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Battery Pack Design, Validation, and Assembly Guide using A123 Systems AMP20m1HD-A Nanophosphate® Cells

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Preface

About this document

Purpose of this document

This guide provides information that may be useful for designing, validating, and assembling battery packs with A123 Nanophosphate® cells. Creating a well designed battery pack requires many considerations. The scope of this guide is to outline the unique aspects of designing battery packs with A123 AMP20M1HD-A Nanophosphate® cells. A123 Energy Solutions recommends the study of additional relevant documentation from appropriate sources before designing validating, and assembling battery packs with A123 Nanophosphate cells. This document may not be applicable to any cells not provided by A123.

Anyone involved in the design, use, or assembly of products that use A123 cells should read and understand this document.

⚠ WARNING

Designing, validating and assembling battery packs is potentially dangerous to personnel and property. Therefore, these activities should only be attempted with a complete understanding of all aspects of proper battery pack design and construction. A123 is not responsible for any battery pack designed by any party other than A123. Anyone involved in building a battery pack with A123 cells must have the training and experience necessary to safely handle the cells and prevent accidental short circuits and arc flashes.

How to Use this Guide

The chapters in this guide are organized sequentially as they relate to design requirements that must be considered and understood before and during designing, validating, and assembling battery packs with A123 Nanophosphate cells. This guide contains the following information:

- **Chapter 1, Possible Dangers Involved with Handling Cells and Battery Packs** – describes dangers involved with handling cells and battery packs.
- **Chapter 2, Transportation, Storage and Recycling** – describes regulations and laws required for transporting lithium-ion batteries or products containing them.
- **Chapter 3, Nanophosphate Technology and Cell Characteristics** – describes how Nanophosphate electrode technology influences power, safety, and cycle life performance.
- **Chapter 4, Battery Pack Design** – describes the various stages of battery pack design, covering aspects of A123 Energy cells, which may be different from other cells.
- **Chapter 5, Summary of Battery Pack Testing** – describes performance, abuse, and compliance testing.
- **Chapter 6, Pack Manufacturing** - describes the processes for cell incoming inspections, material handling and storage, and cell welding.
- **Appendix A, Specifications** - describes electrical, physical, and environmental specifications and maximum charge and discharge currents per cell
- **Appendix B, Acronyms and Terminology** - describes terms and acronyms used in this guide.

Conventions Used in this Guide

This document uses the following conventions for notes, cautions, warnings, and danger notices.

NOTICE	A notice presents information that is important, but not hazard-related.
⚠ CAUTION	A notice presents information that is important, and may be hazard-related.
⚠ WARNING	A warning contains information essential to avoid a hazard that **can** cause severe personal injury, death, or substantial property damage if the warnings are ignored.
⚠ DANGER	A danger contains information essential to avoid a hazard that **will** cause severe personal injury, death, or substantial property damage if the warnings are ignored.

Related Documents and Resources

- http://www.iata.org/whatwedo/cargo/dgr/Pages/lithium-batteries.aspx
- http://www.ups.com/media/news/en/intl_lithium_battery_regulations.pdf
- http://www.welding-consultant.com
- http://www.ccl.fraunhofer.org/
- Sandia Report SAND20053123 "FreedomCar Electric Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications"

Chapter 1

Possible Dangers Involved With Handling Cells and Battery Packs

A123's cells are highly stable and abuse-tolerant; however, handling a battery pack remains potentially dangerous to personnel and property; therefore, anyone attempting to design or handle battery packs must first completely understand all aspects of proper battery pack design and construction. The dangers involved in building a battery pack include those described in the following sections.

- Thermal Events
- Short Circuits
- Arc Flashes
- High Voltage

Thermal Events

A thermal event is one where excessive heat in or around the cell destroys it immediately. Proper battery pack design is essential to allow the thermal safety features of A123's cells to function as designed. A123 cell design includes a safety feature that allows over-overheated cells to relieve dangerous pressure buildup by venting and dispersing the gases into the environment. However, an improperly designed battery pack can prevent the gases from safely dispersing.

For example, if the cell vents are blocked when a cell overheats, pressure within the cell can cause the overheated cell to rapidly disassemble and damage a poorly designed enclosure or other battery pack components. This document highlights some recommendations on the pack's physical and electrical design, which when followed, can mitigate these dangers.

⚠ WARNING Adding an ignition source to vented gases can create a dangerous thermal event.

⚠ WARNING The battery pack **must** ventilate these expelled gases to the environment after the gases are vented from the cell itself.

Short Circuits

⚠ WARNING Because A123 cells have relatively little internal resistance, an improperly designed battery pack may allow short circuits with dangerous levels of current.

Arc Flashes

⚠ WARNING A poor battery pack design may increase the chances of an arc flash. An arc flash caused by a short circuit involving both high voltage and high current, emits extremely high intensity visible and ultra violet light with the potential to damage property and cause blindness and burns to personnel.

High Voltage

⚠ DANGER Assembling a battery pack involves combining cells in series or parallel to achieve higher voltages and currents, respectively. As the voltage and current increase, so does the danger to personnel assembling the battery pack. Without the proper training, experience, tools and personal protective equipment (PPE), handling high voltage battery packs will result in injury or death.

Chapter 2

Transportation, Storage and Disposal

This chapter provides information about transportation regulations, storage specifications, and disposal considerations applicable to A123's AMP20 m1HD-A cells and battery packs designed with them. This chapter includes the following sections:

- Transporting Batteries
- Storing Batteries
- Disposing Batteries

NOTICE This document does not constitute legal advice or training. This document is not intended to substitute for training that may be required by laws and industry standards applicable to the transport of lithium ion batteries in every legal jurisdiction. You should seek advice on laws and relevant industry standards applicable to the transportation, storage, and disposal of dangerous goods prior to transporting, storing, or disposing of A123 batteries or cells.

Transporting Batteries

Certain batteries are considered "Dangerous Goods" because of their inherent stored energy and flammability. Lithium ion batteries of a certain size are considered "Class 9" Dangerous Goods and must be transported in accordance with international regulations.

Transporting Dangerous Goods is regulated internationally by the International Civil Aviation Organization (ICAO) Technical Instructions and corresponding International Air Transport Association (IATA) Dangerous Goods Regulations and the International Maritime Dangerous Goods (IMDG) Code. In the United States, transportation of these batteries is regulated by the Hazardous Materials Regulations (HMR), which is found at Title 49 of the Code of Federal Regulations, Sections 100-185. All of these regulations that govern the transport of rechargeable lithium ion cells and batteries are based on the UN Recommendations on the Transport of Dangerous Goods Model Regulations.

All lithium ion cells and batteries must meet the test criteria set forth in the UN "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria", chapter 38.3 (known as UN 38.3) in order to be transported.

Other laws and regulatory requirements may apply depending upon a given location. It is required for one to become familiar with the laws and regulatory requirements as they apply to each individual situation.

Useful References:

http://www.iata.org/whatwedo/cargo/dgr/Pages/lithium-batteries.aspx
http://www.ups.com/media/news/en/intl_lithium_battery_regulations.pdf

Shipping Process Overview

Table 1 provides an overview of the steps typically required to ship a product that contains lithium ion cells both internationally and in the U.S.

Table 1 – Steps required to transport a lithium ion battery

Step Number	Process Step	Comments
1	Design the battery pack.	Design the battery pack to ensure it will pass UN Manual of Tests and Criteria.
2A	Ship the battery pack to the UN 38.3 test house if using an outside test laboratory.	Use the "Prototype" shipping special provisions. Ship by ground (or cargo air with special approval) only.
2B	Test the battery pack. Refer to "UN Test Types", below.	Perform UN testing T1-T5, & T7 for batteries.
3	Obtain UN compliant packaging.	All Class 9 Dangerous Goods (DG) must be shipped in UN compliant packaging.*
4	Package the cell or battery.	Follow the packaging manufacturer's instructions.
5	Mark and label the package.	Insure that packaging container has all the required labeling. Refer to "Lithium Ion UN Numbers" below. *
6	Fill out the shipping documentation.	Complete shipper's declaration for dangerous goods, airway bill, and so on. *
7	Ship the package.	Ensure that shipping company can ship dangerous goods and that a Safety Data Sheet (SDS) and any Competent Authority Approval accompanies the package. *
* U.S. and international regulations require that anyone involved in the packaging, documentation, and labeling of Dangerous Goods for transportation must be officially trained to do so.		

UN Test Types

The UN Manual of Tests and Criteria Section 38.3 consists of the following tests:

- Test T.1: Altitude Simulation
- Test T.2: Thermal Test
- Test T.3: Vibration
- Test T.4: Shock
- Test T.5: External Short Circuit Test
- Test T.6: Impact/Crush (Cell only)
- Test T.7: Overcharge
- Test T.8: Forced Discharge (Cell only)

Lithium Ion Numbers

The following lists the proper shipping name for lithium ion/metal batteries as well as the corresponding UN number:

- UN 3480: Lithium ion batteries
- UN 3481: Lithium ion batteries packed with equipment
- UN 3481: Lithium ion batteries contained in equipment
- UN 3090: Lithium metal batteries
- UN 3091: Lithium metal batteries packed with equipment
- UN 3091: Lithium metal batteries contained in equipment

Class 9 Classification and Regulatory Requirements Overview

Cells and battery packs have transportation and packaging requirements based on their storage capacity Watt hours (Wh) or their equivalent lithium content (ELC) depending on the country of origin and transportation mode.

For purposes of transportation regulations, a battery pack and cell are defined as:

- A battery pack consisting of two or more cells that are electrically connected together and fitted with devices necessary for use, for example, case, terminals, marking and protective devices is considered a “battery”. However, a single cell battery is considered a "cell."
- A cell is a single encased electrochemical unit (one positive and one negative electrode) that exhibits a voltage differential across its two terminals.

Determining the Nominal Watt Hour Ratings of Cells and Batteries

To determine the nominal watt hours of a cell, multiply the nominal voltage (volts) of the cell by the cell’s nominal capacity (Amp-hours).

Eq 1. Nominal Watt hours (Wh) of the cell = Nominal Voltage of the cell (V) x Nominal Capacity of the cell Amp-hours (Ah)

To determine the nominal watt hours of a battery, multiply the number of cells by the nominal watt hours of the cells that make up the pack. That is, the number of cells multiplied by their nominal voltage and then by their nominal capacity.

Eq 2. Nominal Watt hours of a battery (Wh) = Number of cells x Nominal Watt hours (Wh) of a cell

Determining the Equivalent Lithium Content (ELC) of Cells and Batteries

Equivalent Lithium Content (ELC) of a cell is calculated as 0.3 times the rated capacity of a cell (Ah) with the result expressed in grams (g). The ELC of a battery is equal to the sum of the grams of ELC contained in the component cells of the battery.

Eq 3. ELC of a cell (g) = 0.3 x Nominal Capacity (Ah) of a cell

Eq 4. ELC of a battery (g) = 0.3 x Nominal Capacity (Ah) of a cell x Number of cells in the battery

Table 2 shows the nominal Wh ratings and ELC for each of the commercially available A123 cells.

Table 2 – Nominal energy and ELC of A123 cells

Cell	Nominal Voltage	Nominal Ah Rating	Nominal Wh	ELC
APR18650m1A	3.3	1.1	3.63	**0.33**
ANR26650m1B	3.3	2.5	8.25	**0.75**
AHR32113m1	3.3	4.5	14.9	**1.35**
AMP20m1HD-A	3.3	19.5	64	**5.85**

The following sections give a brief overview of how cells and batteries are classified for transportation and some of the regulations required to ship a product containing lithium ion cells or batteries both in the US and internationally.

US Regulation Requirements Overview

For any transport of cells or batteries inside the US borders, by road or rail, Table 3 and Table 4 summarize how cells and batteries are classified with respect to Class 9 Dangerous Goods. For such shipments, cells and batteries are classified by their equivalent lithium content (ELC) as either Class 9 or *Excepted*.

Table 3 – US transportation classification of cells

Watt hours	Cell Size	Shipping Classification	Required Testing	Are there Special Packaging / Markings?
ELC less than 1.5 g per cell	Small	Excepted	UN 38.3 Tests T1-T8	Yes. Packages containing more than 24 cells must meet certain packaging, marking, and shipping paper requirements. (See IATA.org for details)
ELC less than 5.0 g per cell	Medium	Excepted for Road and Rail transport in the US.		
ELC greater than 5.0 g per cell	Large	Class 9		Yes. Requires Class 9 markings, label, specification packaging, and shipping papers.

Table 4 – US transportation classification of batteries

Watt Hours	Battery Size	Shipping Classification	Required Testing	Are there Special Packaging / Markings?
ELC less than 8.0 g per battery	Small	Excepted	UN 38.3 Tests T1-T5, & T7	Yes. Packages containing more than 12 batteries must meet certain packaging, marking, and shipping paper requirements. (See IATA.org for details)
ELC less than 25 g per battery	Medium	Excepted for Road and Rail transport in the US.		
ELC greater than 25 g per battery	Large	Class 9		Yes. Requires Class 9 markings, label, specification packaging, and shipping papers.

International Regulation Requirements Overview

For any transport of cells or batteries outside of the US borders, or transport by ocean OR air anywhere in the world including the US, Table 5 and Table 6 summarize how cells and batteries are classified with respect to Class 9 Dangerous Goods. For such shipments, cells and batteries are classified by their nominal energy rating as either Class 9, or *Excepted*.

Table 5 – International transportation classification of cells

Watt hours	Shipping Classification	Required Testing	Are there Special Packaging / Markings?
Cell ≤ 20 Wh	Excepted	UN 38.3 Tests T1-T8	Yes. Even though not Class 9, the package must be properly marked. (See Figure 7.4.H of the IATA Dangerous Goods Regulations). Additional requierements apply when shipping by air. *
Cell > 20 Wh	Class 9		Yes. Requires Class 9 markings, label, specification packaging, and shipping papers.

Table 6 – International transportation classification of batteries

Watt Hours	Shipping Classification	Required Testing	Are there Special Packaging / Markings?
Battery ≤ 100 Wh	Excepted	UN 38.3 Tests T1-T5, & T7	Yes. Even though not Class 9, the package must be properly marked. (See Figure 7.4.H of the IATA Dangerous Goods Regulations). Additional requierements apply when shipping by air. *
Battery > 100 Wh	Class 9		Yes. Requires Class 9 markings, label, specification packaging, and shipping papers.

* Note: ICAO limits the number of cells and batteries you can ship before being required to claim them as Class 9. See ICAO or IATA Packing Instruction 965 and Table 7 for details.

Using the IATA Rules to Test, Package, and Label

The International Air Transport Association (IATA) regulations provide requirements for testing, packaging, and labeling of lithium batteries. These regulations are found in Packing Instructions PI-965 – PI-970.

IATA Packing Instructions PI-965, PI-966, and PI-967 apply specifically to *air shipment* of lithium ion batteries. They provide specific requirements for the materials used and the “survivability” of packaging and *over packs* to potential damage, provision for safety venting, and prevention of short circuits when cells, batteries, products packaged with batteries and products containing batteries are packed for transportation by air.

Table 7 and Table 8 list IATA PI-965 – PI-967 requirements for packaging batteries for air transport. The complete set of instructions can be found on the IATA.org web site:

http://www.iata.org/whatwedo/cargo/dgr/Pages/lithium-batteries.aspx

Table 7 – International air transport (IATA) packaging and quantity restrictions (PI-965)

Requirement	PI-965 – Lithium Ion Cells and Batteries					
				Section II		
	Section 1A* (Class 9)	Section 1B (Cell ≤ 20 Wh and Max. # Cell > 8/pkg	Section 1B (Batt. ≤ 100 Wh) and Max. # Batt. > 2/pkg	Cells and/or batteries ≤ 2.7 Wh and Max. # Cell/Batt. No Limit/pkg	Cell (2.7 Wh < Cell ≤ 20 Wh) and Max. # Cell ≤ 8/pkg	Batt. (2.7 Wh < Batt. ≤ 100 Wh) and Max. # Batt. ≤ 2/pkg
Capacity Labeling	Yes **	-	Yes***	Batteries Only***	-	Yes***
Meet the requirements of the UN Manual of Tests and Criteria, Part III, subsection 38.3	Yes					
Max quantity - Passenger Aircraft	5 kg Net	10 kg Gross		2.5 kg Net	N/A	N/A
Max quantity - Cargo Aircraft††	35 kg Net	10 kg Gross		2.5 kg Net	N/A	N/A
Outer Pack Standards	General Packing Requirements 5.0.2 AND Packing Group II performance Standards	5.0.2.4, 5.0.2.6.1, 5.0.2.12.1		5.0.2.4, 5.0.2.6.1, 5.0.2.12.1	5.0.2.4, 5.0.2.6.1, 5.0.2.12.1	5.0.2.4, 5.0.2.6.1, 5.0.2.12.1
Inner packaging required to enclose battery	Yes	Yes		Yes	Yes	Yes
Prevent accidental activation						
Prevent short circuits	Yes	Yes		Yes	Yes	Yes
Provide Safety Venting	Yes	No (A123 Yes)		No (A123 Yes)	No (A123 Yes)	No (A123 Yes)
1.2 m drop test (pack + content)	NA (see performance standard for Packing Group II)	Yes		Yes	Yes	Yes
Prevent Dangerous Reverse Current flow	Yes	No (A123 Yes)		No (A123 Yes)	No (A123 Yes)	No (A123 Yes)

Requirement	PI-965 – Lithium Ion Cells and Batteries					
	Section 1A* (Class 9)	Section 1B (Cell ≤ 20 Wh and Max. # Cell > 8/pkg	Section 1B (Batt. ≤ 100 Wh) and Max. # Batt. > 2/pkg	Section II		
				Cells and/or batteries ≤ 2.7 Wh and Max. # Cell/Batt. No Limit/pkg	Cell (2.7 Wh < Cell ≤ 20 Wh) and Max. # Cell ≤ 8/pkg	Batt. (2.7 Wh < Batt. ≤ 100 Wh) and Max. # Batt. ≤ 2/pkg
Class 9 hazard label	Yes	Yes		No	No	No
Lithium Battery Label	No	Yes; Repeat on overpack also.		Yes; Repeat on overpack also.	Yes; Repeat on overpack also.	Yes; Repeat on overpack also.
Proper Shipping Name and UN Number	Yes	Yes		Yes	Yes	Yes
Complete Shipper's Declaration for Dangerous Goods	Yes	Yes		No	No	No
A document with following information: • Package contains lithium batteries • Package must be handled with care and flammability hazard exists if package is damaged • Special procedures must be followed in the event package is damaged, to include inspection and repacking if necessary • Telephone number for additional information	No	Yes		Yes	Yes	Yes
Air waybill	No	No		Lithium ion batteries in compliance with Section II of PI 965 (if using an air waybill)	Lithium ion batteries in compliance with Section II of PI 965 (if using an air waybill)	Lithium ion batteries in compliance with Section II of PI 965 (if using an air waybill)
* Lithium batteries with mass ≥ 12kg and having a strong, impact-resistant outer casing, or assemblies of such batteries, may be transported when packed in strong outer packaging in protective enclosures. These require approval of the authority having jurisdiction (copy of approval to accompany shipment.)						
**Batteries manufactured after 31 December 2011 must be marked with Watt-hour rating on the outside case.						
***The Watt-hour rating must be marked on the outside of the battery case except those manufactured before 1 January 2009						
† Lithium battery label required if package contains more than four cells or two batteries installed in the equipment; except button cell batteries installed in equipment (including circuit boards.) †† Cargo Aircraft only label must be on all shipments that are only allowed on Cargo Aircraft.						

