5. Document the time for discharge.
6. Repeat the test until the results of three successive tests are within 2% of each other.

c. Data collection and reporting

i. Log the data in the designated sheets.

Activity 1 – Battery Cell Nameplate Data		
Item	**Data**	**Notes**
Model #		
Serial #		
Date code		
Voltage		
Amp-Hour capacity		
Manufacturer		

Activity 1 – Manufacturer's data		
Item	**Data**	**Notes**
Battery Vmax		
Battery Vmin		
Charging Procedure		
Temperature High Limit		
Temperature Low Limit		
List other specifications:		

Activity 1 – Charging documented		
Item	Data	Notes
Initial battery voltage		
Time for Constant Current Charging (Bulk stage)		
Maximum Temperature reached (Bulk stage)		
Ambient Temperature (Bulk stage)		
Time for Constant Voltage Charging (Absorption stage)		
Maximum Temperature reached (Absorption stage)		
Ambient Temperature (Absorption stage)		
Test i – Self Discharge		
Item	Voltage	Time
Initial battery voltage		
Open circuit voltage 1		
Open circuit voltage 2		
Open circuit voltage 3		
Open circuit voltage 4		
Open circuit voltage 5		
Open circuit voltage 6		

Open circuit voltage 7		
Open circuit voltage 8		
Open circuit voltage 9		
Open circuit voltage 10		
Open circuit voltage 11		
Open circuit voltage 12		
Open circuit voltage 13		
Open circuit voltage 14		
Open circuit voltage 15		
Open circuit voltage 16		
Open circuit voltage 17		
Open circuit voltage 18		
Open circuit voltage 19		
Open circuit voltage 20		
Open circuit voltage 21		
Open circuit voltage 22		
Open circuit voltage 23		
Open circuit voltage 24		
Open circuit voltage 25		
Open circuit voltage 26		
Open circuit voltage 27		
Open circuit voltage 28		
Open circuit voltage 29		
Open circuit voltage 30		
Open circuit voltage 31		

Open circuit voltage 32		
Open circuit voltage 33		
Open circuit voltage 34		
Open circuit voltage 35		
Open circuit voltage 36		
Open circuit voltage 37		
Open circuit voltage 38		
Open circuit voltage 39		
Open circuit voltage 40		
Open circuit voltage 41		
Open circuit voltage 42		
Open circuit voltage 43		
Open circuit voltage 44		
Open circuit voltage 45		
Open circuit voltage 46		
Open circuit voltage 47		
Open circuit voltage 48		
Open circuit voltage 49		
Open circuit voltage 50		

Test ii – Controlled Discharge c/3 rate		
Item	Data	Time
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/3		

Test iii – Controlled Discharge c/2 rate		
Item	Data	Time
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/2		

Test iv – Controlled Discharge c/1 rate		
Item	Data	Time
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/1		

Test v – Partial Discharge c/3 rate		
Item	**Data**	**Time**
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
Open-circuit voltage measured after 1-1/2 hours		

Test vi – Open circuit voltage vs state-of-charge. c/1 discharge rate		
Item	**Data**	**Time**
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Three-minute discharge #1 completed		
Cell temperature		

Item	Data	Time
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #2 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #3 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #4 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #5 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		

Item	Data	Time
Three-minute discharge #6 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #7 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #8 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #9 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #10 completed		
Cell temperature		

Item	Data	Time
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #11 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #12 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #13 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #14 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		

Item	Data	Time
Three-minute discharge #15 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #16 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #17 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #18 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #19 completed		
Cell temperature		

Item	Data	Time
Rest for one hour reached		
Open circuit voltage		
Three-minute discharge #20 completed		
Cell temperature		
Rest for one hour reached		
Open circuit voltage		

Test vii – Capacity Verification c/1 rate	Test #1	
Item	**Data**	**Time**
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/1		

Test vii – Capacity Verification c/1 rate	Test #2	
Item	**Data**	**Time**
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/1		

