	USER DOCUMENTATION		
	Date: February, 2013	Document #:493005-001E	

Cylindrical Battery Pack Design, Validation, and Assembly Guide

DOCUMENT NOTICE AND DISCLAIMER: This document is the property of A123 Systems, LLC ("A123 Systems"). The information in this document is subject to change without notice. A123 Systems is under no obligation to update the information in this document. A123 Systems reserves the right to make changes in the design of its products or components as progress in engineering and manufacturing may warrant. It is the user's responsibility to satisfy itself as to whether the information contained herein is adequate and sufficient for any particular purpose. Nothing in this document modifies the terms of sale or the rights, obligations and warranties of A123 Systems purusant to any agreement that may exist between the user and A123. This document does not create any additional obligation for A123 Systems and does not add to any warranty set forth in such agreement. The user is responsible for ensuring that all applications of A123 Systems' products are appropriate and safe based on conditions anticipated or encountered during use. In making this document available, A123 Systems is not rendering professional or other services on behalf of any entity, or undertaking to perform any duty owed by any person or entity to someone else. The user of this document should rely on his or her own independent judgment in the use of the information herein or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in the specific circumstances. While A123 Systems has used reasonable endeavors to indicate the application of certain legal requirements, this document is not legal advice and should not be relied upon as such. It is the user's responsibility at all times to ensure its use of this document, and any activitites relating thereto, is in compliance with all legal requirements applicable to the user and the user's application(s).

Contents

Figures

Tables

Chapter 1

About this document

Purpose of this document

This manual provides information on designing and validating battery packs with A123 Systems Nanophosphate® cells. It is not intended to cover all aspects of proper battery pack design, or make design recommendations. This guide is primarily focused on outlining the unique aspects of A123 Systems' cells to account for when designing a battery pack. A123 Systems recommends obtaining and studying relevant documentation from the appropriate sources before starting a project. This document should not be used in association with any cells not provided by A123 Systems.

NOTICE Anyone involved in the design, use, or manufacture of A123 Systems cells should read and understand this document.

⚠ DANGER **This document is not a comprehensive set of instructions to assist audiences in building battery packs. Designing, validating and assembling battery packs is potentially dangerous to personnel and property; therefore, it should only be attempted with a complete understanding of all aspects of proper battery pack design and construction, which is outside the scope of this document. A123 Systems is not responsible for any battery pack designs developed by any party other than A123 Systems. 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.**

Chapter 2

Possible Dangers Involved With Handling Cells and Battery Packs

A123 Systems’ cells are highly stable and abuse tolerant; however, handling a battery pack remains potentially dangerous to personnel and property, and should only be attempted with a complete understanding of all aspects of proper battery pack 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

Proper battery pack design is essential to allow the safety features of A123 Systems’ cells to function as designed.As a safety feature, overheating A123 cells vent gases to relieve dangerous pressure buildup to disperse into the environment. However, an improperly designed battery pack can prevent the gases from safely dispersing, or prevent the cells from venting altogether.

⚠ DANGER Adding an ignition source to improperly-vented gases can create a dangerous thermal event. You **must** ventilate these expelled gasses from the environment itself after the gases are vented from the cell itself.

While A123 cells normally vent gases to relieve dangerous pressure buildup caused by heat or excessive voltage, extreme situations may cause the cells to violently eject their contents (the layers of anode and cathode material within the battery).

For example, the heat generated by overcharging, overdischarging, or excessively cycling an 18650,26650, or 32113 cell will destroy the cell, and it can damage a poorly designed enclosure or other surrounding components of a battery pack. This document highlights some recommendations on the pack’s physical and electrical design which can mitigate these dangers.

Short Circuits

DANGER

Because A123 cells offer relatively high-power potential, an improperly designed battery pack may allow short circuits with dangerous levels of current.

Arc Flashes

DANGER

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 while causing blindness and burns to personnel.

High Voltage

DANGER

Assembling a battery pack involves combining cells in serial or parallel to achieve higher voltages and currents, respectively. As the voltage and current involved 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 may result in personnel injury or death.

Chapter 3

Transportation and Storage

This chapter includes the following sections:

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 you. You should seek your own advice on laws and relevant industry standards applicable to the transportation and storage of dangerous goods prior to transporting or storing A123 batteries or cells.

Transporting Batteries

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 (including lithium ion polymer) cells and batteries (which are classified dangerous goods) are based on the UN Recommendations on the Transport of Dangerous Goods Model Regulations.