Table 8 - International air transport (IATA) packaging and quantity restrictions (PI-966 & PI-967)

Requirement	PI-966 – Lithium Ion Cells and Batteries Packed <u>with</u> Equipment			PI-967 – Lithium Ion Cells and Batteries Contained <u>in</u> Equipment		
	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9
Capacity Labeling	-	Yes	Yes **	-	Yes	Yes **
Meet the requirements of the UN Manual of Tests and Criteria, Part III, subsection 38.3	Yes			Yes		
Max quantity - Passenger Aircraft	Number of batteries required to power unit plus 2 spares (per package)		5 kg (weight of cells or batteries per package)	–		5 kg (net weight of cells and batteries per piece of equipment)
Max quantity - Cargo Aircraft††	Number of batteries required to power unit plus 2 spares (per package)		35 kg (weight of cells or batteries per package)	–		35 kg (net weight of cells and batteries per piece of equipment)
Outer Pack Standards	5.0.2.4, 5.0.2.6.1, 5.0.2.12.1		General Packing Requirements 5.0.2 AND Packing Group II performance Standards	Equipment must be packed to: 5.0.2.4, 5.0.2.6.1, 5.0.2.12.1		Equipment must be packed to: 5.0.2.4, 5.0.2.6.1, 5.0.2.12.1
Inner packaging required to enclose battery	Yes (inner pack completely encloses then packed with equipment)		Yes (inner pack completely encloses then packed with equipment)	–		–
Prevent accidental activation	Yes (and prevent motion relative to outer pack)		Yes (and prevent motion relative to outer pack)	Yes: equipment secured against movement within outer packaging		Yes: equip. secured against movement within outer packaging
Prevent short circuits	Yes		Yes	No		Yes
Provide Safety Venting	No (A123 Yes)		Yes	No (A123 Yes)		Yes
1.2 m drop test (pack + content)	Yes (for each package of cells or batteries, or completed package)		NA (see performance standard for Packing Group II)	No		No
Prevent Dangerous Reverse Current flow	No (A123 Yes)		Yes	No (A123 Yes)		Yes
Class 9 hazard label	No		Yes	No		Yes
Lithium Battery Label	Yes; Repeat on over pack also.		No	Yes†; Repeat on overpack		No
Proper Shipping Name and UN Number	Yes		Yes	Yes		Yes
Complete Shipper's Declaration for Dangerous Goods	No		Yes	No		Yes
A document with following information: • Package contains lithium batteries • Package must be handled with care and flammability hazard exists if package is damaged • Special procedures must be followed in the event package is damaged, to include inspection and repacking if necessary	Yes		No	Yes†		No

Requirement	PI-966 – Lithium Ion Cells and Batteries Packed <u>with</u> Equipment			PI-967 – Lithium Ion Cells and Batteries Contained <u>in</u> Equipment		
	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9
• Telephone number for additional information						
Air waybill	Lithium ion batteries in compliance with Section II of PI 966 (if using an air waybill)		No	Lithium ion batteries in compliance with Section II of PI 967 (if using an air waybill)		No

* Lithium batteries with mass ≥ 12kg and having a strong, impact-resistant outer casing, or assemblies of such batteries, may be transported when packed in strong outer packaging in protective enclosures. These require approval of the authority having jurisdiction (copy of approval to accompany shipment.)
**Batteries manufactured after 31 December 2011 must be marked with Watt-hour rating on the outside case.
***The Watt-hour rating must be marked on the outside of the battery case except those manufactured before 1 January 2009
† Lithium battery label required if package contains more than four cells or two batteries installed in the equipment; except button cell batteries installed in equipment (including circuit boards.)
†† Cargo Aircraft only label must be on all shipments that are only allowed on Cargo Aircraft.

Note: Competent Authority Approval is required to ship by air for at least the following conditions. Otherwise, it is prohibited to ship by air:

- Any batteries over 35kg, even those that have passed UN testing
- Waste lithium batteries
- Prototype vehicles containing prototype batteries

Cells and batteries are prohibited from being transported by air for any reason if they have been identified by the manufacturer as:

- Defective for safety reasons
- Damaged
- Having the potential of producing a dangerous evolution of heat, fire, or short circuit

To gain Competent Authority Approvals, contact your local jurisdiction's Department of Transportation. For example in the US, contact the US DOT and request a CA Approval by stating your case. This approval process can be lengthy (3 – 6 months or longer).

Storing Batteries

A123 cells can be stored for over 10 years in a cool environment. For long storage periods, a refresh charge is required every four years at 25 °C. For temperatures above 40 °C a refresh charge is required every year. Batteries should not be stored continuously above 65 °C.

Battery Disposal

Do not incinerate or dispose of cells or batteries. Return end-of-life cells or batteries to your nearest recycling center per the appropriate regulations.

Chapter 3

Nanophosphate® Technology and Cell Characteristics

This chapter includes the following sections:

- Nanophosphate Technology
- Power
- Safety
- Life

Nanophosphate® Technology

A123's low impedance Nanophosphate® electrode technology provides significant competitive advantages over alternative battery technologies, including:

- **Power:** A123's Nanophosphate® products can pulse at high discharge rates to deliver unmatched power by weight or volume.
- **Safety:** A123's Nanophosphate® technology is designed to be highly abuse-tolerant, while meeting the most demanding customer requirements of power, energy, operating temperature range, cycle life, and calendar life.
- **Life:** A123's Nanophosphate® technology delivers exceptional calendar and cycle life. A123 cells can deliver thousands of 100% Depth-of-Discharge (DOD) cycles, a feat unmatched by other commercial lithium ion cells.

Power

A123 cells are designed to deliver high power in pulse and continuous applications. Figure 1 shows the cell voltage remains relatively flat during the discharges and the delivered Ah capacity does not change significantly, no matter what the rate of discharge.

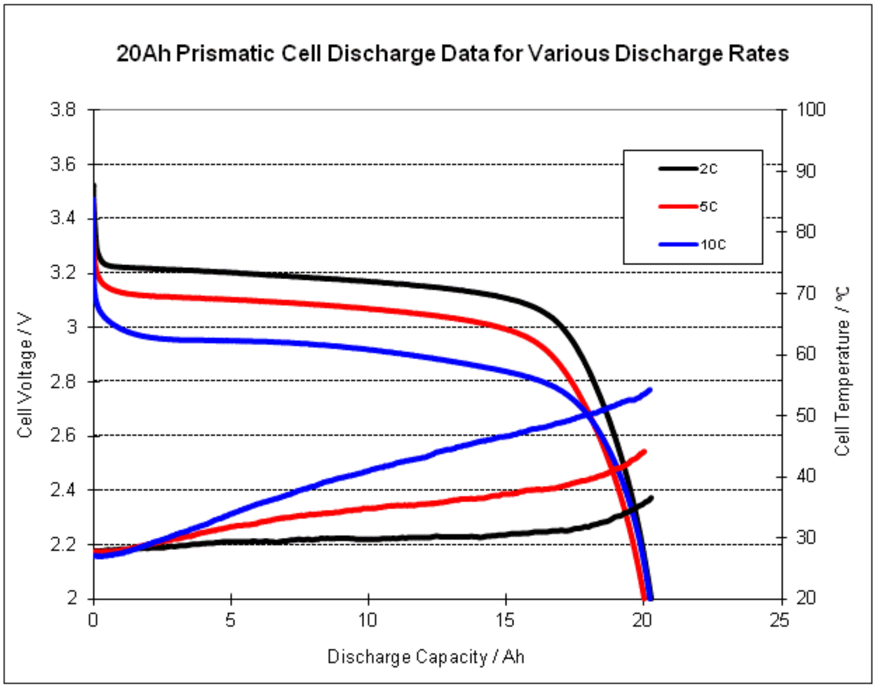


Figure 1 – 20Ah Prismatic cells discharge curves

Cell resistance changes with cell temperature. The warmer the cell, the lower its resistance becomes. Figure 2 shows how temperature affects the cell's terminal voltage during a one hour discharge.

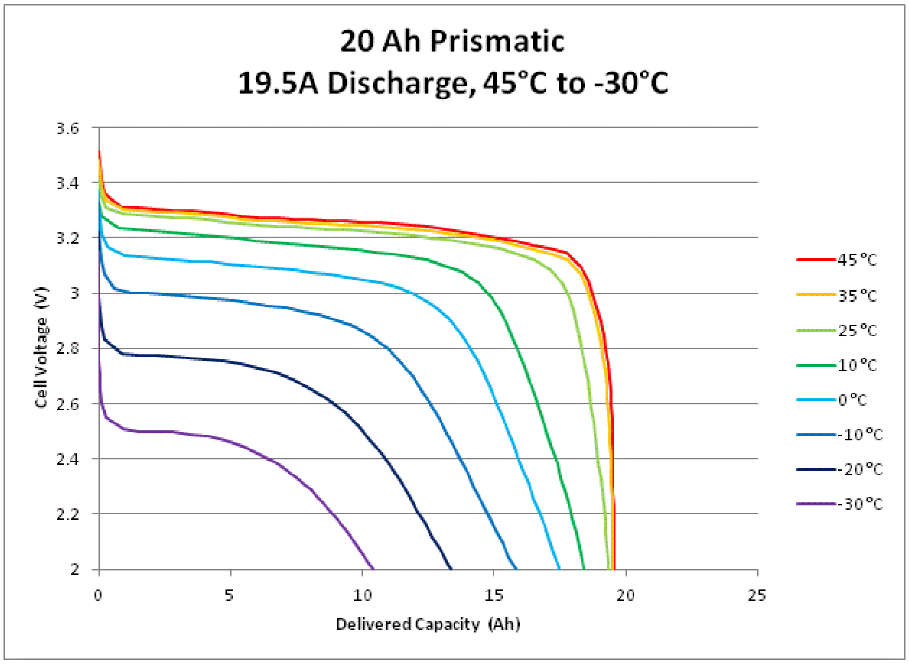


Figure 2 – A123 20Ah Prismatic cells discharge curves at various temperatures

Safety

Nanophosphate® releases only a small amount of heat and oxygen under abusive conditions so cells made using Nanophosphate® chemistry do not exhibit the energetic thermal runaway that metal oxide lithium ion cells experience. This greatly reduces the likelihood of cascading failure—where an incident in one cell spreads to adjacent cells—within a battery pack designed with Nanophosphate® chemistry. Even if all of a pack's safety systems fail, the increased safety inherent to Nanophosphate® chemistry provides an additional layer of protection that reduces the incidence, severity and probability of energetic failures.

That said, proper handling and battery pack design must be followed to make sure the A123 Nanophosphate® cells operate safely. These cells can store significant amounts of energy and (unlike most other types of cells) deliver this energy very quickly. Appropriate pack design must provide sufficient mechanical and environmental protection to ensure the cells operate within their proper voltage, current, and temperature limits.

⚠ WARNING

The following minimum safety precautions must be followed at all times. Failure to follow the following safety instructions may result in personal injuries or damage to the equipment!

- Cells must not be subjected to ambient conditions greater than 65 °C while in storage. If this condition occurs cell life will be degraded.
- Cells must not be heated to or self-heated to a skin temperature in excess of 85 °C during operation. If this condition occurs cell life will be degraded or the cell will be rendered inoperable.
- Cells must not be charged or discharged outside the operating temperature range in the datasheet, and reduced charging limits must be followed for extreme operating temperatures (See Table 15, Table 16, Table 17, and Table 18).
- Cells must not be incinerated, nor should they be stored or used near open flames.
- Cells must not be punctured, ruptured, dented, or crushed.
- Cell packaging must not be altered in any way.
- Cells must not be immersed or exposed to water or liquids.
- Never use a mechanism to hold the cells in a way that leads to blocked cell vents. If the vents are blocked, the gas cannot exit the cell in case of cell failure. Cells shall be mounted in the application in a way that will not interfere with the vent function on the cell. See Figure 12.
- If the cell or battery emits smoke or flames, ventilate the area immediately and avoid breathing the fumes. See Safety Data Sheet (SDS) for additional precautions.
- Cells must not be subjected to reverse polarity or short circuited. Individual cell fusing is required in pack designs with cells in parallel to be compliant with international regulations that are harmonized with the UN Recommendations on the Transport of Dangerous Goods. UN 38.3, US-DOT and other international shipping regulations.

Life

A123 cells offer long cycle and calendar life, with minimal impedance growth over the life of the cells. The cycle life graph in Figure 3 shows how the capacity of the cell decreases with respect to the number full Depth of Discharge (DoD) cycles that it delivers. For example, at 25 °C, the cell can deliver over 5000 full DoD cycles before its capacity decreases to 80% of its original beginning of life (BOL) capacity.

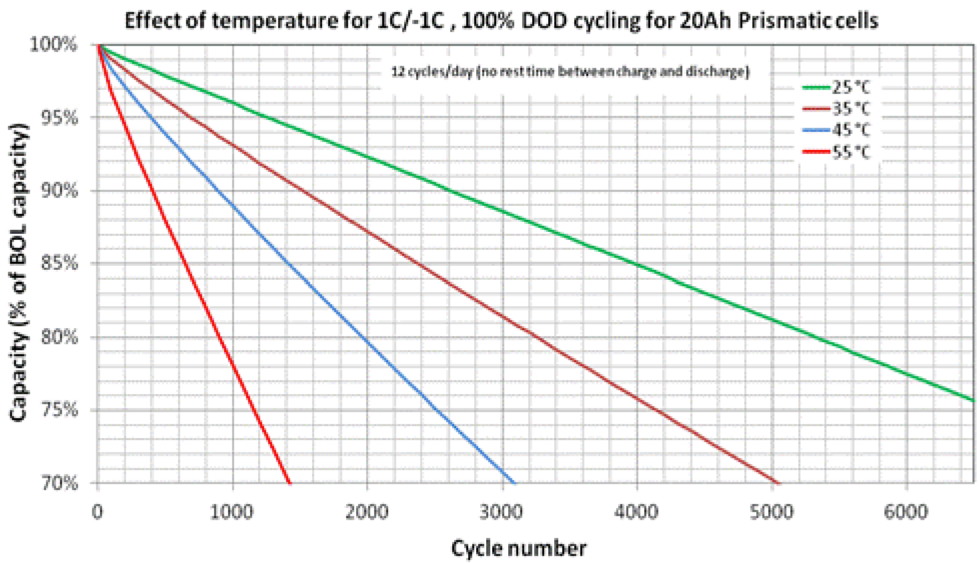


Figure 3 - 20Ah Prismatic cells cycle life (1C charge / 1C discharge rates)

Figure 4 shows how the cells lose capacity over time, sitting at 100% SOC in various temperatures. Within three months, the cells lose 3% of their initial capacity, but the aging slows, and over the next one year they only lose another 1% at 25 °C. Temperature is a significant factor in calendar aging. For example in two years, the capacity loss is 6% at 25 °C, 11% @ 35 °C and 22% at 45 °C.

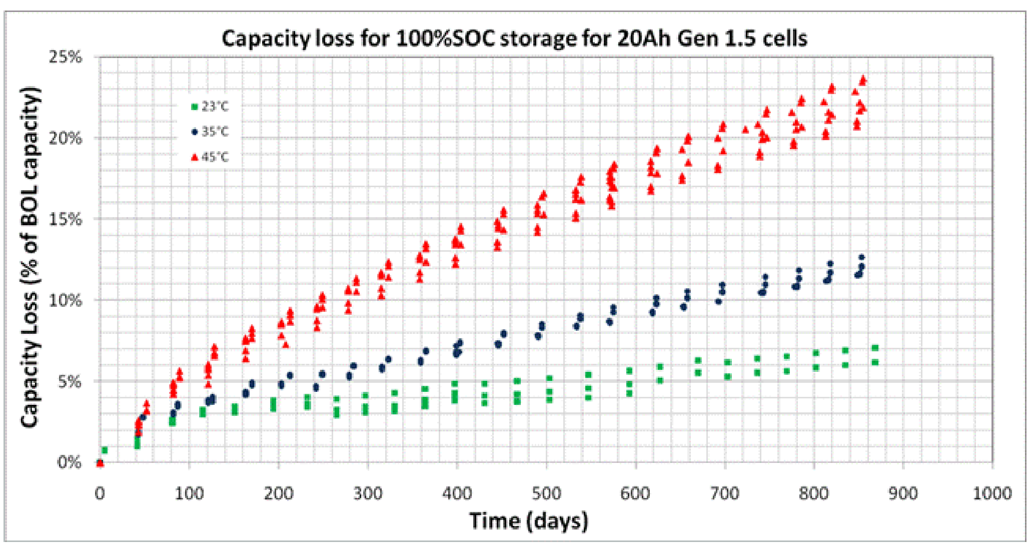


Figure 4 – Capacity loss due to calendar aging

A123 ENERGY SOLUTIONS

Chapter 4

Battery Pack Design

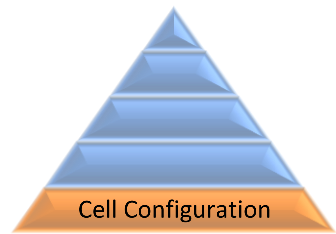
This chapter includes the following sections:

- Design Overview
- Configuration of Cell in a Battery Pack
- Battery Pack Structural Design
- Cell Protection
- Battery Pack Management
- Battery Pack Use

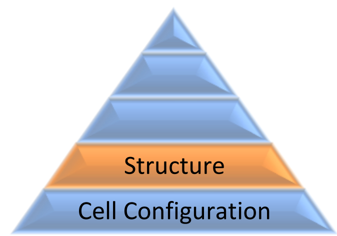
Design Overview

A battery pack is a system of multiple components and functions and its design involves the application of knowledge and practice in the electrochemical, electrical, mechanical, thermodynamic, and control fields. The following sections summarize the various stages of a battery pack design, covering specific aspects of the A123 cells which may be unique from other cells.