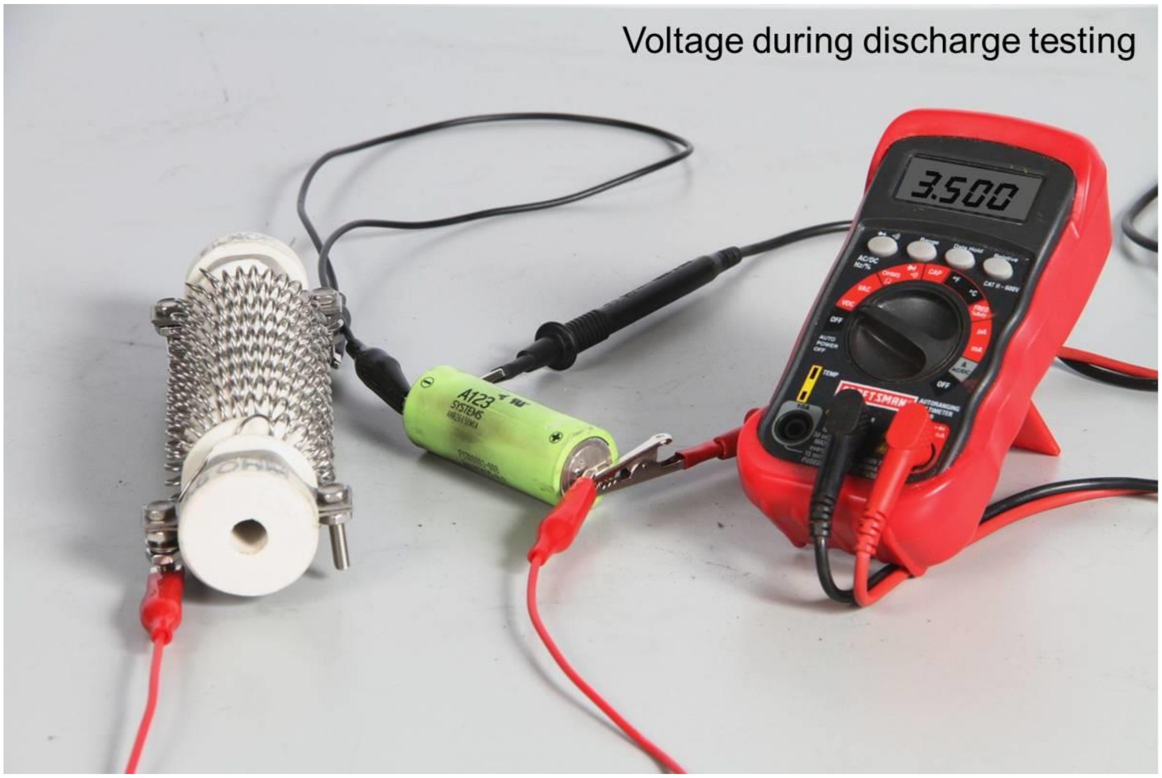
Test vii – Capacity Verification c/1 rate	Test #3	
Item	Data	Time
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/1		

Test vii – Capacity Verification c/1 rate	Test #4	
Item	Data	Time
Initial battery voltage		
A-H capacity rating		
Discharge resistor value		
V_{min} specification		
Initial cell temperature		
Maximum cell temperature		
V_{min} reached		
Discharge time c/1		

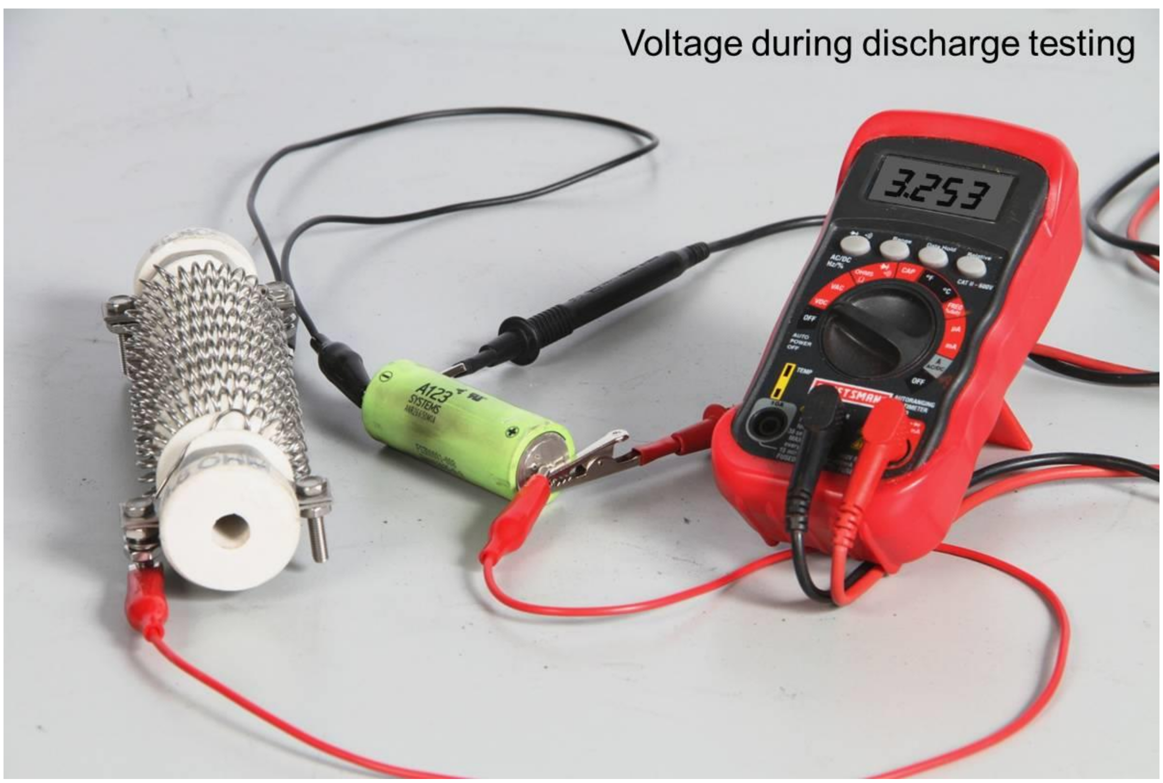
For the instructor (not to be printed with the student lab)