All energy storage systems (ESS), or components thereof, containing lithium ion chemistry must meet the test criteria set forth in the UN "Recomendations on the Transport of Dangerous Goods, Manual of Tests and Criteria", chapter 38.3 (known as UN 38.3) in order to be shipped in PG II packaging.

Other laws and regulatory requirements may apply depending upon your location. It is your obligation to become familiar with and adhere to the laws and regulatory requirements as they apply to you.

Overview of the Shipping Process

The following tables shows a brief overview of the steps typically required to ship a product that includes lithium ion both internationally and in the U.S.

Step Number	Process Step	Comments
1	Design the Battery.	Design the battery to ensure it will pass UN Manual of Tests and Criteria.
2	Test the Cell or Battery. Refer to "UN Test Types", below.	Perform UN testing T1-T8.
3	Obtain UN certified packaging.	All Class 9 Dangerous Goods (DG) must be shipped in UN certified packaging.
4	Packaging the cell or Battery.	Pack per regulations and close per packaging manufacturer's instructions.
5	Marking and labeling. Refer to "Lithium Ion UN Numbers", below.	Insure that packaging container has all the required labeling.
6	Fill out proper 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 an MSDS and any Competent Authority Approval accompanies the package.

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 (Cell only)
- Test T.7: Overcharge
- Test T.8: Forced Discharge (Cell only)

Lithium Ion Numbers

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

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

Requirements for Excepted and Regulated Cells and Batteries

Cells and battery packs have transportation and packaging requirements based on their watt hours.

Individual **cells** with with not more 20 Wh are excepted from regulated Class 9 requirements. Cells exceeding 20 Wh are regulated as Class 9.

Battery packs with not more 100 Wh are excepted. Batteries exceeding 100 Wh regulated as Class 9.

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).

- *Nominal Watt hours (Wh) of the cell = Nominal Voltage of the cell (V) x Nominal Capacity of the cell (Ah)*

To determine the nominal watt hours of a battery, multiply the number of cells by the equation above. That is, the number of cells multiplied by their nominal voltage and then by their nominal capacity. Typically, individual A123 Systems cells do not exceed the 20 watt hour threshold.

For example, this formula is as follows for A123 Systems cell battery values:

- *Nominal Watt hours of a battery (Wh) = Number of cells x Nominal Voltage of a cell (V) x Nominal Capacity of a cell (Ah)*

Determining Watt Hour Ratings for the ANR26650m1B

To determine the nominal watt hours of a ANR26650m1B cell:

- *Nominal Watt hours (Wh) of the ANR26650m1B cell = Nominal Voltage of the cell (3.3V) x Nominal Capacity of the cell (2.5Ah)*

To determine the nominal watt hours of a battery using ANR26650m1B cells:

- *Nominal Watt hours of a battery (Wh) = Number of cells x Nominal Voltage of a cell (3.3V) x Nominal Capacity of a cell (2.5Ah)*

ANR26650 m1B batteries typically exceed this value when comprised of 12 or more cells.

Determining Watt Hour Ratings for the ANR18650m1A

To determine the nominal watt hours of a ANR18650m1A cell:

- *Nominal Watt hours (Wh) of the ANR18650m1A cell = Nominal Voltage of the cell (3.3V) x Nominal Capacity of the cell (1.1Ah)*

To determine the nominal watt hours of a battery using ANR18650m1A cells:

- *Nominal Watt hours of a battery (Wh) = Number of cells x Nominal Voltage of a cell (3.3V) x Nominal Capacity of a cell (1.1Ah)*

ANR18650m1A batteries typically exceed this value when comprised of 26 or more cells.

Determining Watt Hour Ratings for the AHR32113m1

To determine the nominal watt hours of a AHR32113m1 cell:

- *Nominal Watt hours (Wh) of the A AHR32113m1 cell = Nominal Voltage of the cell (3.3V) x Nominal Capacity of the cell (4.5Ah)*

To determine the nominal watt hours of a battery using AHR32113*m1* cells:

- *Nominal Watt hours of a battery (Wh) = Number of cells x Nominal Voltage of the cell (3.3V) x Nominal Capacity of the cell (4.5Ah)*

AHR32113*m1* batteries typically exceed this value when comprised of six or more cells.

Overview of the Regulatory Requirements

The following tables show a brief overview of the regulations required to ship a product that includes lithium ion both nationally and internationally.