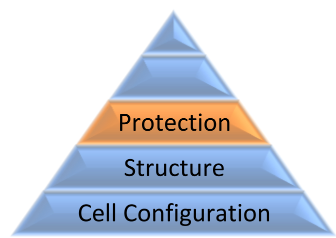
1. The first step in the design of the pack is to determine the configuration of cells, i.e. how many cells overall, how many are in series, and how many are in parallel. This is the foundation of the design process, since all other design decisions follow from the cell configuration.



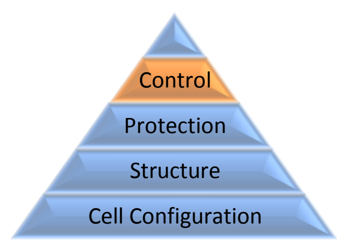
2. The second step is to design a mechanical structure around the cells to support and protect them. This step requires knowledge of electrical, mechanical and thermodynamic requirements and properties of the cells, application, and the materials used in the pack.



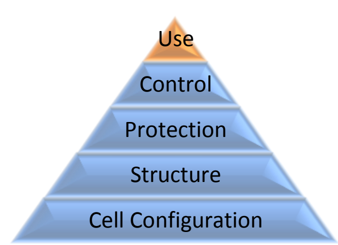
3. The third step is to design the protection of the cells, particularly electrical protection. The pack must be protected from inadvertent short circuits internal and external to the pack as well as excessive charging and discharging imposed on its terminals.



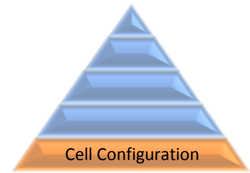
4. The fourth step is to design a control system that monitors and manages the cells, keeping them from being damaged and maintaining the pack at peak performance.



5. Finally, a pack performs best when it is used properly. The final section of this chapter describes how to charge and discharge the battery pack to make it perform its best.



Configuration of Cells in a Battery Pack



The battery pack's terminal voltage and current ratings must match those of the device(s) to which it interfaces. If the pack requires the energy of just one cell, the designer's options are limited to the ratings of that one cell. However, as more energy is required of the pack, requiring more cells to be interconnected, the degrees of freedom increase, allowing the designer to choose a combination of cell-to-cell interconnections that provide the right voltage and currents to interface properly in the application. Once a configuration of cells is chosen, the designer must insure that the resulting ratings of the pack are compliant with the systems that will connect to it. This section covers:

- Voltage and Capacity
- Series Strings
- Parallel Cells

Voltage and Capacity

Cells can be combined together either in series or in parallel to achieve higher operating voltages and power, respectively. This section describes the electrical aspects of interconnecting cells. When connecting cells, the designer must consider the mechanical principles of basic pack design discussed in the section Battery Pack Structural Design on page 31.

Series Strings

Cells combined in series strings will achieve higher operating voltages by connecting the positive terminal of one cell to the negative terminal of the next cell. Connect strings of series cells using their current collection tabs in a manner similar to that illustrated in Figure 5.

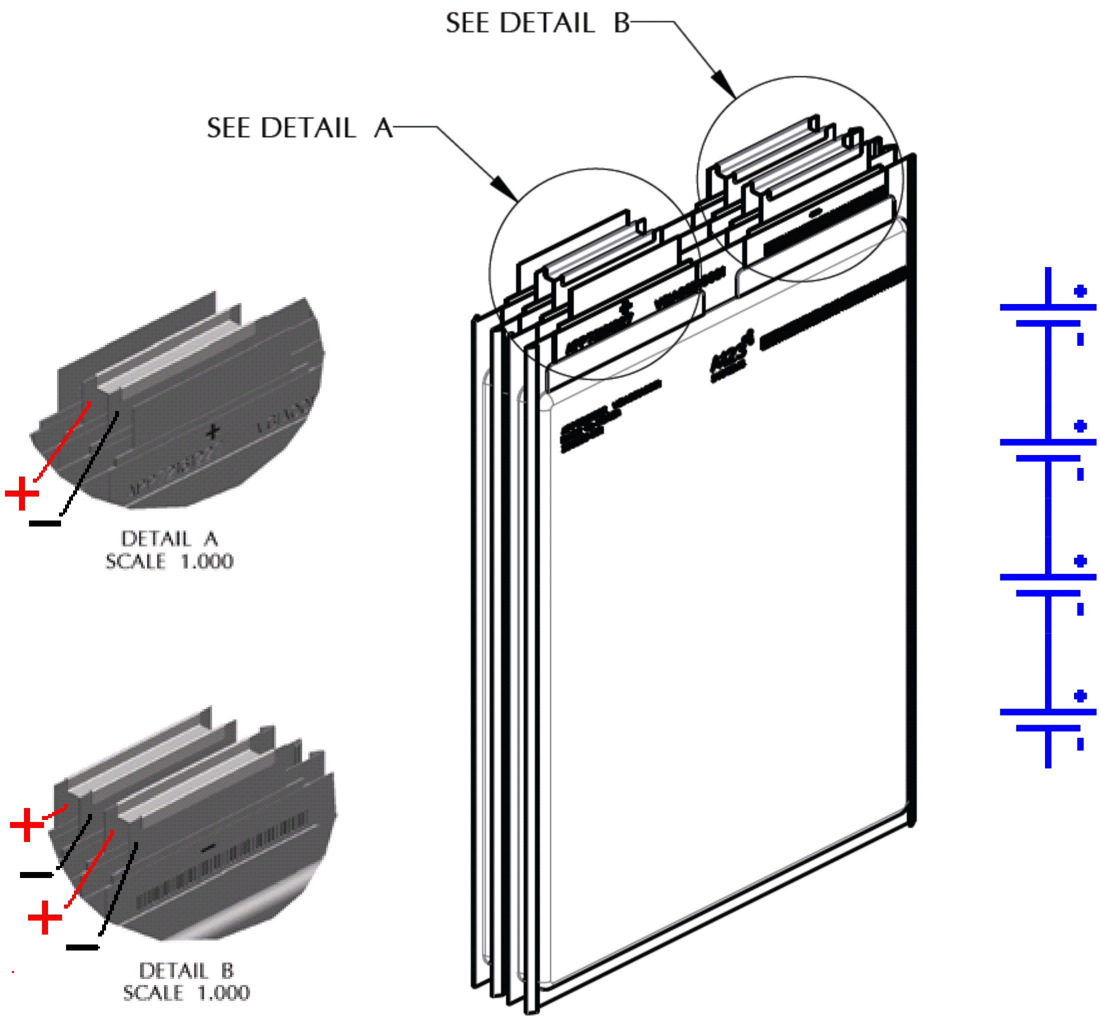


Figure 5 - Example of AMP20*m1*HD-A cells connected in series

Two cells in series: 2 x 3.3V = 6.6V (nominal)
Four cells in series: 4 x 3.3V = 13.2V (nominal)

A single cell's normal operating range is between 2V and 3.6V (See Appendix A for complete specifications). A pack with n multiple cells in series would then have an operating voltage range of n x 2.0 to n x 3.6 (where n is the number of cells in series). For example, a two series cell combination would have a voltage range between 4 and 7.2V, with a nominal voltage of 6.6V.

Parallel Cells

Cells connected in parallel can achieve higher operating power by connecting like-polarity terminals of adjacent cells to each other. Connect groups of parallel cells using their current collection tabs in a manner similar to that illustrated in Figure 6.

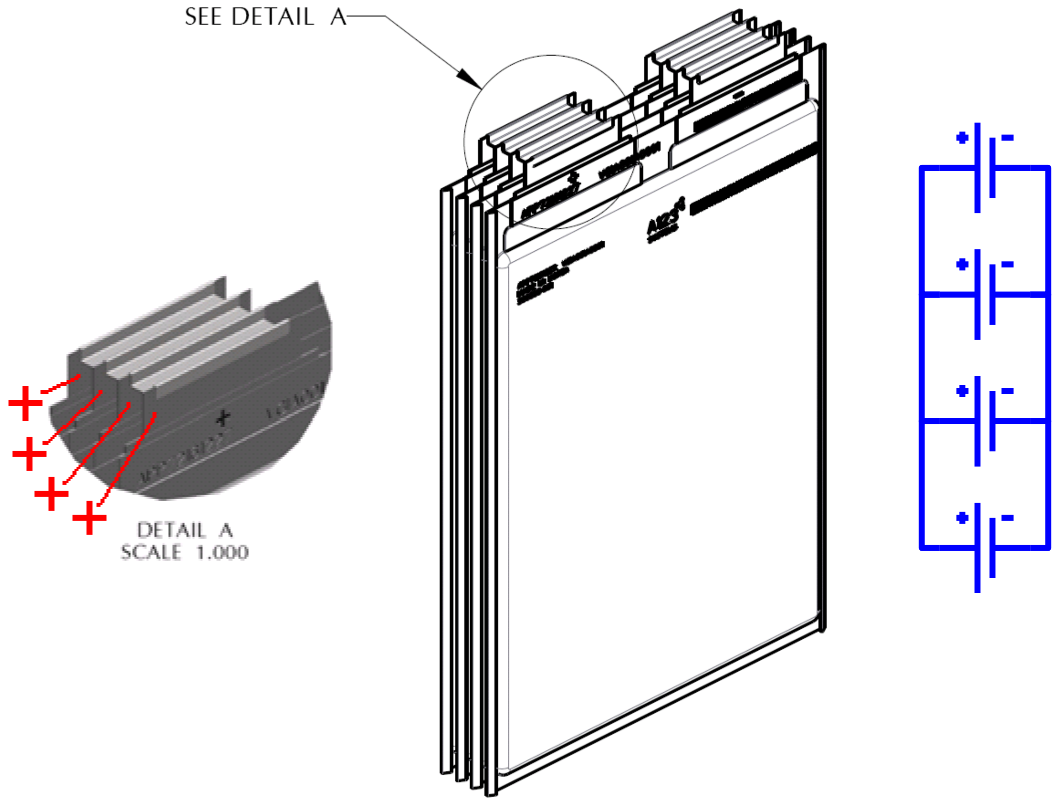
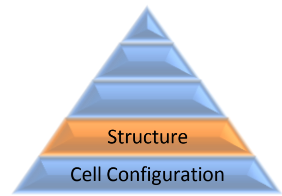


Figure 6 - Cells connected in parallel

Two cells in parallel: 2 x 19.5Ah = 39Ah
Four cells in parallel: 4 x 19.5Ah = 78Ah

Battery Pack Structural Design



A well designed battery pack protects and replicates the individual cell performance of multiple cells in the pack. It provides mechanical protection and integrity, thermal stability, and electrical protection and performance. The electrical interconnections, mechanical supports and thermodynamic systems are all essential elements of the battery pack's structural design. This section covers:

- Electrical Connection and Protection
- Mechanical Cell Support
- Thermal Management

Electrical Connection and Protection

The electrical interconnections in a battery pack must be designed to carry the expected maximum current for both the maximum time and ambient temperature in which the pack is expected to operate. In addition, the electrical interconnections shall be designed to prevent accidental short circuits that may result from heavy vibration (vehicle operation), or extreme shock (drop or impact), or loose hardware.

<u>Cell Interconnections</u>

Cell interconnections should be sized for the expected maximum current carrying capability. Improperly sized tabs could heat up excessively, resulting in damage to themselves, nearby components, structures or even the cells. For reliable welded connections at the terminals, A123 recommends either copper or copper alloy straps welded to the copper tabs and Aluminum straps welded to the Aluminum tabs. Cell interconnections (straps) should be neither soldered on the cells tabs nor attached using extreme heat. A123 recommends tabs be resistance or laser-welded to the tabs of the cells. See the Cell Welding section in Chapter for more details.

Mechanical Cell Support

To operate at its peak performance and have the longest possible service life, the prismatic cell needs to be mounted with some amount of pressure on its two broad faces. This pressure must be evenly distributed and be compliant to the regular expansion cycles the cell experiences during cycling and over its service life. A123 performed extensive testing on the effects of the pressure on the faces of the cells on the cycle life of the cells. Figure 7 shows that the optimum pressure on the cell's face is between 4 and 18 psi.

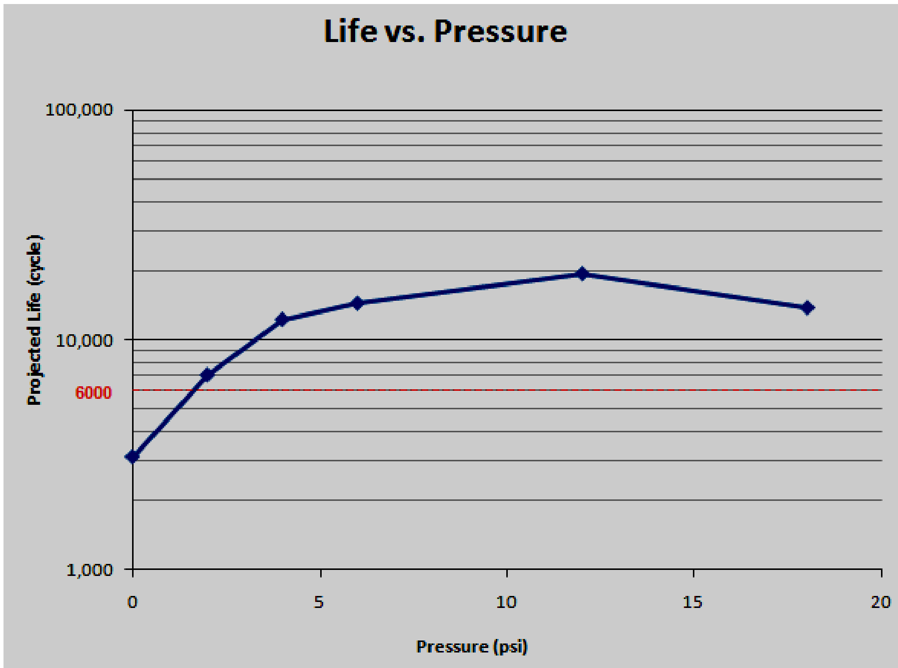


Figure 7 – Cycle life of the cell can be optimized by applying the proper pressure to the face of the cell and maintaining that throughout the life of the cell

Cell thickness expansion

During the regular cycling that a cell experiences from 100% SOC to 0% and back, the cells will expand approximately 1% their initial thickness. Over the course of the cell's lifetime as it ages during regular service, its thickness will grow to be 3 – 5% greater than initial thickness.

The graphs in Figure 8 show how much the cells can expand over the course of a charge and discharge cycle.

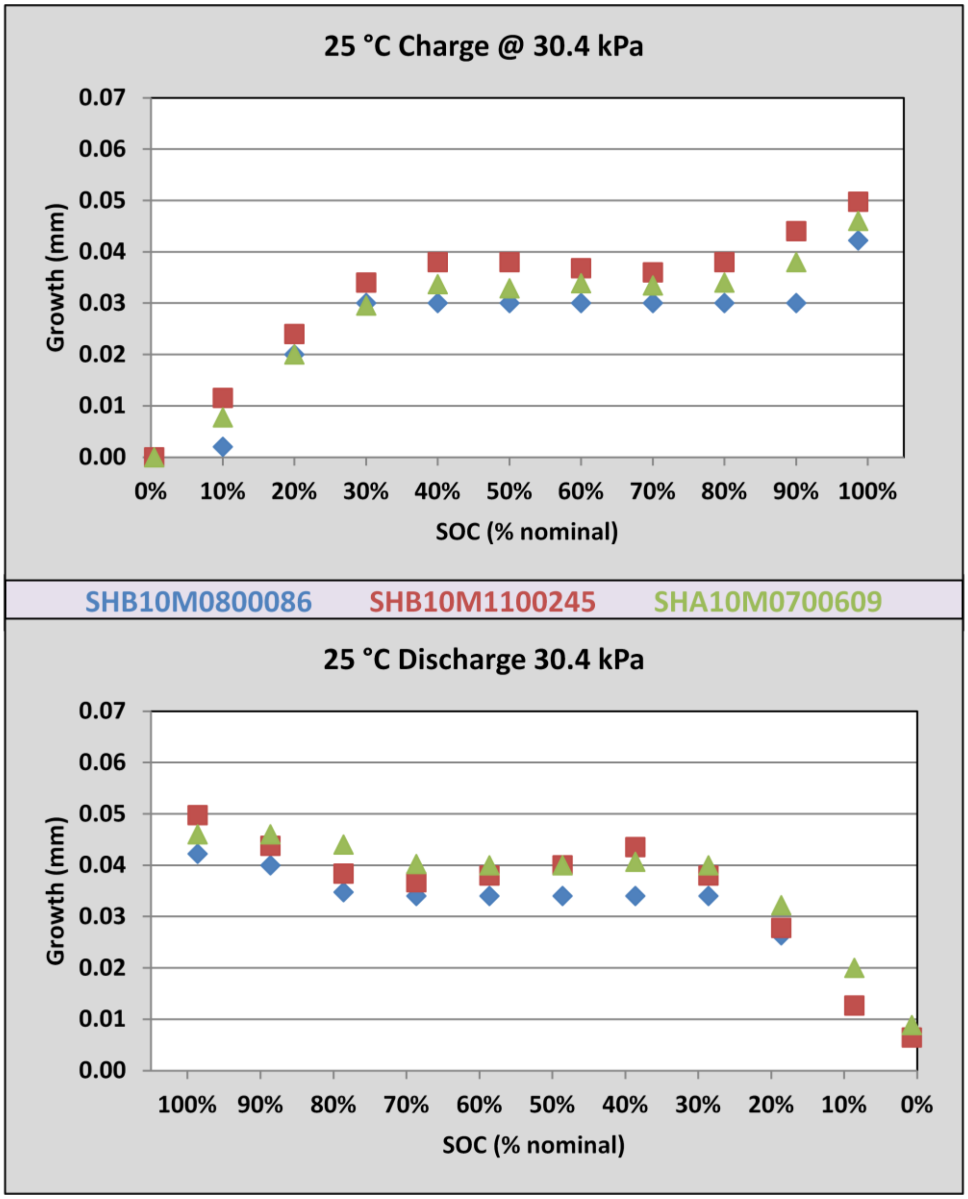


Figure 8 – 20Ah cell thickness variation wrt SOC for three representative 20Ah cells

Compliant Pads Between Cells

To maintain proper cell support and account for expansion during the charge and discharge cycles, A123 uses a compliant pad between cells. The compliant separator is chosen to maintain the pressure range of 4 – 18 psi against the cell's surface. By way of example, Figure 9 shows how much pressure is exerted by a 1.19 mm compliant pad of a certain durometer. Using this chart, one can choose the initial deflection (16%) such that the regular expansion of the cell during its cycling keeps the pressure between 4 and 18 psi.