This section will guide the students through the testing procedures necessary to evaluate and sort the batteries for state-of-health categories. The data from these diagnostic tests should be entered into a spreadsheet that will make it easier for electronic sorting.

Supplies for Charging



Initial Voltage Measurement (example)



Subsequent Voltage Measurement (lower)


Temperature measurement
during charging and
discharge testing
°C/°F
CAUTION
A123
SYSTEMS

II. Safety and Regulation

Section A: Concerns for Recycling and Repurposing Batteries

Lithium and Lithium ion batteries are both considered to be Class 9 Hazard as defined by the U.S. Hazardous Materials Regulations (HMR) and are defined by several sections in the Code of Federal Regulations (CFR). Chief Officer's at Toxoco, the largest battery recyclers in the United States, have noted that while they provide the physical and chemical methods for repurposing and recycling batteries, their most valued asset is their ability to sell compliance to these federal standards. Thus, any student or person wishing to enter this market is well advised to become fully acquainted with all the regulations. In this section, a brief description of the types of regulations one can expect will be discussed.

49 CFR 173.185 dictates seven criteria for the transport of these hazardous materials. Detailed descriptions are given in the federal register as designated by the parts and subparts.

49 CFR REFERENCE	REGULATION
173.185 (A)	Lithium cells or batteries must confirm to the following…
173.185(A)(1)	Must meet each test requirement in the UN Manual of Tests and Criteria.
173.185(A)(2)	Incorporate a safety venting device or be designed to preclude violent rupture.
173.185(A)(3)	Be equipped with an effective means to prevent dangerous reverse current flow.
173.185(A)(4)	Be packaged properly conforming to part in 49 CFR 178 (L) and (M)
173.185(A)(5)	Be equipped with effective means of preventing external short circuits
173.185(A)(6)	Cells or batteries containing specific sulfur based electrolytes may not be transported unless specific discharge current or open circuit voltage is below certain values.
173.185(B)	Lithium cells or batteries packed with equipment may be transported if items in (a) above are met, must contain strong outer packaging that eliminates movement which could lead to short circuits.
173.185(C)	Lithium cells or batteries contained in equipment, meet requirements of equipment is water proof…
173.185(D)	Lithium cells or batteries going to a recycling center are exempted from the requirements provided they are provided from short circuit
173.185(E)	Exemption from (a)(1) if transporting a prototype cell or battery with proper packaging.
173.185(F)	Batteries or cells that do not comply need approval by Associate Administrator
173.185(G)	Batteries employing strong impact resistance outer casings and exceeding 26.5lbs may be packed in strong packaging and protective enclosures, must be secured to prevent movement and terminals may not support weight of other superimposed elements. Batteries of this type may not be transported via passenger aircraft.

Other regulating agencies include the International Civil Aviation Organization (ICAO), the International Air Transportation Authority (IATA), the International Maritime Dangerous Good (IMDG), the U.S. Department of Transportation (DOT) and the U.S. Environmental Protection Agency, as well as any federal or state Occupational, Safety, and Health Organizations. As seen the above table for 49 CFR 173.185, the primary aim of all these organization is to make sure that the following basic criteria are followed.

1 Cells or batteries must be separated in some manner to prevent short circuits.

2 Strong outer packaging is often required.

3 Limits to the number of cells or batteries will be specified.

4 Specific labeling requirements (agency specific) can be required for the outer packages.

5 Employees must be trained and certified for hazardous material shipping training when packaging cells or batteries that will be transported.