Neither table is all inclusive of the required regulations to ship a product. These tables are meant to help you understand the complexity involved in shipping a lithium-ion product. The regulations cited here are intended to assist you to adhere to proper regulatory requirements; it is your responsibility to confirm all of the requirements that may be applicable to you, depending on your location, the specific contents of the goods you are shipping, the method of shipment and other factors that may be relevant in your jurisdiction. U.S. and international regulations require that anyone involved in the handling Dangerous Goods (Hazardous Material) must be trained to do so.

International Regulation Requirements Overview

The following table shows an overview of the international regulation requirements.

Lithium Ion Cell /Battery	**Shipping Classification/Testing**	**Are there Special Packaging/Markings?**
20 Wh cell / 100 Wh battery Maximum Watt hours	**Excepted / T1-T8**. Cells and batteries must pass UN T1-T8 Tests. Cells and batteries passing UN Tests are excepted from regulation. **NOTE**: The IMDG Code contains a grandfather clause for testing "small" cells and batteries until December 31, 2013.	Yes
Greater than 20 Wh cell / 100 Wh battery	**Class 9 I T1-T8**. All cells and batteries must pass UN Manual of Tests and Criteria Section 38.3 Tests T1-T8. They must also ship as a Class 9 dangerous goods.	**Yes**. Requires Class 9 markings, label, specification packaging, and shipping papers.

US Regulation Requirements Overview

The following table shows an overview of the U.S. regulation requirements.

Lithium Ion Cell /Battery*	**Shipping Classification /Testing**	**Are there Special Packaging/Markings?**	**Battery Size**
1.5 g / 8.0 g Max. ELC	**Excepted / T1-T8**. All cells and batteries must pass UN Manual of Tests and Criteria Section 38.3 Tests T1-T8.	**Yes**. Packages containing more than 12 batteries or 24 cells must meet certain packaging, marking, and shipping paper requirements.	Small
5.0 g / 25 g Max. ELC	**Class 9 / T1-T8**. All cells and batteries must pass UN Manual of Tests and Criteria Section 38.3 Tests T1-T8 and must be shipped as Class 9 hazardous materials **unless transported by motor vehicle or rail car**.	**Yes**. Requires Class 9 markings, label, specification packaging, and shipping papers **unless transported by motor vehicle or rail car**.	Medium
Anything greater than 5.0 g / >25 g ELC	**Class 9 / T1-T8**. All cells and batteries must pass UN Manual of Tests and Criteria Section 38.3 Tests T1-T8 and must be shipped as Class 9 hazardous materials.	**Yes**. Requires Class 9 markings, label, specification packaging, and shipping papers.	Large

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

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 PI965-PI970.

IATA Packing Instruction PI-965, PI-966, and PI-967 apply specifically to *air shipment* of lithium ion batteries.

⚠ WARNING Products packaged with or containing lithium batteries must be packed to guard against accidental activation during transportation.

All Lithium ion cells and battery types (regardless of whether cells in batteries have undergone separate testing) require testing according to the UN Manual of Tests and Criteria, Part III, subsection 38.3. Cell and batteries that have met the criteria of UN38.3 are allowed to be shipped per the packing instruction described in section 3.9.1.

Where testing indicates that the lithium ion batteries are to be classified as Class 9 – Miscellaneous Dangerous Goods, the batteries must be packed for transport according to Packing Group II specifications, as well as labeled in accordance with Dangerous Goods Regulations requirements.

IATA PI965-PI967 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 batteries, battery packs, products packaged with batteries and products containing batteries are packed for transportation by air.

The following table lists IATA PI965-PI967 requirements for packaging batteries for air transport.

Requirement	PI-965 – Lithium Ion Cells and Batteries			PI-966 – Lithium Ion Cells and Batteries Packed with Equipment			PI-967 – Lithium Ion Cells and Batteries Packed in Equipment		
	Cell ≤ 20 Wh	**Batt. ≤ 100 Wh**	**Class 9***	**Cell ≤ 20 Wh**	**Batt. ≤ 100 Wh**	**Class 9**	**Cell ≤ 20 Wh**	**Batt. ≤ 100 Wh**	**Class 9**
Capacity Labelling	-	Yes	Yes **	-	Yes	Yes **	-	Yes	Yes **
Max quantity (Gross) - Passenger Aircraft	10 kg (per package)		5 kg (per package)	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 (Gross) - Cargo Aircraft	10 kg (per package)		35 kg (per package)	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	5.0.2.4, 5.0.2.6.1, 5.0.2.12.1		General Packing Requirement s 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 pack required to enclose battery	Yes		Yes	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