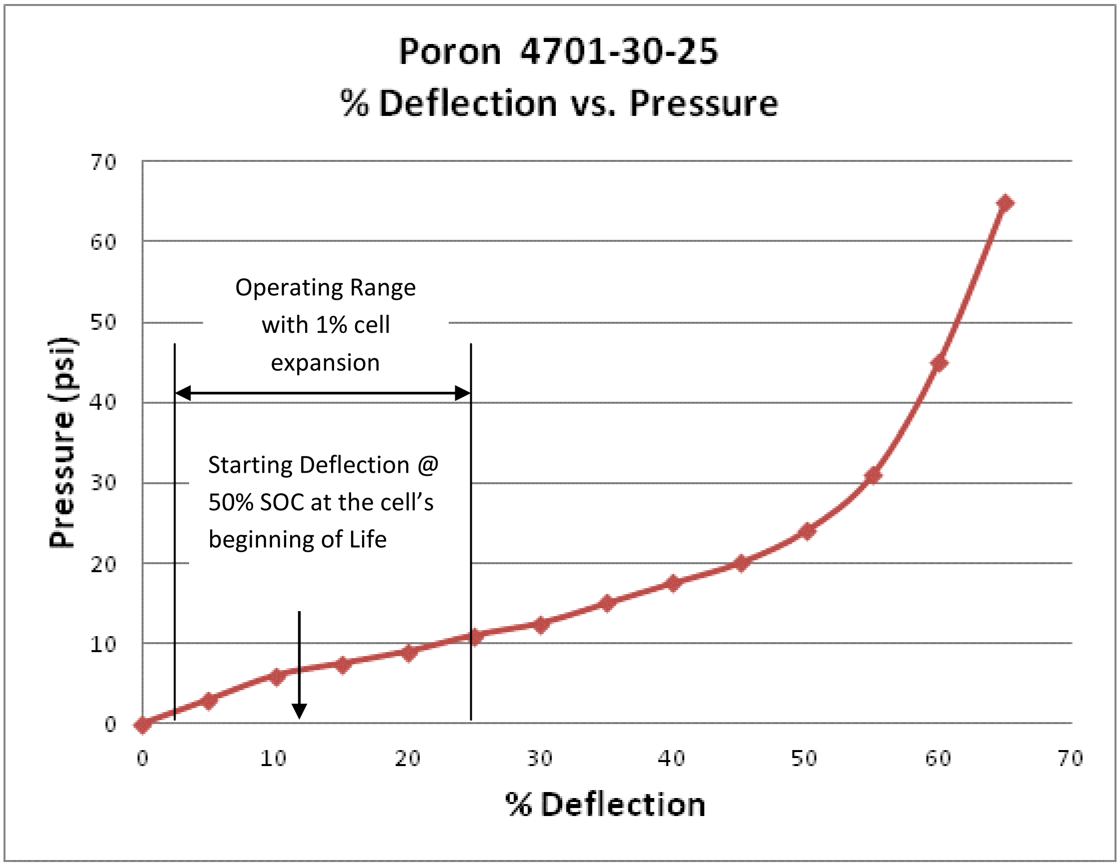


Figure 9 – Graph of the pressure vs. deflection of an example compliant pad, which may be used between 20Ah cells in a battery pack.

Of course each pack design will be different, so the deflection parameters need to be calculated independently for each. This is just an example of one particular compliant pad.

Cell Pressure Uniformity

Another advantage of a compliant pad between the cells is that pressure is kept relatively constant across the whole surface of the cell. Figure 10 shows simulated pressures at various points across the cell with and without the compliant pad in place.

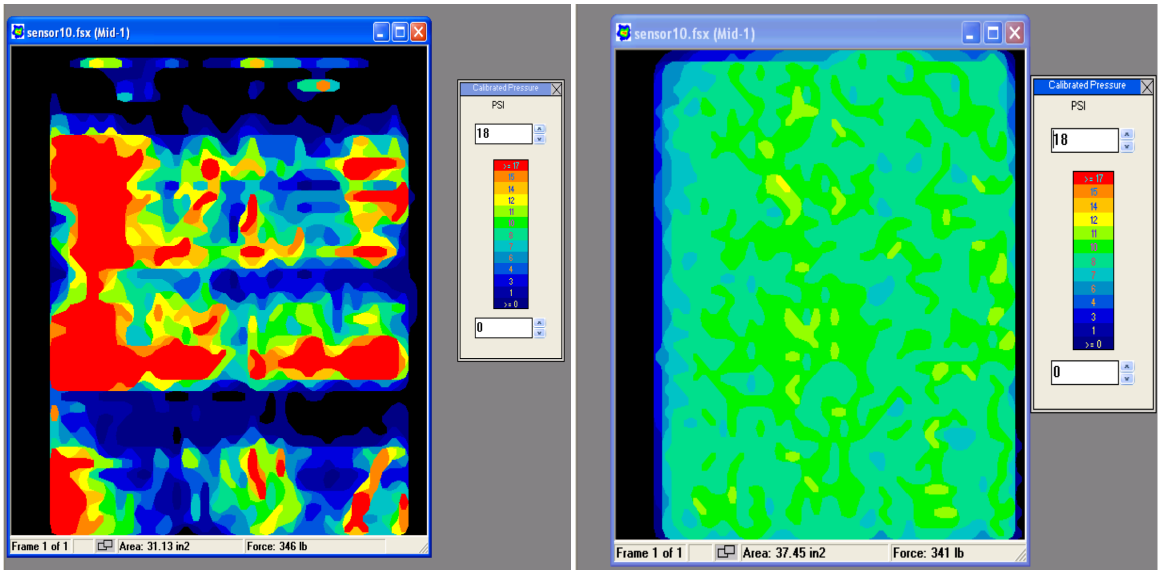


Figure 10 – Pressure on cell face without compliant pad (left) and with compliant pad (right)

Another factor that can affect the uniformity of the cell pressures is the rigidity of the end plate exerting pressure on the very end of the cell stack. The more flexible this is, the more variation in pressures one will see on the end cell's face. The best way to determine this variation is by FEA simulation of the design. Figure 11 is a 3D graph showing the variation of pressures across the face of a cell using a particular end-cap design. The differences are visually more striking than they really are. In this particular design, the pressure variation across the pack is only +5/-2% off the average.

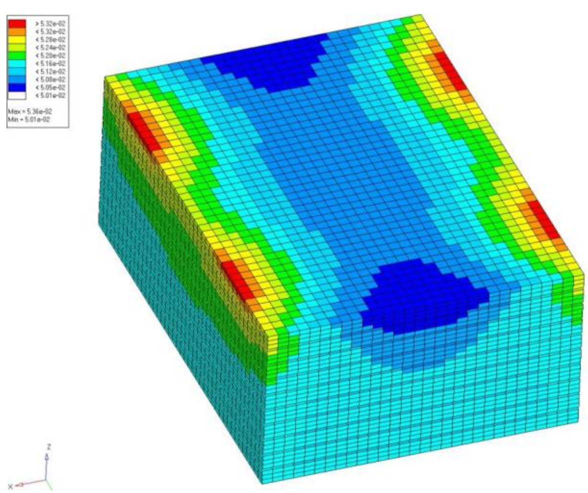


Figure 11 – Pressure map across the surfaces of each cell in a stack showing the results of a non-ideal but acceptable end-cap design.

Cell Insulation

The outside of the prismatic cell is electrically isolated from the electrode terminals but at a high enough voltage (> 2500 Vrms Hi-Pot testing), a flashover can occur. Therefore in the battery pack design, it is important that there is adequate and consistent insulation between the outer surfaces of the cell and any surrounding conductive surfaces, such as heat sinks, conductors, and/or the chassis.

Cell Environmental Protection

In addition to supporting the cells, a well-designed chassis will protect cells from exposure to corrosive substances and oxidizing catalysts, such as dust and moisture. The necessary level of protection for cells in a battery pack varies depending on the intended application. For example, a battery pack designed for use in an HEV must have an enclosure that isolates cells from shock and vibration, protects them from dirt and debris, as well as shielding them from other environmental dangers, such as salt spray. Unless it is hermetically sealed, even a sealed enclosure is subject to pressure differentials between its insides and the ambient, causing minute amounts of air exchange. Therefore, over time, some moisture may accumulate and condense on inside surfaces. A battery pack designed to be sealed from the environment (from dust, moisture, and VOCs) must have a way to benignly drain off whatever condensate does manage to leak into it and keep it away from circuits and conductors. In addition, enclosures protecting cells must work with the thermal management system to achieve optimum durability and safety of the battery pack. For example, a poor choice of materials for the enclosure, combined with insufficient cooling and controls, may cause the battery pack to overheat.

Allowing the Cell to Vent in a Fault Condition

During abusive conditions (such as Overcharge), the electrolyte inside the cell will decompose into gaseous compounds and cause pressure to build within the cell. When the pressure is high enough, the gases will evacuate or vent through an intentional weak spot in the top corner of the cell. Although this process of venting irreversibly damages and ultimately makes the cell unusable, it prevents the cell from exploding in an uncontrolled manner.

A properly designed battery pack will allow the vent to operate in a situation where the cell is significantly abused. Any mechanical constraints in this corner shall be avoided.

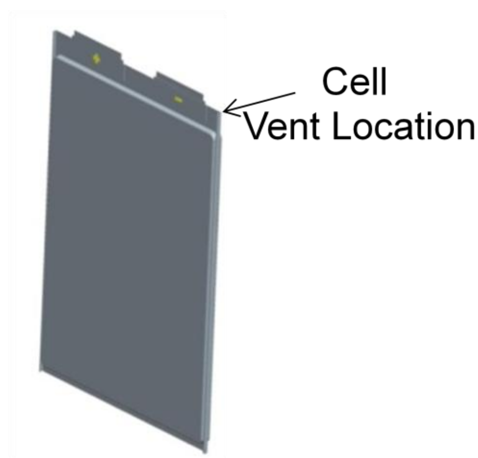


Figure 12 - Corner that will vent under extreme internal pressure

Thermal Management

A123 cells operate very well in a wide temperature range; however, they are most effective between 10 °C and 50 °C. The temperature differential between the coolest cells and the hottest cells should be no more than 10 °C. Careful attention to thermal management is necessary to keep the cells operating at peak efficiency and avoiding fault conditions. In most cases, this will require a cooling system. There are certain applications - such as PHEV vehicles operating in cold climates – in which a heater is beneficial to keeping the cells operating in their optimal range.

Cooling the Cells

When they are stacked together face to face, there are two options to cool them:

1. **Using tabs as thermal conductors to draw the heat out of the cells.** The tabs are conductors of electricity and therefore thermal conductors as well. Heat generated in the cells can conduct along the metal layers and out through the tabs to the exterior of the cell. This method should be used only when the internal rate of heat generation is extremely low. In laboratory testing, the measured thermal "R values" between the inside and ambient ranged between 7 and 8 °C/W. Additionally the variation in temperature within the cell is fairly large.
2. **Using thermally conductive plates inserted between the cells in the cells stack:** Heat can be drawn out from the edges of the stack where it can be conducted to the air or a fluid-based heat sink. R-values in the range from 1 to 2 °C/W have been achieved using this method. Additionally, the thermally conductive plates keep the temperature gradient across the surfaces of the cells relatively even. The thicker and more conductive these plates are, the better their performance will be, but the battery pack will be heavier and occupy more volume. Those are the design tradeoffs to weigh battery pack performance against its attributes. Figure 13 shows a general concept of using a plate and edge-situated heat sink to cool the cells.

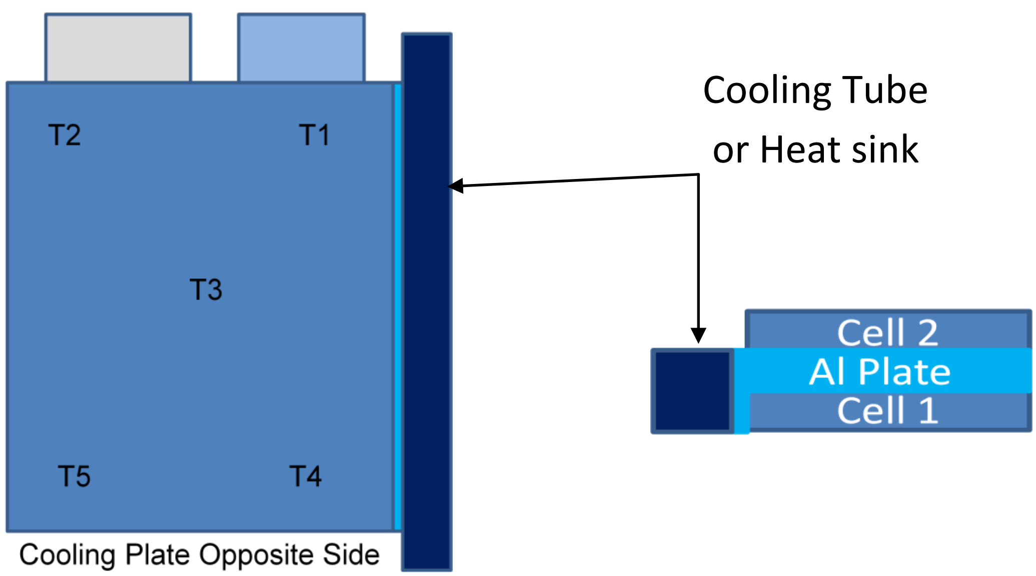


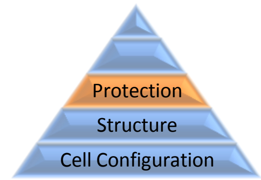
Figure 13 – Diagram of optional 20Ah cell cooling concept

Air convection or liquid-cooled heat sinks or tubes can be used to draw heat away from the ends of the cells. The design choice will be made based on project and product budget and performance requirements. The goal is to keep the cell's temperatures at or below 35 °C to maximize their service life. Air cooled options for some applications employed by A123 can handle up to 1C peak and C/2 continuous RMS power and still maintain average cell temperatures of 35 °C. In contrast, liquid cooling options employed by A123 can enable 4C peak and 2C continuous power and maintain average temperatures below 40 °C. These results are examples only and highly dependent on the external cooling system design and parameters, such as flow, inlet temperature, interfaces, and control; but indicate what can be expected with proper design.

* Note: "C" in the context of this paragraph refers to a rate of power usage. For example, 1C rate of power is a rate that would discharge the battery in one hour. C/2 is a rate that would discharge the battery in 2 hours. 2C rate would discharge the battery in 30 minutes.

Cell Protection

The battery pack must be protected from inadvertent short circuits internal and external to the pack as well as excessive charging and discharging imposed on its terminals.



Short Circuit Protection

Because of the very low impedance of the A123 cells, a short circuit can cause excessive internal and external damage if not limited in either duration or current magnitude. Coordinated fusing in the pack interrupts excessive current at the cell or module level, helping to prevent the main fuse from blowing. Likewise, a fault at the module level will not cause the cell fuses to blow. One can achieve the circuit protection strategy described above by having the individual cell fuses operate at a higher fault current than that of the module. Likewise, the module fuse should blow at a higher level than the main pack fuse. This is considered best practice in the circuit protection field.

Individual Cell Fusing

Refer to Figure 14 for an illustration of an individual cell fusing strategy.