The UN Manual of Tests and Criteria are tests and procedures derived from the United Nations recommendations on the Transport of Dangerous Goods. Lithium-ion battery designs with a gram-equivalent weight greater than 8.0 grams must pass these tests prior to transportation. A gram-equivalent weight of 8.0 grams for Lithium-ion equates to a battery of 100 watt-hours. Thus, to figure out a gram equivalent weight, for a battery pack, the following formula is used.

$$\frac{\text{mAh}}{1000} \text{ x V} = \text{wh}$$

- mAh = milli Amp Hours unit of electric charge found on the battery (if given Ah, do not divide by 1000).
- V = volts
- Wh = watt hours

Example: The Iphone has a rating of 1,400mAh and 3.7 Volts. What is it's gram equivalent weight for lithium?

$$\frac{1{,}400\text{mAh}}{1000} \text{ x } 3.7 = 5.2 \text{ wh}$$

$$5.2\text{wh}\frac{8\text{gEW}}{100 \text{ wh}} = 0.42\text{gram equivalent weight of Li} - \text{ion}$$

Thus, the battery for an iPhone may be transported on your person without special packaging and is allowed on a passenger aircraft as it does not exceed the 8g limit. Once combined or packaged with other batteries however, testing and transportation restrictions may apply.

Clearly, cells and batteries designed for vehicles will always fall above this threshold, but care must be taken to recognize these limits, should individual cells reach a point where their repurposing can bring them near or below the 8.0 gram equivalent weight.

The following tests must be completed prior to transport. The UN Manual may be found in the appendix of this document.

<u>Test T.1: Altitude Simulation</u>

Purpose: Simulate air transport under low-pressure conditions

Test: Test cells and batteries shall be stored at a pressure 11.k kPa or less for at least six hours at ambient temperature (20 +/- ^{o}C). The requirement is met if there is no mass loss, no leakage, no venting, no disassembly, no rupture and no fire and if the open circuit voltage of each test cell or battery after testing is not less than 90% of its voltage immediately prior to this procedure.

<u>Test T.2: Thermal Test</u>

Purpose: Assesses cell and battery seal integrity and internal electrical connections. Conducted using rapid and extreme temperature changes.

Test: Cells and batteries are stored at 75^{o}C for 12 hours, and then cooled to -40^{o}C for 12 hours. The cycle is repeated 10 times with no more than 30 minutes in between the temperatures. The batteries are then examined for mass loss, leakage, venting, disassembly, rupture, fire and open circuit voltage testing should not be less than 90% of its' voltage immediately prior this procedure.

<u>Test T.3: Vibration</u>

Purpose: Simulate Vibration during transport

Test: Cells and batteries are firmly secured to the platform of the vibration machine. Defined vibration sequences are run every 15 minutes for a total of 3 hours (12 minutes) for each of the three mutually perpendicular mounting positions of the cell. The requirement is met if there is no mass loss, no leakage, no venting, no disassembly, no rupture and no fire and if the open circuit voltage of each test cell or battery after testing is not less than 905 of its voltage immediately prior to this procedure.

<u>Test T.4: Shock</u>

Purpose: Simulate possible impact during transport

Test: Cells and batteries are secured to testing machine. Each cell or battery is subjected to a half-sine shock with a specific acceleration and pulse duration. Each cell or battery is subjected to three shocks in the positive direction followed by three shocks in the negative direction of three mutually perpendicular mounting position of the cell or battery for a total 18 shocks. The requirement is met if there is no mass loss, no leakage, no venting, no disassembly, no rupture and no fire and if the open circuit voltage of each test cell or battery after testing is not less than 905 of its voltage immediately prior to this procedure.

<u>Test T.4: External short circuit</u>

Purpose: Simulate an external short circuit

Test: The cell or battery is temperature stabilized to 55^{o}C. A short circuit condition is applied and continued for at least one hour after the cell or battery external case temperature has returned to 55^{o}C. An additional six hour observation period is then performed for the test to be concluded. The requirement is met if the external temperature does not exceed 170^{o}C and there is no disassembly, no rupture and no fire within six hours of the test.

<u>Test T.6: Impact</u>

Purpose: Simulate an impact

Test: Sample cell is placed on a flat surface. A 15.8mm diameter par is placed across entire center of sample. A 9.1kg mass is dropped form a height of 61cm onto the sample. Depending on configuration, cylindrical or prismatic cells will need to be rotate for the impact test. The requirement is met if the external temperature does not exceed 170^{o}C and there is no disassembly, no rupture and no fire within six hours of the test.

<u>Test T7: Overcharge</u>

Purpose: Evaluates the ability of a rechargeable battery to withstand an overcharge condition.

Test: When charge voltage is more than 18V, the minimum voltage shall be 1.2 times the maximum charge voltage. If less than 18 volts, the minimum voltage of the test shall be the less of two times the maximum charge voltage of the battery or 22V. Tests are conducted at room temperature for 24 hours. The requirement is met if there is no disassembly and no fire within seven days of the test.