Requirement	PI-965 – Lithium Ion Cells and Batteries			PI-966 – Lithium Ion Cells and Batteries Packed <u>with</u> Equipment			PI-967 – Lithium Ion Cells and Batteries Packed <u>in</u> Equipment		
	Cell ≤ 20 Wh	**Batt. ≤ 100 Wh**	**Class 9***	**Cell ≤ 20 Wh**	**Batt. ≤ 100 Wh**	**Class 9**	**Cell ≤ 20 Wh**	**Batt. ≤ 100 Wh**	**Class 9**
Prevent short circuits internally	Yes		Yes	Yes		Yes	Yes		Yes
Prevent short circuits externally	No (A123 Yes)		Yes	No (A123 Yes)		Yes	No		Yes
Provide Safety Venting	No (A123 Yes)		Yes	No (A123 Yes)		Yes	No (A123 Yes)		Yes
1.2 m drop test (pack + content)	Yes		NA (see performance standard for Packing Group II)	Yes (for each package of cells or batteries, or completed package)		NA (see performance standard for Packing Group II)	No		-
Prevent Reverse flow	No, but A123 requires this		Yes	No, but A123 requires this		Yes	No, but A123 requires this		Yes
Lithium Battery Label	Yes; Repeat on overpack also.		Lithium battery label can be included with the Class 9 label	Yes; Repeat on over pack also.		Lithium battery label can be included with the Class 9 label	Yes†; Repeat on overpack		Lithium battery label can be included with the Class 9 label
Indicate “Contains Li ion batteries”	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes†		Complete Shipping declarations for Dangerous Goods Transport
Handle with care, flammability risk if damaged	Yes		Complete Shipping declarations: Dangerous Goods Transport	Yes		Complete Shipping declarations: Dangerous Goods Transport	Yes†		Complete Shipping declarations for Dangerous Goods Transport

Requirement	PI-965 – Lithium Ion Cells and Batteries			PI-966 – Lithium Ion Cells and Batteries Packed with Equipment			PI-967 – Lithium Ion Cells and Batteries Packed in Equipment		
	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9*	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9	Cell ≤ 20 Wh	Batt. ≤ 100 Wh	Class 9
Special procedures if pack damaged	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes†		Complete Shipping declarations for Dangerous Goods Transport
Tel # for additional information	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes		Complete Shipping declarations for Dangerous Goods Transport	Yes†		Complete Shipping declarations for Dangerous Goods Transport
Indicate	PI-965; Lithium ion batteries; not restricted		Complete Shipping declarations for Dangerous Goods Transport	PI-966; Lithium ion batteries; not restricted		Complete Shipping declarations for Dangerous Goods Transport	PI-967; Lithium ion batteries; not restricted (if using an air waybill)		Complete Shipping declarations for Dangerous Goods Transport

* 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.

† 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.)

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

Storing Batteries

A123 Systems cells can be stored for up to 10 years in a cool environment. For long storage periods, a refresh charge is required every 4 years at 25°C. For temperatures above 40°C a refresh charge is required every year. Batteries should not be stored continuously above 60°C.

Battery Disposal

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

Chapter 4

Nanophosphate® Technology and Cell Overview

This chapter includes the following sections:

Nanophosphate Technology

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

- **Power:** Our **high-power,** Nanophosphate products can pulse at high discharge rates to deliver unmatched power by weight or volume.
- **Safety:** A123 Systems' 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 Systems' Nanophosphate technology delivers **exceptional calendar and cycle life**. At low rates, our cells can deliver thousands of cycles at 100% Depth-of-Discharge, a feat unmatched by other commercial lithium ion cells.

Power

A123 Systems cells are designed to deliver high power in pulse and continuous applications. Figure 1 displays typical discharge curves showing that the voltage remains virtually flat during the discharges and the delivered AH capacity doesn't change significantly, no matter what the rate of discharge.