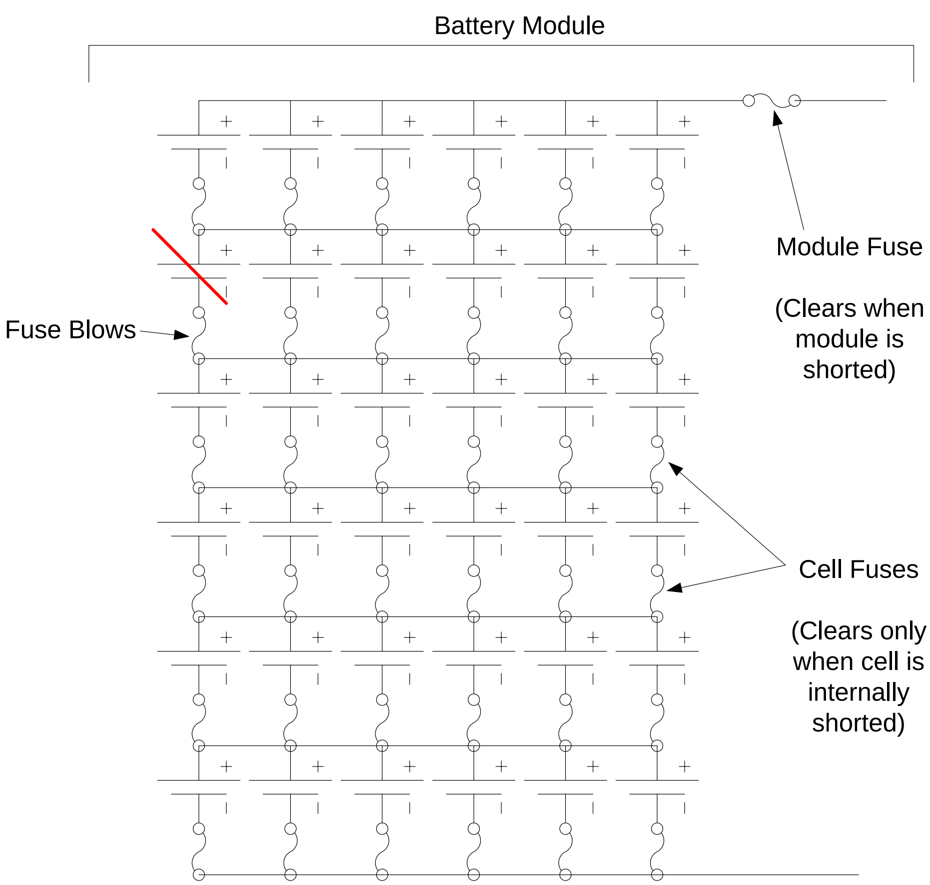


Figure 14 - Individual cell fusing strategy

The cells provided by A123 do not have any fusing built into the cells. In order to implement cell-level fusing, individual cell fusing can be accomplished by constricting the interconnecting metal material near the cell terminal. This is done by stamping out a pattern of holes in the tabs. Some experimentation and modeling is required to find the right pattern to offer the proper protection and coordination with the entire system. A123 uses the following pattern shown in Figure 15 in the tabs of cells integrated into its modules:

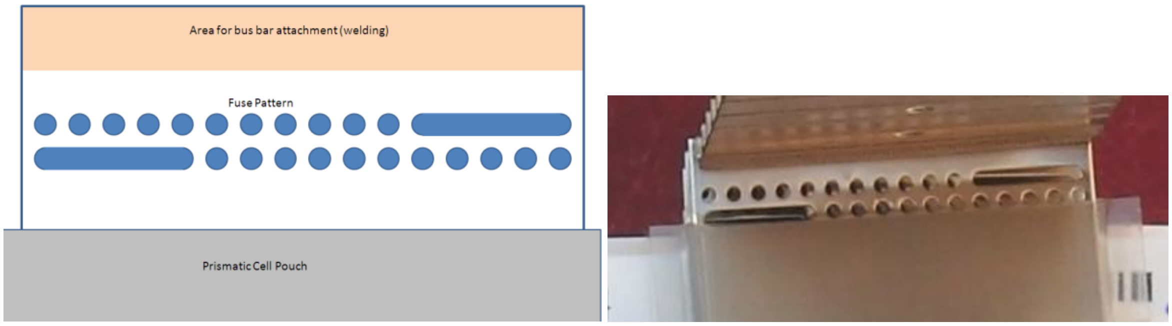


Figure 15 – Example cell fuse pattern in cell terminals

The fuse pattern in Figure 15, stamped into 0.2 mm copper, clears in approximately in 1 sec while carrying 1800 A. This and possible alternative designs should be verified using modeling software and bench testing prior to design release.

The current-time chart in Figure 16 shows how this particular fuse coordinates with other current limiting devices in the system.

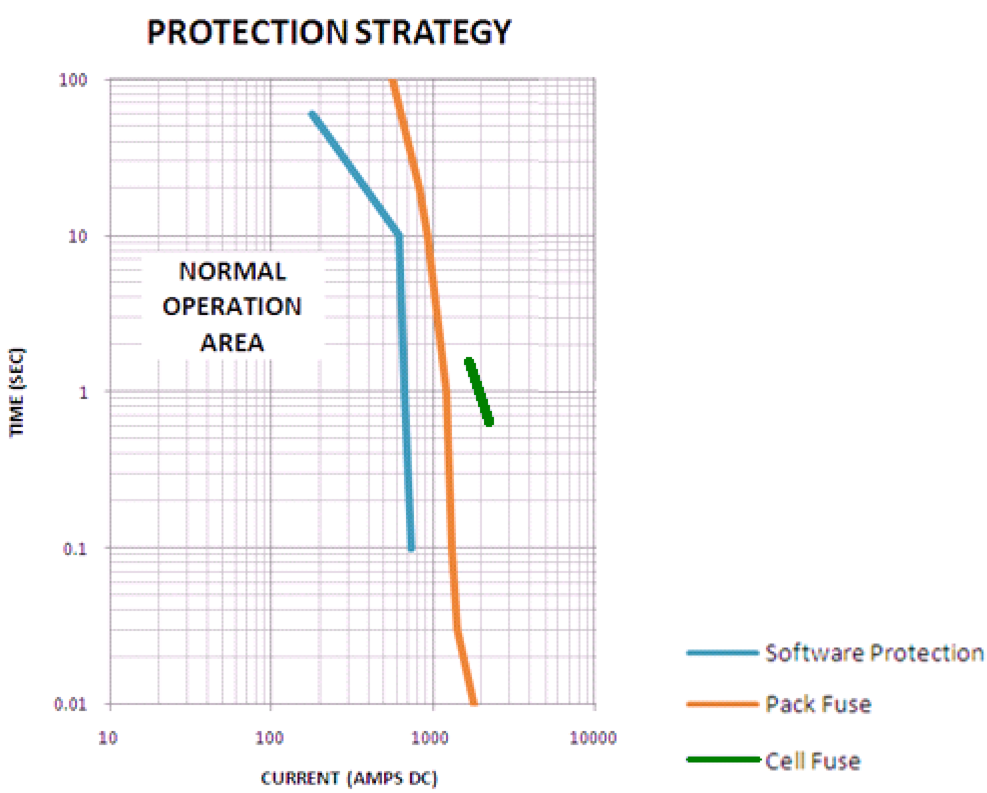


Figure 16 - Example of total system fusing strategy

Module Fuse Rating

The module fuse should blow at a lower current than that of the individual cell fuses. This ensures that the module fuse blows before any of the cell fuses in response to a fault on the module terminals. In addition, the module fuse must interrupt any short circuit path that may exist around multiple series modules situated between the main pack fuse and possible short circuit locations. Note in Figure 17, a short circuit involving four modules is possible with an internal fault.

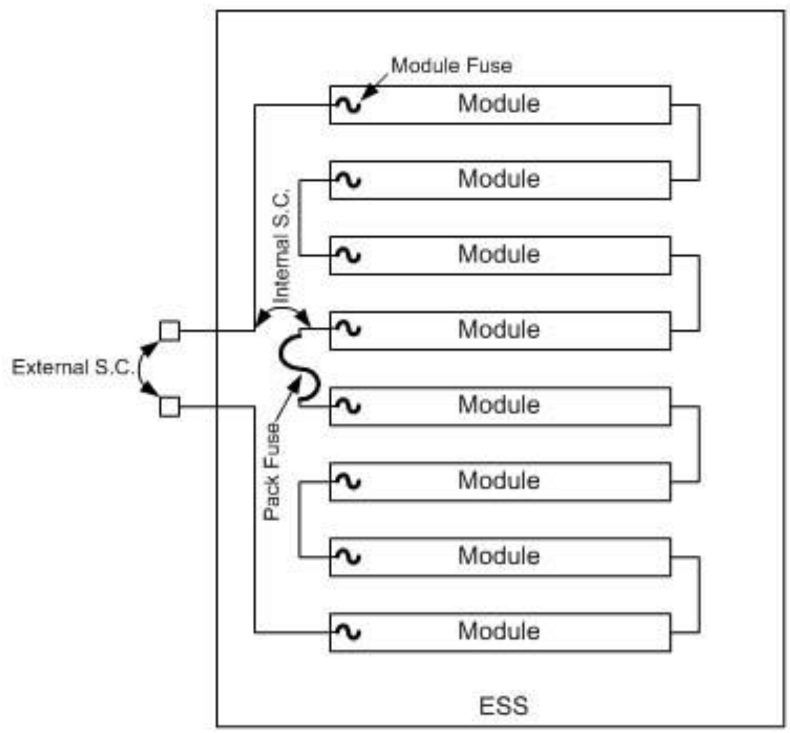


Figure 17 - Battery pack with representative short circuit faults

Pack Fuse Rating and Position

The pack fuse needs to interrupt the full fault current of the battery pack at its worst-case maximum terminal voltage. The pack fuse should be rated such that it carries the system load current continuously at all rated temperatures. The pack fuse in the battery pack should blow well before the module fuses. This ensures that if an external fault occurs, then only the pack fuse is damaged. A pack fuse is often more-easily replaced than the module fuses.

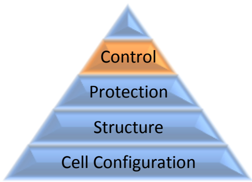
Fuse Coordination and Testing

Proper fuse coordination can ensure safe operation of the battery pack, even in fault conditions. Once a prototype fusing strategy is in place, the DVT process should **perform the short circuit testing using the full ranges of cell temperature and SOC**, because these can significantly affect the test results.

Overcharge Protection

The only way to provide fool-proof protection from overcharging the cells in a pack is to interrupt the current when such a condition is sensed.   Electronic switches, relays or contactors can be used to interrupt the current entering the cells. Electronic circuitry monitoring each cell can be used to trigger the interrupting device when any cell voltage goes outside of its safe operating range. The following section describes this function in more detail.

Battery Pack Control (Monitoring and Management)



When joining cells together, A123 recommends using a Battery Management System (BMS) to accurately monitor cell voltage, current, impedance and other conditions of the cells. The BMS may be implemented as discrete circuitry and/or through a microcontroller. This section covers the following topics:

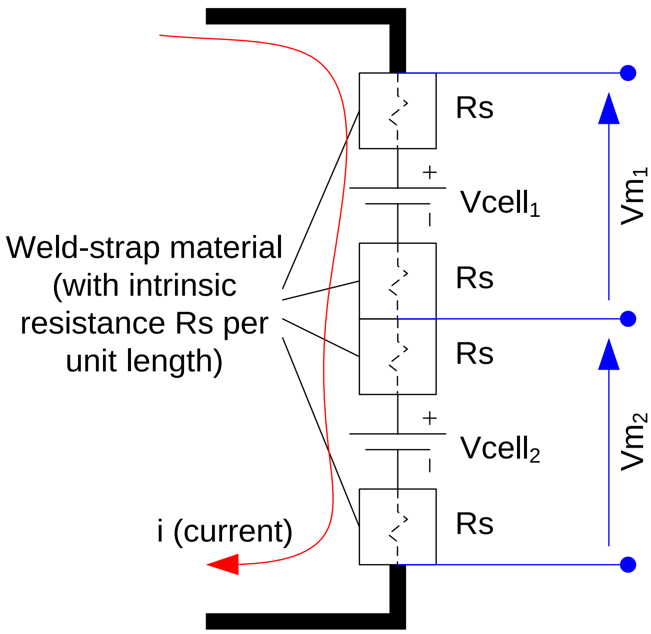
- Cell Monitoring
- Supervising Battery Pack Behavior
- Cell Balancing
- Fuel Gauging
- Integrated Circuits

Cell Monitoring

Cell Voltage

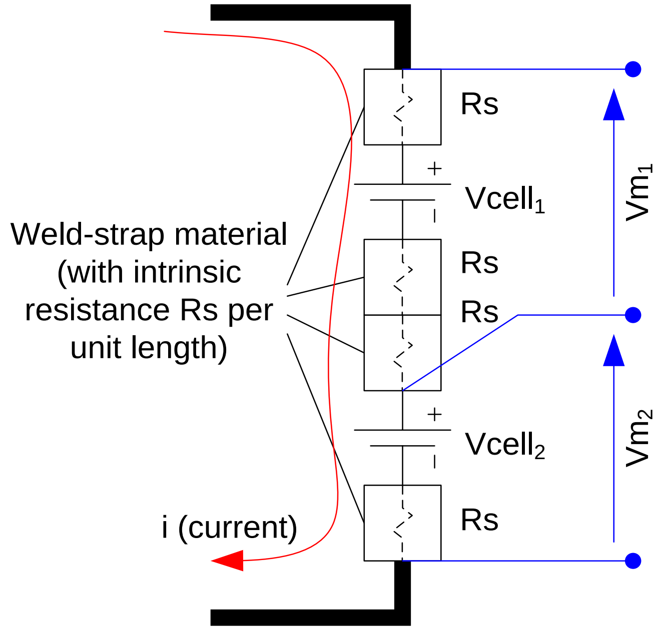
To ensure optimal performance, safety, and durability of the pack, the Battery Management System must monitor the voltage of each individual series cell in a battery string. The voltage monitoring connections shall be in a place where they are not affected by high currents going through the interconnection elements.

The diagram below depicts an optimal positioning of the voltage monitoring contact points in an idealized setting:



In this case, Vm1 = Vcell1 – 2 x i x Rs and Vm2 = Vcell2 – 2 x i x Rs. The result of Vm1 – Vm2 would be exactly what is desired, and that being Vcell1 – Vcell2.

If the contact points are placed asymmetrically, such as shown below:

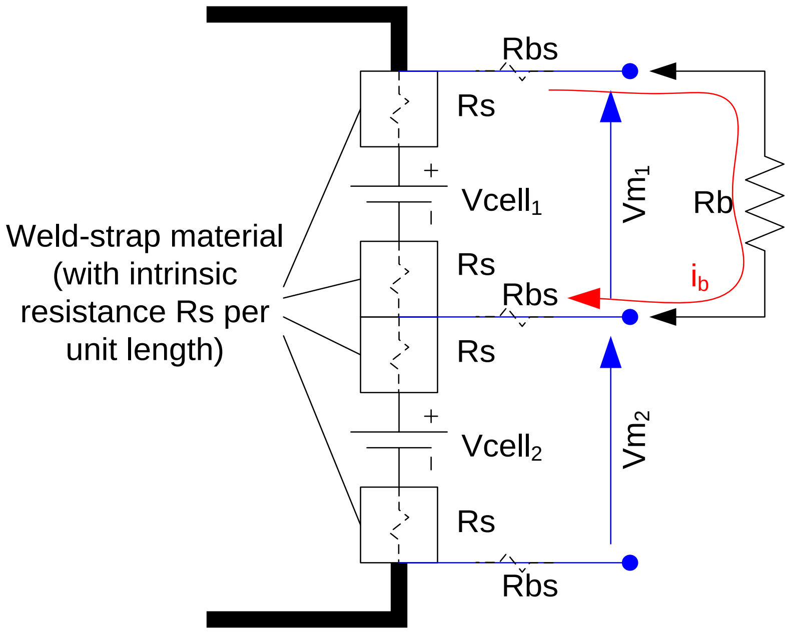


Vm1 = Vcell1 – **3** x i x Rs and Vm2 = Vcell2 – i x Rs. The result of Vm1 – Vm2 would contain an undesirable offset in it: Vcell1 – Vcell2 + -2(i x Rs) where Voffset =-2(i x Rs).

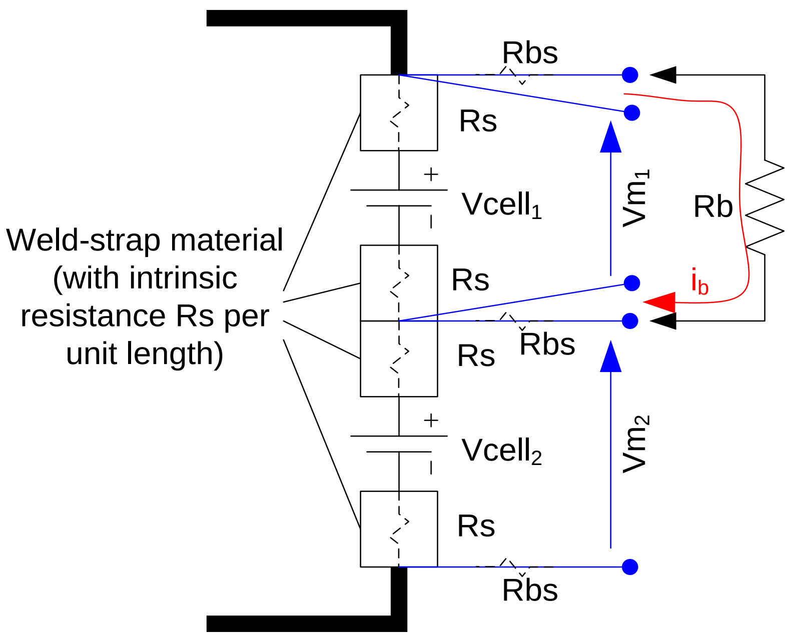
This offset in the voltage readings would cause the BMS to read that there is more charge in one cell while the current is flowing in one direction, and have less charge in it while current is flowing in the opposite direction. So while the battery is discharging, the BMS would try to balance some of the cells, and while it is recharging, the BMS would try to balance the others. This results in a great deal of wasted heat and energy that contributes to a reduced performance and service lifetime of the battery.

Additionally, the balancing currents should not flow through the voltage sensing leads. Otherwise, the balancing currents will affect the voltage reading proportionally, increasing the time needed to achieve proper cell balancing, if not making it impossible.

The following circuit depicts a condition in which the measured voltages would be affected by balancing currents going through the sense leads:



In such a case, if Rb were connected to cell 1, Vm1 would read Vcell1 – ib x 2 x (Rbs + Rs). Having a separate wire for balancing current from the sensing wires eliminates a good portion of the error, as shown in the following diagram:



In this case, Vm1 = Vcell1 – 2 x ib x Rs. If Rs is small, then Vm1 will substantially be the same as Vcell1.

If balancing current does flow through voltage sensing leads, then the microcontroller should turn off balancing currents during voltage sampling periods, so that the voltage measured is unaffected by the balancing current.

Cell Temperature

Ideally, the temperature of every series element or cell would be monitored by the BMS; however, it is not as important as voltage, and is often impractical in cost-effective systems. A high-temperature condition is typically the result of monitored voltage and current conditions either being out of bounds or caused by an external thermal source. For such cases, monitoring a few representative places in a module or section of the battery pack is adequate for proper battery pack management and cell protection. Thermocouples can be placed on a representative worse-case cell's surface to monitor its temperature (that is, the hottest cell in the pack).