<u>Test T8: Forced Discharge</u>

Purpose: Evaluate the ability of a primary or a rechargeable cell to withstand a forced discharge condition.

Test: Each cell is forced discharged at ambient temperature by connecting it in series with a 12V D.C. power supply at an initial current equal to the maximum discharge current specified by the manufacturer. Each cell shall be forced discharged for a time interval (in hours) equal to its rated capacity divided by the initial test current (in ampere). Requirement is that no disassembly and no fire with seven days of the test.

Section B: Storage considerations:

Most lithium ion batteries are not fully discharged even when in operation and contain circuitry which prevents the voltage from going much below 3.0V. If repeated cycles of low (0 voltage) and fully charged (3.7 to 4.0V) occur or if the battery is stored at low voltages for an extended period of time, degradation may occur due to electrochemical corrosion of the copper current connectors. This can lead to impedance growth which then may result in a thermal runaway upon charging.

Batteries and cells should not be stored at temperatures above 140^{o}F. This is because the solid Electrolyte Interface (SEI) may breakdown. The SEI layer is crucial to the stability of the lithium-ion batteries that use carbon anodes. The SEI layer is formed when the cell is first charged. This layer, which forms on the carbon electrode, is usually a reaction between the graphite and the carbonates or polymers in the electrolyte. Once formed, the lithium can intercalate into the graphite.

In the design of the battery specific consideration is given to the separator. Tasked with the purpose of preventing a short circuit followed by thermal runaway, the condition of the separator may prevent the battery or cell from being reused. Some separators are extremely thin in order to reduce resistance across the cell. As might be expected, as the separators become thinner, the likelihood for a hole to develop becomes greater. Several battery packs use gel type separators or material with lower melting points, so that if a separator does becomes damaged, any heat generated by a short circuit will cause the separator to melt and reseal or close the gap. However, since examination of the cell would require disassembly of the cells, which is most likely economically unfavorable, bad separators would be expected to result in failed electrical tests of the cell and the cell should be destroyed and cell components recycled.

When assembled, great care is taken to make sure that water is not present. Some anode materials may use materials such as $LiPF_6$ which when wet can form Hydrofluoric acid. This acid has the ability to dissolve or react with important components in the cell such as the aluminum conductor.

All Lithium-ion batteries contain some sort of battery pack protection circuitry or battery management system. Disabling or removing the battery protection circuit module (PCB) and allowing the battery to remain intact, can result in a catastrophic failure leading to fire if runaway occurs. This is especially true if an overcharge was to occur while in this state. PCB should never be disabled if the battery configuration is to be maintained while in storage.

Unlike cells or batteries that use the highly flammable lithium metal (when exposed to air or water), the lithium-ion does not spontaneously ignite. Instead, thermal runaway and increased temperatures often result in the breakdown and eventual ignition of the surrounding components. Many of these organic compounds are highly flammable. If produced as gases inside the cell, upon exposure to air and ignition can release a large amount of chemical energy. (Chemical energy comes from the exothermic release of energy during the combustion of the organic components, similar to the combustion of gasoline in a car engine, although maybe not quite so violent until at temperature). For storage purposes, fire suppression techniques that limit the amount of oxygen will take precedence over using fire suppression designed for metals, as would be done a lithium battery, not a lithium-ion battery.

III. Re-purposing batteries

Section A: Post-Diagnosis / Sorting:

A. **End Goals:** This section describes the sorting process for the battery cells using the State of Health (SOH) of each battery and prioritizing the results.

B. **To the Student:** The focus of this section will be to use the diagnosis data and sort the batteries into groups of similar performance.

C. **Content Outline:**
- Safety
- Prioritization

D. **Body of Knowledge:**

1. Safety

This section will deal with data only, and will be performed on paper and/or using a computer. No hazards are identified.

2. Prioritization

The batteries will be sorted into categories that will be the most advantageous for building a battery pack. We will be taking care not to compromise the total pack performance because of lower performing cells.

The data will be retrieved from the following tests:

- Self-discharge
- Controlled discharge, c/3
- Controlled discharge, c/2
- Controlled discharge, c/1
- Partial discharge, c/3
- Open circuit voltage vs state-of-charge
- Capacity verification

The order of priority is defined as:

Self-discharge
Capacity verification
Open Circuit Voltage vs State-of-Charge

Groups within each of these categories will include batteries with test results within 3% of each other. An explanation of the rationale for each of these priorities follows:

Self-discharge – This characteristic of a battery will affect its capacity over time; the batteries should discharge at the same rate to maintain equal capacity reduction without a load.

Capacity verification - If the capacities of the batteries are not matched, the weaker cell will limit the entire battery pack. The data from the capacity verification will assure matching values based on measurements of capacity reduction under load.