Supervising Battery Pack Behavior

The circuitry that monitors the cells in a battery pack should also be used to supervise the battery pack environment and use, to preserve the safety and life of the pack by protecting it from external fault conditions such as overcharge, over discharge, overvoltage, undervoltage, over current and undercurrent. Methods of supervising and controlling the battery pack include firmware based controls or special purpose integrated circuits. Regardless of how the BMS supervises the pack's behavior, protection from fault conditions should be its highest priority function.

When monitoring cell behavior in the pack, histograms can be stored (e.g. saved in non-volatile EEPROM memory) to record important details about the conditions that the pack saw while in service. This can be helpful in troubleshooting problems and arriving at a root cause and corrective action if necessary. Suggested service histograms are as follows:

- Current and voltage
- Representative cell temperature
- State of Charge
- Energy Throughput

An example of the histogram for temperature data that can be stored is shown in Table 9:

Table 9 – Example histogram data showing product's time at different temperatures

Temperature Range	Duration (seconds)
< -20 °C	0
-21 – 0 °C	10
1 – 10 °C	110
11 – 20 °C	450
21 – 30 °C	70457
31 – 40 °C	5042
41 – 50 °C	250
51 – 60 °C	60
61 – 70 °C	10
> 70 °C	0

Similar data sets would also be stored for state of charge, energy throughput, voltages, and currents.

Cell Balancing

Reasons for Cell Balancing

A123 recommends cell balancing circuitry when more than one cell is put in series in a battery pack. This is important to achieve maximum life, reliability and safety. Over time and use, the spread between the highest and lowest cells' state of charge (SOC) widens. SOC spreads large enough result in the string delivering a noticeably smaller percentage of its energy content during full discharge cycles. This is because some of the cells are not being fully charged during recharge and the other cells are not being fully discharged during pack discharge. The *effective* capacity of the pack is reduced proportionally by the difference between the minimum and maximum SOC of the cells in that pack. If the string is balanced, every cell can be charged to its maximum SOC during recharge, and every cell can be brought to its minimum allowable SOC during discharge. In this case every cell delivers its full energy to the load.

Each cell in every battery string will have different rates of self-discharge with respect to each other. Cell SOC divergence due to variations in cell construction, environment and aging requires some means of balancing. Three factors can cause series elements to diverge from each other over time:

- **Construction Variations** in the cell manufacturing process and operational conditions. Tolerances in the electrode material loading, active material make-up, and other factors can lead to how fast each cell will lose charge over time.
- **Environment Variations** in cell temperature across the series string can lead to different rates of self-discharge between each of the series elements.
- **Aging Variations** in cell performance can grow over time as each of the cells ages differently in response to its environment and physical construction.

⚠ CAUTION Whether or not the BMS includes cell balancing in the pack management, the BMS must at least monitor the voltages of each of the series cells to stop the charge when any one of them gets to the upper safe limit, as well as to stop discharging when any one of them gets to the lower voltage limit.

When to Balance Cells

There are practical limitations to any BMS design that govern when balancing occurs. First, there are power limitations. The cells diverge at a very low rate, so it may not make sense to have a balancing circuit that shuttle a large amount of charge in a small period of time. The cost, size and efficiency considerations usually lead to a balancing circuit that slowly drains some of the cells to compensate for the slow divergence that can be expected in a collection of A123 cells. Whatever the balancing rate, the BMS must make sure that it can balance the cells as often as it is necessary in order to not get too far behind the cell's inherent divergence. For example, if the cells diverge at a hypothetical rate of 1% per month between each other, and the balancing current can shuttle 1% of the cell's SOC in one hour, the BMS needs to operate its balancers for at least 0.14 % of the time.

A second governing factor is the limitation of accuracy of cell voltage sensing, especially on the flat part of the Open Circuit Voltage vs. State of Charge curve. If the SOC is not accurate, the balancing operation may itself cause the cells to diverge. Depending on the application, some compromises can be made. For example, if the pack is intended for applications where the pack is fully recharged after each discharge, accurate cell balancing can be achieved when the pack is nearly-fully charged. When the pack is nearly full of charge, the State of Charge (SOC) of each cell can be accurately determined from their terminal voltages. However, if the pack is used in a charge-sustaining application, where it is rarely charged to its full SOC, the cell to cell voltage variation is more difficult to ascertain, because in the mid-SOC range, the voltage is very flat with respect to SOC. Balancing decisions must be made opportunistically under the following conditions:

- The pack current is under C/2
- The SOC is greater than 90% or less than 30% SOC (where the dV/dSOC is large)

Waiting for the current to be small eliminates errors due to resistive drops along the interconnecting bus bars and straps. Waiting for the SOC to be near the upper and lower limits reduces the error due to the very small dV/dSOC that the A123 cells exhibit in the middle ranges of SOC.

Fuel Gauging (Types, Methods)

There are a number of ways to estimate SOC, the "fuel" or chare that is remaining in the cell or battery. Due to an inherent amount of uncertainty in each method, a combination of methods may be necessary to maintain a reasonably accurate SOC measurement. In addition, different applications dictate the necessary level of accuracy, so there is no single ideal method that works for every application. This section describes the following types and methods that can be used for fuel gauging:

- Voltage SOC (vSOC)
- Coulomb Counting SOC (iSOC)
- Combination of vSOC and iSOC

<u>Voltage SOC (vSOC)</u>

One method of determining SOC uses only voltage. Lithium ion batteries store a specific amount of charge at a characteristic voltage potential. The amount of storable charge is specified by its amp-hour (Ah) rating. The chemistry of the electrode materials determines the amount of voltage potential that drives the charge out during discharge and must be overcome during recharge. A123's Nanophosphate® chemistry produces about 3.3V on average during a discharge. This voltage is dependent on a number of factors, including current, history, age, temperature and SOC. Figure 18 shows the open circuit voltage (OCV) voltage compared to Depth of Discharge (DoD) of the 20Ah cell.

The BMS takes a reading of the OCV and correlates it to the SOC using look-up tables based on the graph in Figure 18. The problem with this algorithm is that the voltage readings need to be extremely accurate for the A123 battery technology. There are a couple of flat portions in the middle ranges of SOC, which are less than 1mV per 1% SOC. If a BMS were to rely on voltage alone for its SOC estimates, it would be required to have extremely accurate voltage sensing capability, on the order of 1mV resolution and accuracy per series cell. In addition, the battery current affects the voltage reading proportional to the battery impedance, which depends on a number of factors such as temperature, age, and previous operational history. Figure 19 illustrates the possible range in SOC values resulting from uncertainty measuring OCV.

It is appropriate to mention *hysteresis* at this point. There are two OCV vs. SOC curves that the battery exhibits depending on whether it just delivered a discharge or received a charge. For any given battery SOC, an open circuit reading taken after the current goes INTO the battery will result in one voltage, while an open circuit reading taken after current is taken OUT of the battery will result in another. The difference between these two voltages varies over SOC and even temperature. Figure 18 & Figure 19 show the two different voltages for each SOC point at 23 °C.

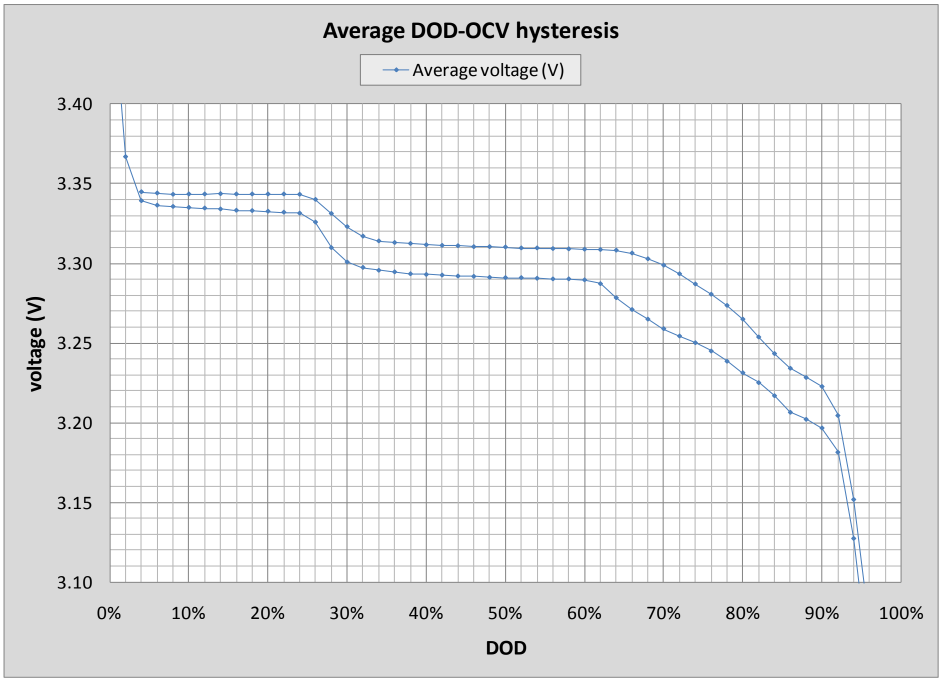


Figure 18 - 20Ah Voltage vs. SOC at 23 °C

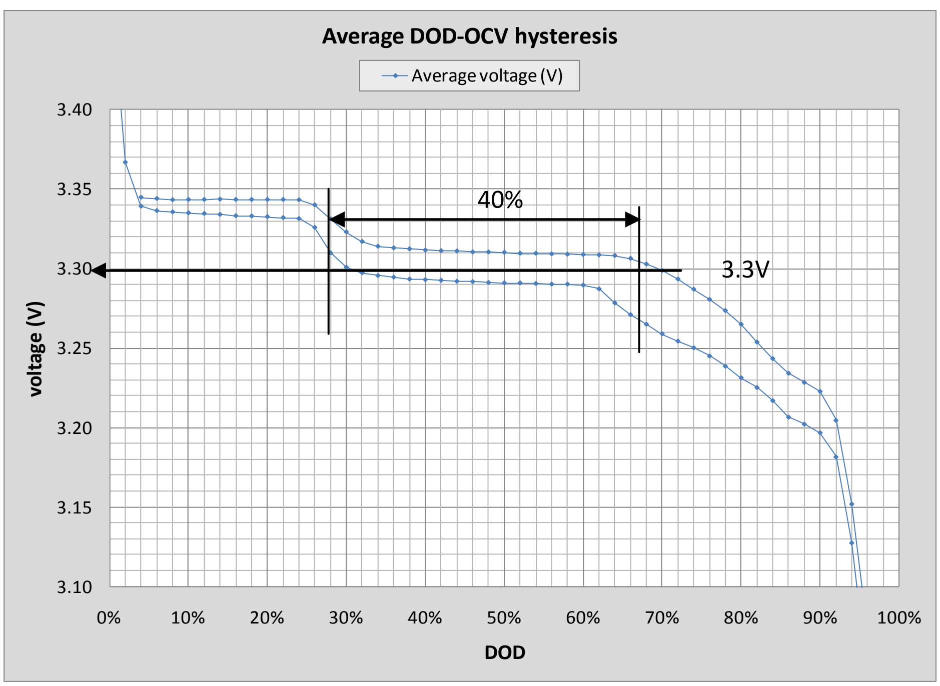


Figure 19 - vSOC sensitivity to OCV error

For a single voltage of 3.3V, the OCV can represent either 70% SOC or 30% SOC depending on whether the cells were just discharged or charged. Because some of the sections of the curve are very flat; < 1 mV per % SOC, even a small 1 mV error in the voltage reading can result in an error of several percent.

Temperature also affects the OCV values of the cell, but its effect depends on the SOC of the cell. Above 30% SOC, the effect of temperature is positive on the OCV and below 30%, its effect is negative. Figure 20 shows the highly non-linear relationship between SOC and the effects of temperature on OCV. The rate of change for each point is linear between -30 and +35°C. So for example, at 50% SOC, the OCV will vary with temperature, from -30 to +35 °C, at a positive linear rate of 0.13 mV/°C

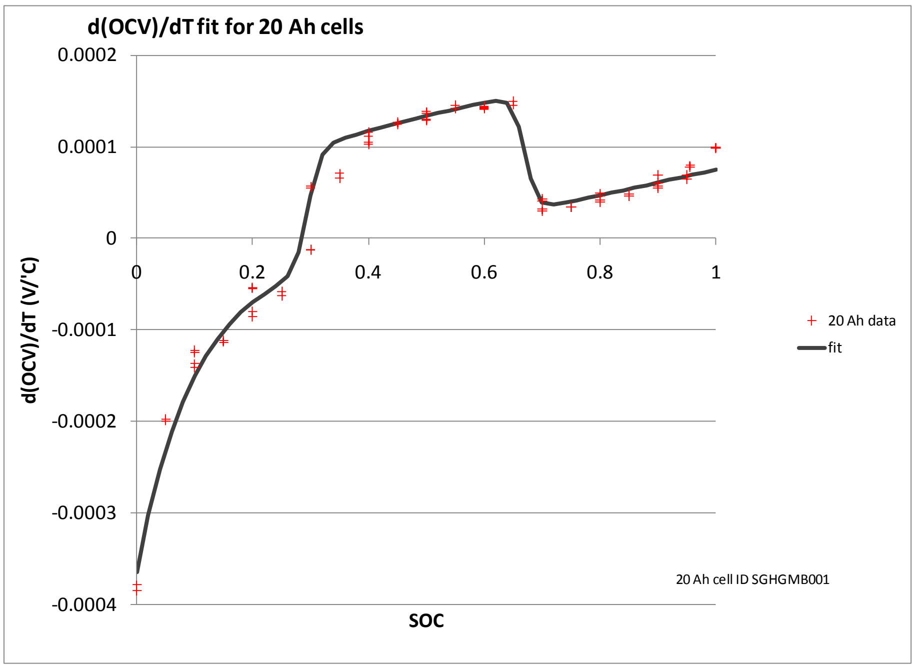


Figure 20 – Temperature effects on OCV with respect to SOC

Coulomb Counting SOC (iSOC)

Another method of fuel gauging uses only current and time. Based on a known starting SOC point, the BMS calculates the present SOC by integrating the measured current going into and out of the battery. This method is as accurate and resolved as the current and time measurements are. The problem with this algorithm is that the starting SOC is not always known. In addition, because the algorithm integrates the current signal, very small current levels, noise, inaccuracy and small offsets can gradually increase the error over time.

Combination of vSOC and iSOC

The problems with both vSOC and iSOC can be somewhat mitigated by using a combination of the two algorithms. For example, one can determine the vSOC fairly accurately at times when the actual SOC is either near the top of charge of bottom of charge. At these times, vSOC can be weighted higher than iSOC. During other times, when the actual SOC is in the middle range, the iSOC can be used to measure the reported SOC. The estimated OCV is based on the actual terminal voltage minus the current times the estimated battery impedance. The impedance is a variable with respect to the actual SOC but especially with temperature. Figure 21 shows the effect on DCR (direct current resistance) by temperature and SOC. Notice there is very little effect on DCR by SOC, but a large effect from temperature.

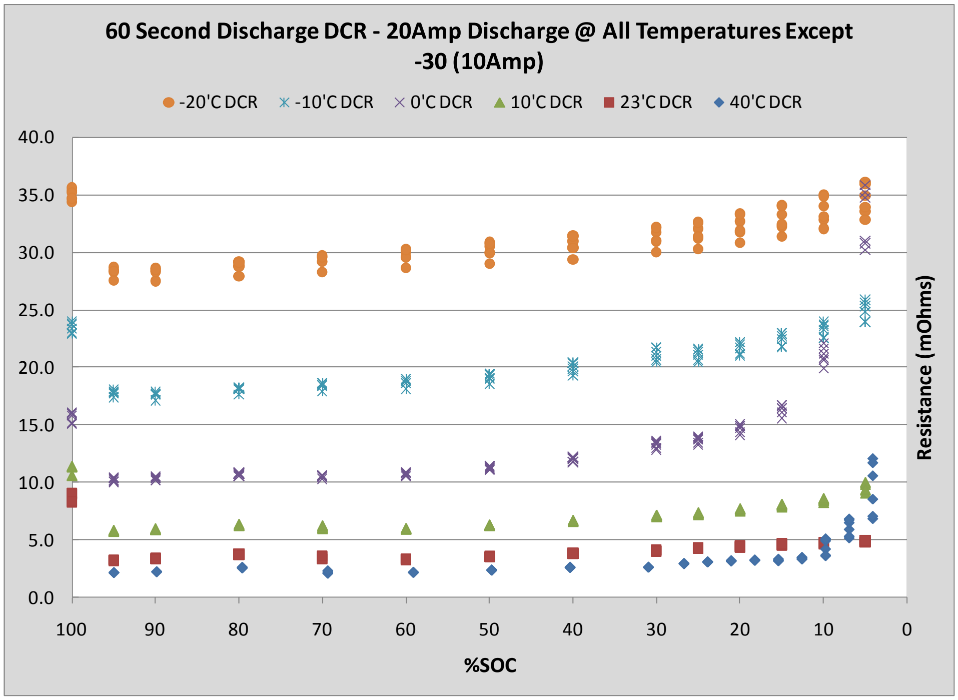


Figure 21 – 60s, 20A DCR measurements wrt SOC at various temperatures.

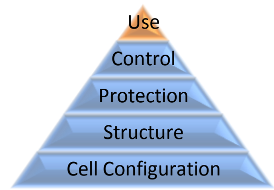
Integrated Circuits

Integrated circuit cell monitors can work within the Battery Management System to offer complete, scalable design for use in packs of varying sizes. The integrated circuit monitor could be connected to each series cell in a string and would report data measurements to a controller via an internal communication bus. Measurements taken on an individual cell level would allow measurement close to each individual cell, resulting in improved accuracy. In addition to monitoring functions, integrated circuit controllers offer cell balancing, protection, SOC calculation and SOH estimation. Some of them are fully programmable using custom firmware while others are programmed from the factory and no firmware development is required. Most of them are user-configurable to suit a variety of applications, cell types and pack sizes.

For example, manufacturers such as TI offer Analog Front Ends (AFEs) that may be suitable for a variety of applications. AFEs integrate a digital communication interface (such as I2C or SPI) to allow a BMS to monitor cell voltages and temperatures, enable cell balancing, enter different power modes, set current protection levels and blanking delay times. Certain Seiko Electronics ICs provide safety protection for various fault conditions such as short circuits and cell overvoltage. Maxim and TI offer SOC monitors that are designed to work with A123 cells.