Open Circuit Voltage vs State of Charge – This characteristic will assure that the overall voltage of the battery pack is shared in similar proportions among the individual batteries, at multiple states of charge. This helps to maintain a consistent discharge characteristic with the battery pack as a whole and consistent loading of each battery within the pack.

Lab 10 – Post Diagnosis, Sorting

End Goals: This lab is designed to guide the student through the analysis of the data from the diagnosis to sort the batteries into categories.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Data sheets from diagnostic tests
- Computer with Excel or other spreadsheet software

Purpose: This lab will be used to sort the batteries into categories that will be the most advantageous for building a battery pack without compromising its performance based on lower performing cells.

Activities

7. Activity 1 – Sorting through the data
    a. Steps
        i. Retrieve the following data from multiple battery tests:
            1. Self-discharge
            2. Controlled discharge, c/3
            3. Controlled discharge, c/2
            4. Controlled discharge, c/1
            5. Partial discharge, c/3
            6. Open circuit voltage vs state of charge
            7. Capacity verification
        ii. Organize the data for each of the cells tested by the above test results

Test	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9
Self Discharge	Volts	Volts	Volts	Volts	Volts	Volts	Volts	Volts	Volts
Controlled Discharge c/3	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes
Controlled Discharge c/2	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes
Controlled Discharge c/1	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes
Partial Discharge c/3	Volts	Volts	Volts	Volts	Volts	Volts	Volts	Volts	Volts

Open circuit voltage vs state of charge	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts	Minutes Volts
Capacity verification	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes	minutes

iii. Group cells by the following, in order:
  1. Self-discharge (in 3% increments)
  2. Within each self-discharge group, by Capacity verification (in 3% increments)
  3. Within each Capacity verification group, by Open Circuit Voltage vs State of Charge (in 3% increments)

iv. Document each group of batteries with the individual characteristic data for re-assembly into re-manufactured battery banks

Analysis (Questions)

a. Why is the priority for sorting: 1)Self-discharge, 2) Capacity verification, 3) Open Circuit Voltage vs State-of-Charge?

b. If batteries are connected in series in the battery bank, what is more critical for the battery pack overall performance: voltage or current performance?

c. Why are batteries with a high self-discharge rate rejected for an end-of-life condition?

For the instructor (not to be printed with the student lab)

This section will go through the procedure of sorting the tested batteries into categories that are useful for matching them up with like cells for the re-building of battery packs.

Answers to the questions:

a. Why is the priority for sorting: 1)Self-discharge, 2) Capacity verification, 3) Open Circuit Voltage vs State-of-Charge?

   The self-discharge characteristics of a battery will affect its capacity over time, they should discharge at the same rate to maintain equal capacity reduction without a load.

   If the capacities of the batteries are not matched, the weaker cell will limit the entire battery pack. The data from the capacity verification will assure matching based on capacity reduction under load.

   The Open Circuit Voltage vs State of Charge will assure that the overall voltage of the battery pack is shared in similar proportions among the individual batteries, at multiple states of charge. This helps to maintain a consistent discharge characteristic with the battery pack as a whole and consistent loading of each battery within the pack.

a. If batteries are connected in series in the battery bank, what is more critical for the battery pack overall performance: voltage or current performance?

   The current performance. The total current of the battery pack is limited by the battery allowing the least amount of current flow.

   Voltage performance of the batteries affects the overall voltage, when connected in series, without limiting the voltage performance of other batteries in the pack.

b. Why are batteries with a high self-discharge rate rejected for an end-of-life condition?

   A high self-discharge condition indicates a fault in the chemistry or the physical characteristics of the battery which could lead to dangerous discharge rates under load and extremely lower performance.

Section B: Post-Diagnosis, re-packaging

B. **Section Title:** Post-Diagnosis / Re-packaging

A. **End Goals:** This section deals with the re-building of a battery pack using sorted, used batteries for optimum performance of the pack.

B. **To the Student:** The focus of this section will be to assemble a battery pack from used, tested batteries that will use the best performance of each individual cell.

C. **Content Outline:**

- Safety
- Documentation
- Physical assembly

D. **Body of Knowledge:**

3. Safety

When the individual batteries are re-assembled into a re-worked battery pack, there will be electrical connections and the batteries themselves have a lot of potential energy. Careful handling includes avoiding shorting the battery terminals and keeping the batteries contained so as not to drop to the floor. With the potential of chemical and electrical exposure, be sure to use proper personal protective equipment (PPE) which includes gloves, safety glasses, no exposed jewelry, and an apron. Have a container available that will be used to contain damaged cells for recycling.

4. Documentation

The documents from sorting the individual battery cells will be used to select the appropriate batteries that will be matched to build each particular pack. Group the actual battery cells that are with a priority section that has enough cells identified to complete a battery pack.

A new label should be put onto the battery pack identifying it as a rebuilt pack, the date of re-assembly, and a new code number. The individual cell identification numbers will be referenced to this code number in the documentation.

5. Physical Assembly

The rebuilding will be in the opposite order of the disassembly process. Even though all of the parts have been cleaned and inspected earlier, take care to inspect all of the components and clean anything necessary upon re-assembly. Be sure to check if torque specifications exist for any of the battery terminals and other fastener components, and be sure to follow these specifications upon re-assembly.

After complete re-assembly, check the voltage of the unit as a whole to verify that all connections have been properly made. Properly cover any exposed terminals and safely store the rebuilt pack to make it available for use in a vehicle.

Lab 11 Post-Diagnosis

End Goals: This lab is designed to guide the student through the re-building of a battery pack using cells that have been diagnosed and sorted for re-use.

Pre-Requisites:

- Understanding of basic diagnostic procedures.
- Understanding of safe practices and personal safety measures.

Materials

- Ruler or tape measure
- Multi-meter
- Power-supply
- Battery recycling container
- Labels
- Marker
- Camera

Purpose: This lab will be used to rebuild a battery pack using batteries with similar States-of-Health.

Safety

A battery pack can have a lot of potential energy stored, even after being idle for many days. Always assume that it is fully charged. It is good practice to observe electrical safety guidelines. These include:

- Having a clean and organized workspace
- Assuring that you are working on a non-conductive table-top to avoid unwanted electrical connections
- Wearing safety glasses to protect your eyes from any sparking while making connections and protection from airborne scraps while stripping and cutting wires
- Whenever possible, making sure that connections and disconnections are made on incomplete circuits, so there is no voltage or current flow present
- When measuring electrical assemblies with batteries, the use of a non-conductive ruler is encouraged

These battery packs also include chemical exposure dangers, be sure to wear gloves and an apron while working on these components.

Before starting, identify the location of the eyewash station, ABC fire extinguisher, and spill kit.

Activities

8. Activity 1 – Rebuilding the battery pack
    a. Setup
        i. Start with the workspace organized and all of the battery pack components and sub-assemblies ready for re-assembly.
        ii. Have the tools available on the lab bench close by.
    b. Steps
        i. From the documentation in the previous lab, gather the cells that will be used in the re-built battery pack.
        ii. Re-assemble the pack in the reverse order of its disassembly, from Lab Activity Module 2 Activity 3.
        iii. Verify total voltage of the pack after assembly as a double check of the wiring configuration.
        iv. Label the completed battery pack and give it a new, unique code number
        v. Safely store the rebuilt pack in a location designated by the instructor, assuring that there are no exposed electrodes and that it is clearly labeled.
    c. Group all of the documentation from testing and assessment of this re-built pack under the new code number.
        i. Make sure that all of the documentation in excel is grouped and identified under a folder which has the new code number as a reference.

Analysis (Questions)

a) Which documentation needs to exist in the file with the new code number?

b) Who might need to access this data in the future, and for what reason?

For the instructor (not to be printed with the student lab)

This section guides the student through the rebuilding and documentation process of creating a rebuilt battery pack.

Analysis (Questions)

IV. Which documentation needs to exist in the file with the new code number?

All forms related to the outer shell and structure of the battery pack, all of the test documents related to each cell that is part of the new remanufactured battery pack, the data used for sorting the cells for remanufacturing.

V. Who might need to access this data in the future, and for what reason?

Any technician that works with the battery pack in the future will want to know the specifications and testing records, the Department of Transportation may require records of the contents of a battery pack, regulation agencies may require records to prove the physical condition while in your control, auto technicians may want to know the performance testing results to assess its effectiveness in a vehicle, OSHA may require the records to prove compliance with safe testing procedures.

Section C: General Considerations

Lithium-ion batteries are already used in applications from the very small, such as in medical applications, to the very large such as those found in electric vehicles. Automobile manufacturers require that (chuck need help, what is minimum Volts/Amps before disserve, can't find in my notes) maintain this level. Below those specifications, the battery pack is to be replaced or reconditioned. But are there other applications which could the battery at levels below those specified for EV and HEV vehicles? In this section, some broad considerations will be given to repurposing these batteries for use as electrical storage.

As discussed in other sections, lithium-ion batteries have a very high voltage compared to most other electrical chemical storage systems. For example, the lead acid battery that most of our familiar has a potential of only 2 volts per cell, while the lithium ion battery is around 4 volts per cell. This will allow the use of less cells where applications require that higher potential, albeit at a much larger cost. However, as re-purposing specifically deals with manufactured cells, the cost to repurpose will depend on the labor, storage, and transportation of re-purposing these cells and the economic willingness of the consumer to trade in or dispose of their battery pack.