For more information on integrated circuit battery management systems and AFEs that may work in your application, contact Texas Instruments, Seiko Electronics, Linear Technology, Analog Devices, Maxim, National Semiconductor, or O2-Micro. A123 does not endorse or provide warranty for these companies' products.

Battery Pack Use



When charging and discharging a battery pack, the current and voltage applied to any cell in the pack shall not be exceeded for the given conditions under which the cell are exposed. Appendix A details the limits within which the cells must be kept for a given cell's temperature and cell's state of charge. This section covers the following topics:

- Charger Limits
- Discharging Current Limits
- Temperature Limits

Charger Limits

When charging or recharging A123 cells in a battery pack, the charger should limit its output current and voltage to match that of the battery pack configuration. During a recharge, the charger shall apply a constant current (CC) charge followed by a constant voltage (CV) charge. In addition, the **charger shall cease charging when either:**

- Any one cell in the series string, has exceeded its maximum recommended charge voltage, or
- The temperature measured in the pack has gone outside the recommended range for charging.

To achieve maximum life, reliability, and safety, A123 recommends using cell balancing circuitry to prevent an increasing spread between highest and lowest battery states of charge. Refer to Cell Balancing on page 47 for more information.

Determine the charge current for a string of cells by multiplying the number of parallel cells in the string by the recommended charge current for a single cell. Note that this calculation does not take into account limitations imposed by any protection electronics or any other features of the battery pack assembly.

Eq 5. *Number of cells in parallel x Recommended Charge Current / cell = Charge Current / string*

Determine the end of charge voltage for a string of cells by multiplying the number of series elements in the string by the recommended charge voltage of a single cell.

Eq 6. *Number of cells in series x Recommended Charge Voltage / cell = Charge Voltage / string*

Refer to Table 10 for examples of various charge currents and voltage configurations.

Table 10 - Charge current and voltage calculation examples

Example 1	If a cell group has 3 cells in parallel (3p), and the recommended charge current per cell is 20A, then the charge current for this group is 60A: (3 cells, parallel) x 20A = 60A
Example 2	If a cell string has 10 cells in series (10s), and the recommended charge voltage per cell is 3.6V, then the end of charge voltage for the string is 36V: (10 cells, series) x 3.6V = 36V

Once the end of charge voltage has been reached, apply a constant voltage hold at this voltage until the current decays to near-zero. This process charges the cells to 100% state of charge (SOC). Refer to Figure 22 for an illustration.

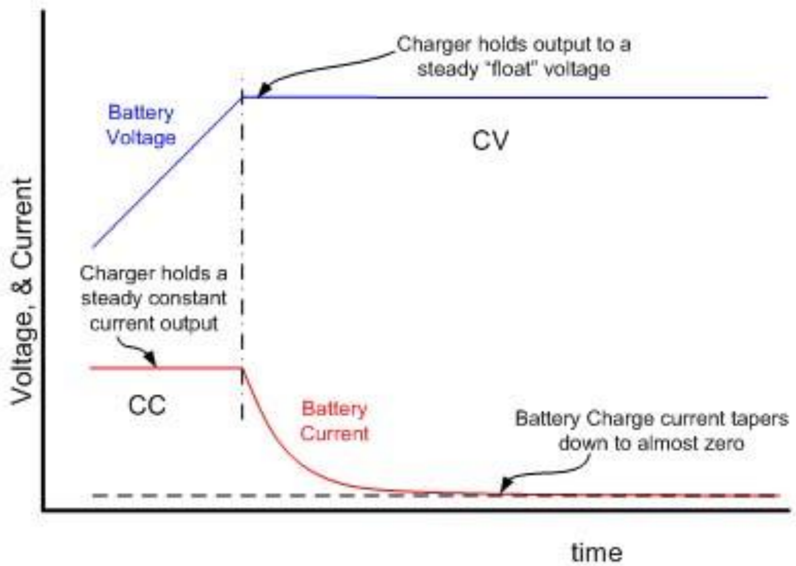


Figure 22 - Battery voltage and current during recharge

<u>Recommended Fast Charge Method for Strings</u>

The cells can be charged at a fast rate if a short recharge time is desired by the application. Faster recharge rates will reduce the cycle life of the battery by:

- Increasing the internal wear and tear on the cell electrodes which reduces its capacity faster than normal
- Increasing the internal temperatures in the cells, which increases degradation rates of the cell's capacity and impedance over time.

Figure 23 shows that a cell that is regularly recharged at a fast rate will suffer an accelerated rate of capacity degradation over its service life.

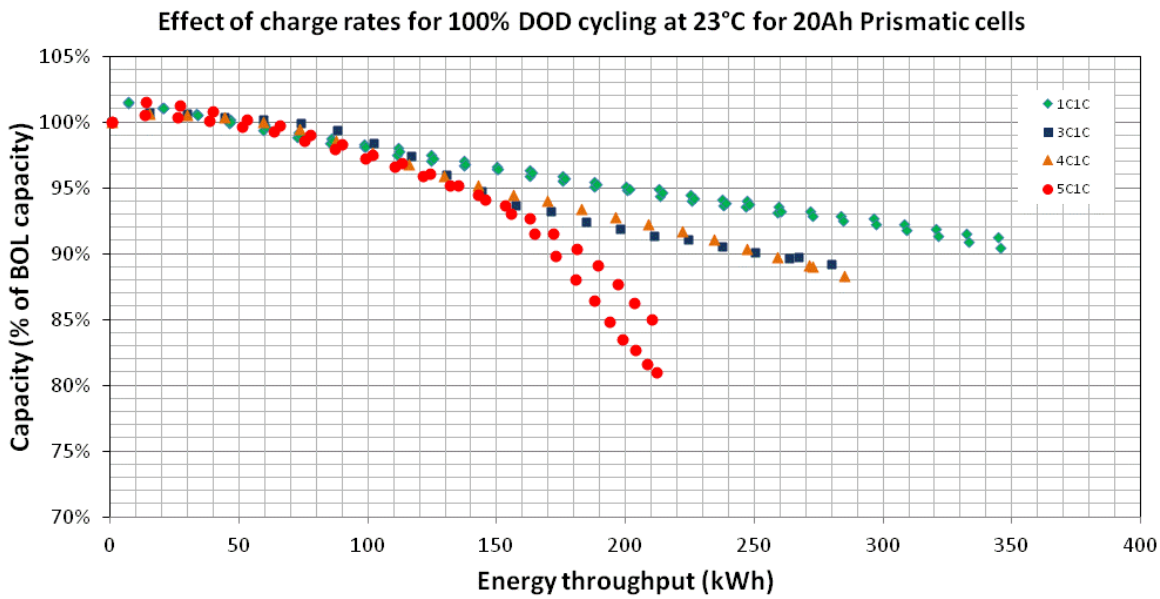


Figure 23 – 20Ah Prismatic cell capacity degradation vs. time for various recharge rates

Refer to Appendix A for the recommended fast-charge current limits of A123 cells.

Recommended Float Charge Method for Strings

To hold the voltage of the cell string at the end of charge voltage (after reaching 100% SOC) for prolonged periods of time, lower the end of charge voltage to the recommended float-charge voltage. Determine the recommended float voltage by multiplying the number of series cells or elements in the string by the recommended float-charge voltage of a single cell.

Eq 7.   Number of cells in series x Recommended Float Charge Voltage / cell = Float Charge Voltage / string

Refer to the Appendix A for recommended float charge voltage.

NOTICE

Note: Even if at the start of the extended float mode, all the cells are balanced, The BMS must monitor all the cell voltages throughout the float mode period. If one of the cells has a higher self-discharge rate than the others, its terminal voltage will fall with respect to the others, and the other cell voltages may rise past the upper cell voltage limits. Therefore it is important that the charge current shall be limited whenever any cell in the string reaches its maximum recommended float voltage.

Discharging Current Limits

In order to safely operate the cells, the current discharging from the cells must be kept below the point at which it generates too much heat inside the cell. Too much heat can cause excessive temperatures which can lead to accelerated capacity loss over time. Temperatures beyond the absolute maximum allowable cell temperature can cause immediate damage to the cell. In general any skin temperature above 35 °C will cause accelerated capacity loss, at varying degrees. However, a skin temperature above 85 °C is likely to cause immediate harm to the cells and should be avoided at all costs.

Recommended Discharge Currents for Strings

Determine the maximum continuous discharge current for a string of cells by multiplying the number of parallel cells in the string by the maximum continuous discharge current for a single cell. Note that this calculation does not take into account limitations imposed by any protection electronics or any other features of the battery pack assembly.

Eq 8. Number of cells in parallel x Max Discharge Current / cell = Max Discharge Current / string

It is important that the cell-to-cell current collection tabs are correctly sized to carry the maximum design current. Currents that are higher than the tab can handle, may cause damage to these tabs and overheat the cells.

Additionally, the design of the cell-to-cell interconnections must insure that the current is equally shared between multiple parallel cells. The internal resistance of A123 cells is low enough to make the task of balancing the current using a less-than-ideal connection material challenging. A123 engineering regularly employs FEA (finite element analysis) to simulate the currents flowing through a pack to meet the design's current sharing specifications.

Voltage Limits

During the end of a discharge, the cell voltage will start to fall precipitously when it has less than 5% of its storable charge in it. A well-designed pack will never allow any cell in the pack to fall below the absolute minimum voltage limits in Appendix A. If the cell voltage falls below these limits, the cell can be damaged immediately. The longer this condition is maintained, the more damage the cell suffers, and the more dangerous it is to operate the cell subsequently. A123 recommends that if any cell falls below the absolute lower limit, that the pack be taken out of service and recycled.

Cut-Off Voltage Limits for Strings

The discharge of a cell or battery should be terminated whenever any cell in the string reaches its lowest recommended discharge cutoff voltage.

The system shall be designed to stop discharging the battery whenever any of the following conditions is true:

- The string of cells reaches the recommended discharge cut-off voltage
- Any one cell in the series connection reaches its minimum allowable cut-off voltage
- The cells exceed the maximum allowable cell temperature

Determine the recommended discharge cut-off voltage for a string of cells by multiplying the number of series elements in the string by the recommended discharge cut-off voltage for a single cell.

Eq 9. Number of cells in series x Recommended discharge cutoff voltage / cell = Cutoff Voltage / string

Pulse Discharge Limits

While the cell or battery can discharge at greater than the maximum continuous discharge current in short pulses, do not allow the individual cells to exceed the maximum allowable cell temperature. During pulse discharges, the cell voltages can safely fall below the recommended discharge cut-off voltage. Although it is safe to temporarily discharge the cell or battery below the recommended discharge cut-off voltage, the cell will suffer a faster rate of permanent capacity loss over its service life when subjected to such repeated discharges.

⚠ CAUTION Under no condition should the voltage of the cells be allowed to go under 0.5V. This can cause permanent damage to the cells.

Discharge Cell Temperature Limits

For optimum life, do not continuously discharge the cells or batteries faster than the maximum allowable continuous discharge current. Do not allow the cells or batteries to self-heat beyond the maximum recommended cell temperature of 60 °C for discharge, recharge or float-charge. Operation above the maximum recommended cell temperature will result in accelerated performance degradation during its service life. At low temperatures, the maximum available discharge current will decrease due to markedly increased internal impedance at these lower temperatures.

Appendix A contains tables that indicate the maximum charge and discharge currents allowed for a range of temperature and states of charge.

Chapter 5

Summary of Battery Pack Testing

To ensure safe operating performance of a battery pack using A123 cells, the battery pack must be designed to pass a critical set of design validation tests. This chapter summarizes the recommended minimal testing to be performed on a battery pack, the performance criteria it must pass, and a set of design guidelines to follow while designing the product. This chapter includes the following sections:

- Performance Testing
- Abuse Testing
- Compliance Testing

Performance Testing

Battery pack performance testing validates that the battery pack performs basic functionality in the application's intended environment. These tests include discharge, recharge, cycling, open circuit, thermal, and environmental testing. Applications for each battery pack can vary significantly, so the key to success is to frame the test conditions around the expected application's conditions.

Table 11 - Performance tests

Name	Description
Constant Power Discharge	Test Capacity of battery pack using various constant power loads
Peak Power Discharge	Test Power Capability of battery pack using 2/3 OCV. I.e. determine at what power levels, the battery voltage falls to 2/3 of the starting OCV.
Application Specific Cycle Tests	Cycle the battery pack using the application's expected cycle profiles. There are two application cycle testing goals. **1.** One is to measure short-term battery pack performance and **2.** the other is to measure long-term performance over time. The latter takes into account the degradation of the battery over time with respect to the amount of usage the battery experiences.
Stand Test	Test Self-Discharge of battery pack while off.
Thermal	**1.** Test temperature rise of cells over ambient temperature during worse-case application cycle conditions. **2.** Test temperature gradient between the coolest and hottest cell during worse-case application conditions.
Vibration	Apply vibration in three axes to simulate a life-time of physical movement and test electro-mechanical integrity of the product throughout.

Abuse Testing

Abuse testing verifies reactions to harsh and out-of-specification conditions under which the product may be exposed. The results of these tests do not necessarily have to show that the product survives and functions after such tests. However, it is expected that a result of the abuse test show that the product will cause little or no damage to personnel and objects near them. Abuse testing is not intended to acknowledge or validate the design outside of proper operating conditions, even if the test units perform with a safe or acceptable reaction.

Reference:

Sandia Report SAND20053123 "FreedomCar Electric Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications"

Table 12 - Abuse tests

Name	Description
Short Circuit	Test the ability of the battery pack limit the output energy in the case of an accidental short circuit on its terminals. This testing also includes short circuiting individual elements within the battery pack, such as modules, groups of modules, cells and cell groups.
Overcharge	Test the ability of the battery pack to prevent one or more of its cells from being overcharged as a result of excessive voltage being applied to the terminals of the battery pack
Crush	Understand what happens when the battery pack is crushed in a calibrated manner.
Drop	Observe the effects of the battery pack being dropped from a specified height.
Shock	Observe the effects of the battery pack being subjected to a large shock in three axes.
Immersion	Test the ability of the battery pack to seal out liquid water when completely immersed.

Compliance Testing

Compliance or conformance testing verifies whether a product meets a set of defined standards dependent on the product application. The battery pack needs to meet standards in areas such as safety, environmental, and electromagnetic compliance. This guide cannot cover all possible applications and uses for A123's cells. Therefore, one must test the pack design based on the compliance standards appropriate for its intended application. That being said, Table 13 lists a variety of useful standards and their applicability.

Table 13 – Useful battery pack standards and their relevant applications

Standard	Type	Application
UL-1973	Safety	US Market
IEC 62133	Safety	Non-US Markets
EU Directive 2006/66/EC	EU Battery Directive	EU and WW Markets
FCC Part 15 Subpart B Class A or B	Radiated Emissions	U.S. Market
IEC 61000-6-1 and IEC 61000-6-2.	Generic EMC Immunity	EU and WW Markets
IEC 61000-6-3 and IEC 61000-6-4	Generic EMC Emissions	WW Markets
REACH Directive (1907/2006)	Environmental	EU Markets
2011/65/EU RoHs	Environmental	EU Markets
China RoHs	Environmental	China Market
UN recommendations on the transport of dangerous goods/test and criteria 38.3 (UN 38.3)	Regulatory Transportation Testing	WW Markets
DOT 49 CFR parts 100 – 185	Regulatory Transportation	US Markets
IATA Dangerous Goods Regulations	Regulatory Transportation	WW Markets

Chapter 6

Battery Pack Assembly

This chapter discusses inspecting cells prior to assembling into packs and guidelines for creating weld schedules for A123 cells. This chapter includes the following sections:

- Incoming Cell Inspection
- Material Handling and Storage
- Cell Welding

Incoming Cell Inspection

Cells are checked for excessive self-discharge at the factory before they are released for sale and shipment. A123 still recommends inspecting cells before assembling them into packs. Cells are shipped at approximately 50% SOC, with a nominal voltage of 3.3V. Test the OCV and compare it to the "Discharge" curve in Figure 18 to determine how much charge was lost during storage and transport. Typically, A123 cells lose less than 1% per month at 25 °C temperature. Loss of greater than 3 - 5% per month is cause for concern and those cells should be quarantined for investigation.

Material Handling and Storage

General Practices

Minimize handling of cells to avoid damaging them. Reject any cell dropped from a height of more than 120 mm. If a cell is dropped from a height of less than 120 mm, carefully inspect the components for damage and then retest the OCV and alternating current resistance (ACR). Reject any cells where damage exceeds acceptable limits or of either OCV or ACR that are not within specified limits. Discard any cells that have been subjected to even a brief external short circuit. Do not damage the cells in any way that would make them unfit for your intended use.

Ambient Conditions

Store and process cells in an environment of 15 °C to 35 °C and less than 75% relative humidity. Keep the cells under cover and protected them from the elements at all times.

Cell Welding

Cell Interconnects

NOTICE Cell interconnects (tabs) should NOT be soldered to the battery terminals or attached using extreme heat.

A123 recommends resistance or laser welding tabs to the terminals of the cell. Because it is impossible to cover every possible weld schedule, A123 recommends meeting with welding consultants to discuss weld schedules optimized to your specific application. Welding consultants that may be able to assist include:

- http://www.welding-consultant.com
- http://www.ccl.fraunhofer.org/

For reliable welded connections at the terminals, A123 recommends copper or copper alloy straps welded to the copper tabs and aluminum straps welded to the aluminum tabs. Cell interconnects (straps) should be neither soldered on the cells tabs nor attached using extreme heat. A123 recommends tabs be resistance or laser-welded to the tabs of the cells.

Resistance welding provides a controlled constant current between electrodes for a consistent period of time through the welded materials. These parameters can be specified and regulated for a high-quality weld every time.

Laser welding provides a consistent amount of heat to a controlled location, which contributes to a high quality manufacturing process. The angle of incidence, power, dwell time, and materials are always the subject of a trial and error process initially until the desired results are produced. A welding expert is a valuable resource to employ during the set-up of this part of the assembly line.

A123 uses a laser process to weld extruded bus bars to the cell's tabs. On the negative side, the 0.53 mm extruded copper bus bars are shaped to slip over the negative copper tabs. On the positive side, the bus bars are 0.84 mm thick extruded aluminum

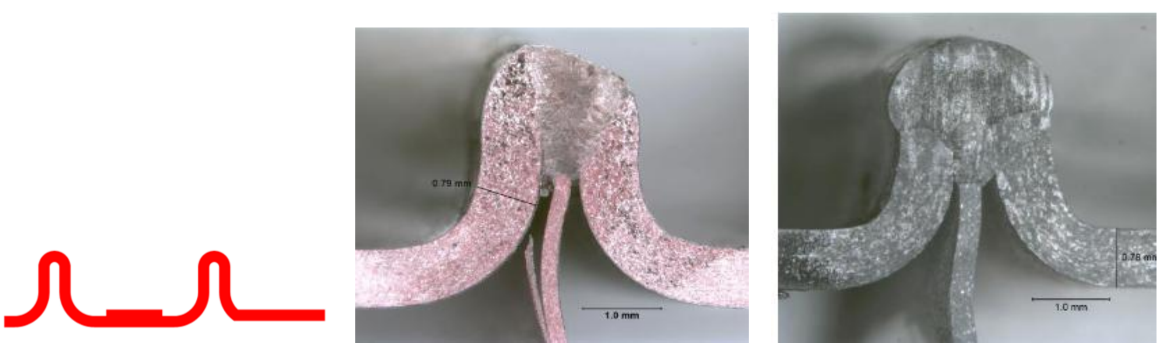


Figure 24 – Bus bar concept diagram and resulting welded cross sections

The copper tab laser is set up with the following parameters: Using a 2.1 kW laser beam travelling at 3 m/min, 0 mm focus, 8 ° incident angle, and 70 °C temperature.

The aluminum tab laser is set up at 1.2 kW, 3 m/min, 0 mm focus, 8 °C and 50 °C temperature.

These parameters may or may not work for all applications, but are a good place to start experimentation.

In order to join a positive terminal to a negative terminal, two dissimilar metals, copper and aluminum need to be connected. A123 recommends that the copper and aluminum straps should be joined together using a welding a process. A123 joins the two types of metals together using an ultrasonic welding method. The copper bus bar is pre-tinned to resist corrosion and to assist in the bonding to the Al bus bars.

Figure 25 – Two types of bus bars ultrasonically bonded in the center to each other

Welders

You may find these welders useful for your needs:

Unitek IPB5000A inverter welding control and an ITB-780A6 transformer, coupled with the 88A/EZ weld head.

Miyachi MDB-4000B welder coupled with the 88A/EZ weld head

Miyachi IS-120B inverter welding control and an IT-1040-3 transformer, coupled with the 88A/EZ weld head (transformer requires water cooling).

NOTICE The welding consultants and welders are referenced above for your convenience only. A123 does not endorse or recommend any particular welder or consultant

Appendix A

Cell Specifications

This design Appendix describes A123's **AMP20M1HD-A** 20Ah Prismatic cell with the specifications outlined in this section.

AMP20M1HD-A General Specifications

Refer to Table 14 for specifications of the **AMP20M1HD-A** cell. Note that actual performance of the cells may vary depending on use conditions and application.

Table 14 - AMP20M1HD-A 20Ah cell specifications

Specification	Value	Notes/Comments
Nominal Capacity	20 Ah	
Minimum Capacity	19.5 Ah	25 °C, 6A Discharge, 3.6V to 2.0V, at BOL
Nominal Voltage	3.3V	@ 50% SOC
Voltage Range	2.0 to 3.6V	Fully Discharged to Fully Charged
Absolute Maximum terminal voltage	4.0	Above which will cause immediate damage to the cell
Recommended maximum charge voltage	3.6V	
Recommended float charge voltage	3.5V	
Recommended end of discharge cutoff	2.0V	
Recommended standard charge current	20A	to 3.6V
Recommended maximum charge current	100A	to 3.6V , Cell temperature < +85 °C
Pulse 10s charge current	200A	23 °C ≤ Tcell < +85 °C, Vcell < 3.8V
Maximum discharge continuous current	200A	23 °C ≤ Tcell < +85 °C, SOC = 50%
Pulse 10s discharge current	600A	23 °C ≤ Tcell < +85 °C, SOC = 50%

Specification	Value	Notes/Comments
Peak 10s Discharge power	820W	SOC = 100%, Tcell = 23 °C, Assumed DCR = 2 mOhm (nominal)
DCR Impedance ACR Impedance	1.5 – 3 mOhm 0.78 mOhm	10s, 240A, @ 50% SOC 1kHz, @ 50% SOC
Operating Temp Range	-30 °C to +60 °C	Ambient around cell
Storage temperature range	-40 °C to +65 °C	
Weight	495 grams	+/- 10g
Cycle Life To 80% Beginning of Life (BOL) capacity	3000 cycles	100% Full DOD cycles, 1C/-2C @ 23 °C, 8 – 14 psi face clamp pressure

Handling/Transportation

Do not open, dissemble, crush or burn cell. Do not expose cell to temperatures outside the range of -40 °C to 65 °C. Refer to Chapter 2 for more information.

Storage Specifications

Store cells in a dry location. To minimize any adverse affects on battery performance it is recommended that the cells be kept at room temperature (25 °C +/- 5 °C). Elevated temperatures can result in shortened cell life.

AMP20m1HD-A Maximum Current Limit Tables

Table 15, Table 16, Table 17, and Table 18 summarize the maximum recommended charge and discharge currents per cell for continuous and pulse operations with respect to (wrt) SOC and cell temperature. Although the cells are capable of the listed currents and the actual limits for each application may be different depending on the battery pack design.

Operating the cells up to the currents listed in Table 15, Table 16, Table 17, and Table 18 may cause heat to build within the cell. If the cell is not cooled between cycles, the cell's temperature may increase beyond the recommended maximum temperature limit. The cells must be properly cooled with heat sinks, or time must be allowed between cycles in order to maintain the proper temperature limits of the cell.

In addition, operating the cells up to the current limits listed in Table 15, Table 16, Table 17, and Table 18 may cause their capacity to degrade faster than expected. In general, charge and discharge rates of 20A or less will yield the longest cycle life. Higher rates of current will reduce the number of charge and discharge cycles that the cells will be able to perform.

Finally, no matter what the cell currents are, even if they are within the limits listed below, the individual cell terminal voltage shall never go beyond the absolute maximum voltage limits listed in Table 15.

Table 15 – Max continuous charge currents wrt temperature and SOC at BOL

Temp(°C)🡻 %SOC🡺	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
85	0	0	0	0	0	0	0	0	0	0	0
75	60	60	60	60	60	60	60	60	60	60	0
30	60	60	60	60	60	60	60	60	60	60	0
25	60	60	60	60	60	60	60	60	60	60	0
15	40	40	40	40	40	40	40	40	40	40	0
10	20	20	20	20	20	20	20	20	20	20	0
0	10	10	10	10	10	10	10	10	10	10	0
-10	6	6	6	6	6	6	6	6	6	6	0
-20	2	2	2	2	2	2	2	2	2	2	0
-30	0	0	0	0	0	0	0	0	0	0	0
-40	0	0	0	0	0	0	0	0	0	0	0

Table 16 – Max 10s pulse charge currents wrt temperature and SOC at BOL

Temp(°C)🡻 %SOC🡺	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
85	0	0	0	0	0	0	0	0	0	0	0
75	200	200	200	200	200	200	200	200	200	200	0
30	200	200	200	200	200	200	200	200	200	200	0
25	200	200	200	200	200	200	200	200	200	200	0
15	200	200	200	200	200	200	200	200	200	200	0
10	200	185	173	161	158	158	157	153	148	147	0
0	200	106	99	93	91	91	90	88	85	85	0
-10	118	52	49	45	45	45	44	43	42	42	0
-20	46	21	19	18	18	18	17	17	16	16	0
-30	17	8	7	7	7	7	7	6	6	6	0
-40	0	0	0	0	0	0	0	0	0	0	0

Table 17 – Max continuous discharge currents wrt temperature and SOC at BOL

Temp(°C)🡻 %SOC🡺	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
85	0	0	0	0	0	0	0	0	0	0	0
75	0	200	200	200	200	200	200	200	200	200	200
30	0	200	200	200	200	200	200	200	200	200	200
25	0	200	200	200	200	200	200	200	200	200	200
15	0	200	200	200	200	200	200	200	200	200	180
10	0	199	200	200	200	200	200	200	200	200	164
0	0	94	116	118	141	154	165	170	173	174	113
-10	0	66	72	75	85	89	91	94	96	96	78
-20	0	46	48	51	53	55	58	57	60	62	51
-30	0	16	15	17	19	21	23	24	25	27	28
-40	0	0	0	0	0	0	0	0	0	0	0

Table 18 – Max 10s pulse discharge currents wrt temperature and SOC at BOL

Temp(°C)🡇 %SOC🡆	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
85	0	0	0	0	0	0	0	0	0	0	0
75	0	600	600	600	600	600	600	600	600	600	600
30	0	570	600	600	600	600	600	600	600	600	600
25	0	498	543	600	600	600	600	600	600	600	600
15	0	392	408	429	483	529	600	600	600	600	600
10	0	354	362	368	423	457	540	567	577	578	600
0	0	199	233	276	307	338	376	395	422	434	450
-10	0	123	155	207	241	282	303	309	321	327	346
-20	0	68	84	100	121	147	170	181	194	197	207
-30	0	45	49	56	65	69	75	77	79	79	82
-40	0	0	0	0	0	0	0	0	0	0	0

AMP20M1HD-A Dimensions and drawing

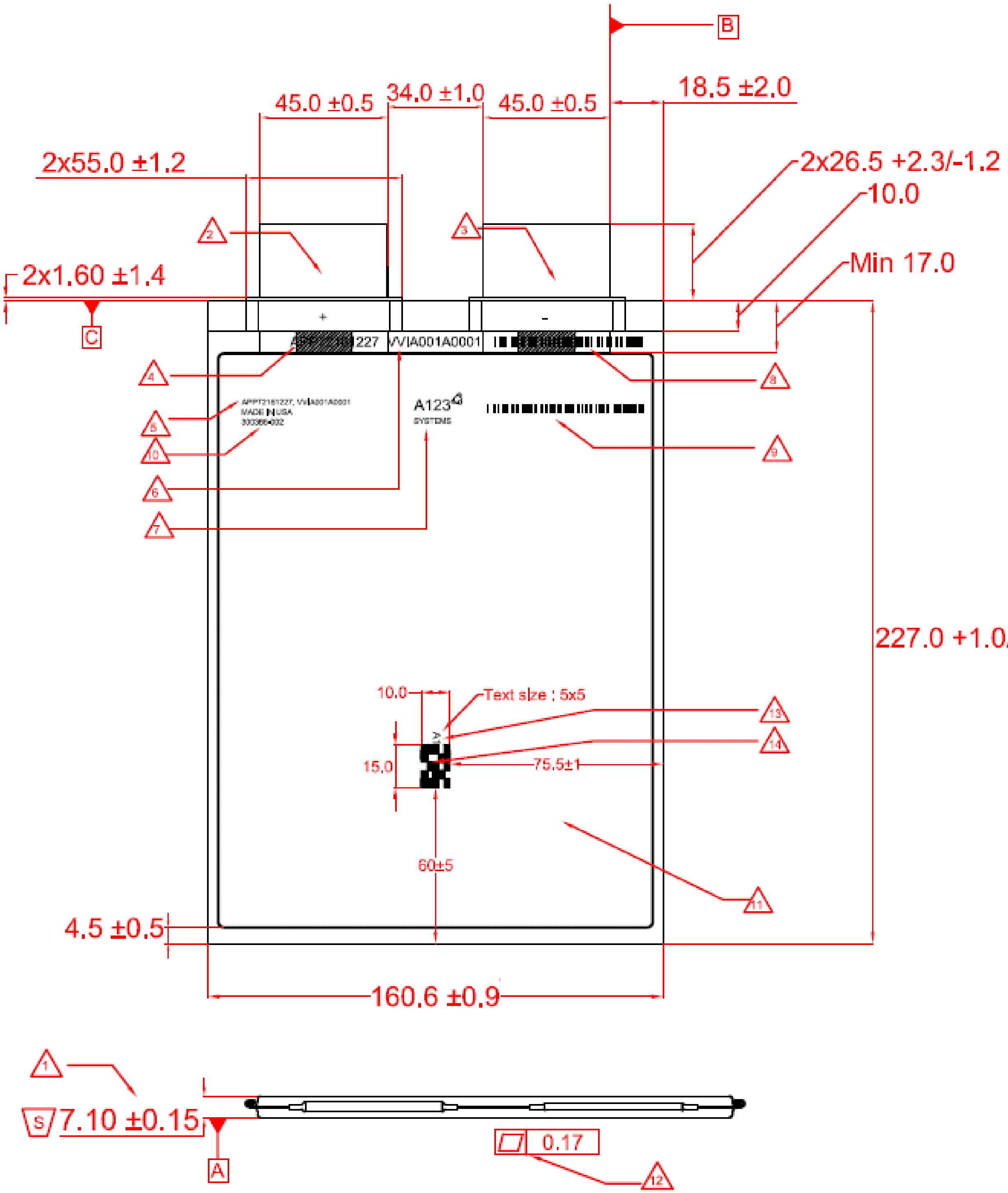


Figure 26 - AMP20M1HD-A 20Ah cell dimensions

NOTES : UNLESS OTHERWISE SPECIFIED

1. THESE CONDITIONS ACHIEVED WITH A 96.5kPa (14psi) LOAD UNIFORMLY APPLIED TO THE ACTIVE SURFACE OF THE CELL (200.5 x 151.6 mm, minimum)

2. POSITIVE TERMINAL :
MATERIAL : UNS A91050, TEMPER 14, PER ASTM B209M-07
THICKNESS : 0.3 ±0.02mm.
"+" SYMBOL TO BE APPLIED TO INSULATIVE CASE BELOW TERMINAL TO AID IN POLARITY IDENTIFICATION
SYMBOL HEIGHT : 3.0mm.

3. NEGATIVE TERMINAL :
MATERIAL : UNS C10200, HOO TEMPER, PER ASTM B152M-06A
THICKNESS : 0.2 ±0.02mm.
"–" SYMBOL TO BE APPLIED TO INSULATIVE CASE BELOW TERMINAL TO AID IN POLARITY IDENTIFICATION
SYMBOL HEIGHT : 3.0mm.

4. MODEL NUMBER DETAILS :
TEXT HEIGHT : 3.0mm
TEXT LENGTH : 23.0mm
PLACE OF ORIGIN :

5. MODEL NUMBER DETAILS :
TEXT HEIGHT : 2X 2.0mm
TEXT LENGTH : 58.0mm

6. LOT NUMBER DETAILS :
TEXT HEIGHT : 3.0mm
TEXT LENGTH : 28.0mm

7. GRAPHIC DETAILS :
TEXT HEIGHT : 8.0mm
TEXT LENGTH : 19.0mm
GRAPHIC DETAILS INCLUDE COMPANY LOGO

8. BAR CODE :
TEXT HEIGHT : 3.5mm
TEXT LENGTH : 49.0mm

9. BAR CODE :
TEXT HEIGHT : 4.0mm
TEXT LENGTH : 60.0mm

10. PART NUMBER DETAILS :
TEXT HEIGHT : 2.0mm
TEXT LENGTH : 21.0mm

11. INSULATIVE CASE : ALUMINUM/POLYMER LAMINATE
TOTAL THICKNESS :153μm
OUTERMOST : 12μm

S 12. FLATTNESS DELTA THICKNESS : MAX 0.17mm

13. CELL CAPACITY GRADE
TEXT HEIGHT : 5mm
TEXT LENGTH : 5mm

14. 2D BARCODE
TEXT HEIGHT : 15mm
TEXT LENGTH : 10mm

S 15. RATED CAPACITY : 19. 5Ah MINIMUM @ 6.0A (23 ±3°C)

S 16. RATED CAPACITY : 19. 3Ah MINIMUM @ 19.5A (23 ±3degree), (OQC INSPECTION)

S 17. OPEN CIRCUIT VOLTAGE : 3.295 ±0.010V (OQC INSPECTION)

S 18. D. C. RESISTANCE : 1.5mΩ ≤ DCR ≤ 3.0mΩ @ 60A, 10sec,(23 ±3°C), (OQC INSPECTION)

S 19. A. C. RESISTANCE : 0.76 ±0.15mΩ (OQC INSPECTION)

S 20. MASS : 495.4 ±10g (OQC INSPECTION)]

Figure 27 – Notes for Figure 26

Appendix B

Acronyms and Terminology

This appendix describes the terminology used in this document.

Table 19 – Acronyms and Terminology Descriptions

Term/Acronym	Meaning
ACR	Alternating Current Resistance. Usually refers to the resistance of a cell for very short pulses of current (< 1 second)
Ah	Amp-Hour is a unit of measure of charge that can be stored or delivered to/from a battery.
Battery	One or more cells that are electrically connected together by permanent means, including case, terminals and markings.
BMS	Battery Management System – The Battery Management System refers to the collection of electronics responsible for monitoring and controlling the battery pack.
BOL	Beginning of Life
CC	Constant Current – A method to charge or discharge a battery in which the current is held constant independent of the battery's terminal voltage.
Cell	A single encased electrochemical unit (one positive and one negative electrode), which exhibits a voltage differential across two terminals.
CID	Current Interrupt Device – A small device integrated into a cell designed to interrupt the flow of current through its terminal when too much pressure or current exists in the cell.
Competent Authority Approval	An approval by the competent authority that is required under an international standard.
CV	Constant Voltage – A method to charge a battery in which the terminal voltage is held constant and the current is determined by the power path impedance or some active current limiting.
DCR	Direct Current Resistance – Usually refers to the internal resistance of the cell for a defined pulse of current and time period. For example, at 10 amps at 10 seconds,

Term/Acronym	Meaning
	the DCR of a cell is ____ ohms.
DVT	Design Verification Testing
ELC	Equivalent Lithium Content
ESS	Energy Storage System
iSOC	Current-based SOC algorithm
OCV	Open Circuit Voltage – voltage reading of a battery when there is no current going in or out of it.
SDS	Safety Data Sheet – describes the safety related handing and use conditions of the a particular product or material.
SOC	State of Charge
vSOC	Voltage based SOC algorithm
Wh	Watt-hour