Good battery systems require high specific energies, low resistance, and good performance over wide temperature ranges. Depending on the application, high power capabilities may also be needed. Advanced lithium-ion batteries are reported to have large specific energies and large energy densities. As a comparison, consider the difference between the Ni-CAD battery used not that long ago and the lithium ion batteries being developed and in use today.

Battery Type	Specific Energy (approximate)	Specific Density (approximate)
Lithium-ion	200 to 240 Wh/Kg	600 to 640 Wh/L
Ni-Cad	40 Wh/kg	430 Wh/L
Pd-Acid	40 Wh/kg	80 Wh/L

Temperature ranges for lithium ion batteries may depend on the specific chemistries involved, but performance quickly suffers below -20^{o}C to -40^{o}C. Around 0^{o}C, increased impedance in the cells begins to result in a voltage drop, thereby reducing some of the benefit of the lithium-ion batteries. At temperatures above 130^{o}C (266^{o}F), thermal runaway starts to become a problem. In addition, lithium-ion batteries as with most batteries do show increased self-discharge under no load as the temperature increases, although at a slower rate than many other batteries. With or without load, the discharge rate for lithium ion batteries is relatively flat resulting in a fairly constant and fairly high voltage. For repurposing, the high and steady voltage lends itself well to allowing the battery pack to be used in high potential applications, but a drop in specific energy capacity may not allow these repurposed batteries to be used in high power applications.

Specific energy = specific power x hours of service

$$\frac{Wh}{kg} = \frac{Wxh}{kg} = \frac{AxVxh}{kg}$$

Where

- Wh = Watt Hrs
- kg = Kilograms
- W = Watts
- h = hours
- A = Amps
- V = Volts

Repurposed automobile Lithium-ion batteries seem to be ideal for applications which require a large amount of energy storage (i.e. thinking beyond the size of a laptop battery), high voltage, and high specific energy capacity. While the same could be said for just about any battery, the high cost of manufacturing lithium-ion batteries seems to encourage re-purposing instead of recycling, especially given the benefits stated above. As mentioned in other sections in this manual, lithium-ion battery packs will require circuitry to prevent under and over voltage. Thus any repurposing will have to make sure that such circuitry is present, functioning, and will have the integrity to continue operating when again entered into service.

The physical conditions under which the battery pack will operate will need to be considered and additional tests may need to be performed. While clearly not a complete list, some of the types of tests are shown below to illustrate the types of considerations that must be taken into account.

- High Pressure Testing (90-120 psi)
- Low Pressure Testing
- Temperature Exposure Testing
- Forced Over Discharge
- Forced Over Charge of a Depleted Cell
- Shock Testing

Battery energy storage systems (BESS) are an example of storage applications that may find great use with repurposed lithium ion batteries. The easiest example to envision is that for wind and solar whereby their low but somewhat consistent power production can be stored until called upon by a load. Of more interest however, is the ability to store energy while energy production is cheap. As an example, electrical utility companies are required to keep a consistent load. In order to this, many operate an unloaded generator and connect as needed. If electrical storage systems could be in place which stored up excess energy produced at night (during times of low-load and excess capacity) and could be called on to deliver the load as needed, thereby eliminating the need to run an unloaded generator. Unfortunately for most residential consumers, price differentials between do not exist throughout the day, so a storage pack in residential units may not be economically favorable, unless some type of alternative energy production is being used.

Re-purposed lithium ion batteries would seem ideal for remote energy storage locations. Batteries repurposed, evaluated, and sold with high energy capacity could provide the large power necessary in these remote locations. Transportation and storage regulations of these batteries would be a major consideration for such applications.

Re-purposed batteries would require battery chargers unique to the lithium-ion cell. Standard chargers such as those used for automobile batteries could not be used. These batteries require special chargers that keep the charge rate within a narrow window and this charge rate is dependent on the temperature of the environment and the battery pack. In order for re-purposed batteries to become common place as storage devices, these charges will need to become commercially available at a competitive price. This of course, is another window of opportunity for entrepreneurs to consider when entering this market place.

The re-purposing of batteries for energy storage devices require high power or high voltage applications is well suited for lithium-ion batteries. Evaluation and consideration of circuit protection and operating temperatures are two of the major considerations when repurposing lithium-ion batteries. The economic feasibility of using repurposed lithium-ion batteries will depend on the ability to find storage applications which take advantage of the specific energy capacity and specific energy density of the lithium-ion batteries. These applications will require that the OEMs, the original consumer, and the re-purposer to identify the price points where it becomes economically reasonable to give up, reuse, or recycle the good cells of a battery pack.