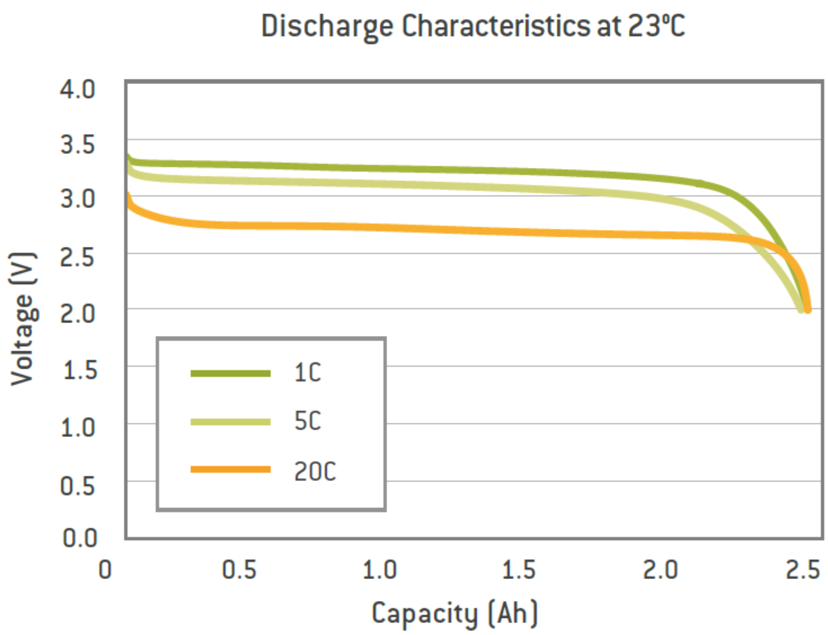


Figure 1 26650 Discharge Curve

Cell resistance changes with cell temperature. The warmer the ambient and/or cell temperature, the lower the resistance. Note that in Figure 5, the cells hold up voltages at cold temperatures less effectively than at ambient room temperatures. Voltages reach parity when the cells heat up to or beyond ambient room temperatures.

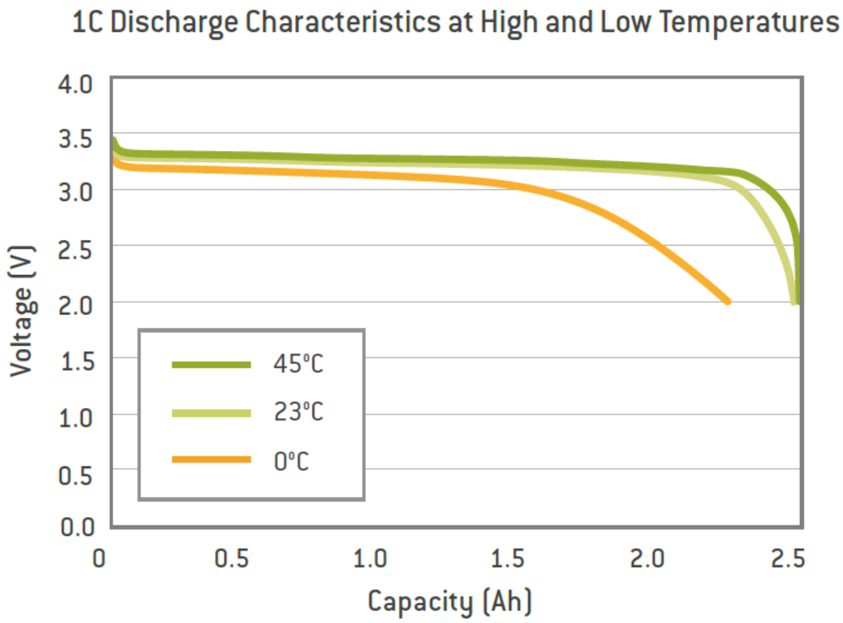


Figure 2 26650 Discharge Curves at Various Temperatures

Safety

Proper handling and battery pack design must be followed to make sure the A123 Systems 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 the proper voltage, current, and temperature limits.

The following <u>minimum</u> 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!

⚠ DANGER

- Cells must not be subjected to ambient conditions or self-heating that result in a temperature in excess of 60°C during operation or while in continuous storage because they will either lose life or be rendered inoperable. Do not incinerate cells, or store or use them near open flames.
  Cells must not be punctured, ruptured, dented, or crushed. The pack design must likewise ensure this under normal operations or in a crash.
- Cell packaging must not be altered in any way.
- Cells must not be immersed or exposed to water or liquids.
- Never use pressure at the top and bottom of the cell to hold cells together 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.
- If the cell or battery emits smoke or flares, ventilate the area immediately and avoid breathing the fumes. See MSDS for additional precautions.
- Cells must not be subject to reverse polarity or short circuited. Individual cell fusing is required in pack designs with cells in parallel to be compliant with UN 38.3, US-DOT and other international shipping regulations. Cells must not be charged or discharged outside the operating temperature range in the datasheet, and reduced charging limits must be followed for lower operating temperatures.

Life

A123 Systems cells offer long cycle and calendar life, with minimal impedance growth over the life of the cells. The ambient temperature cycle life graphs in Figure 3 demonstrates that these cells also offer extended calendar life, even at elevated temperatures.

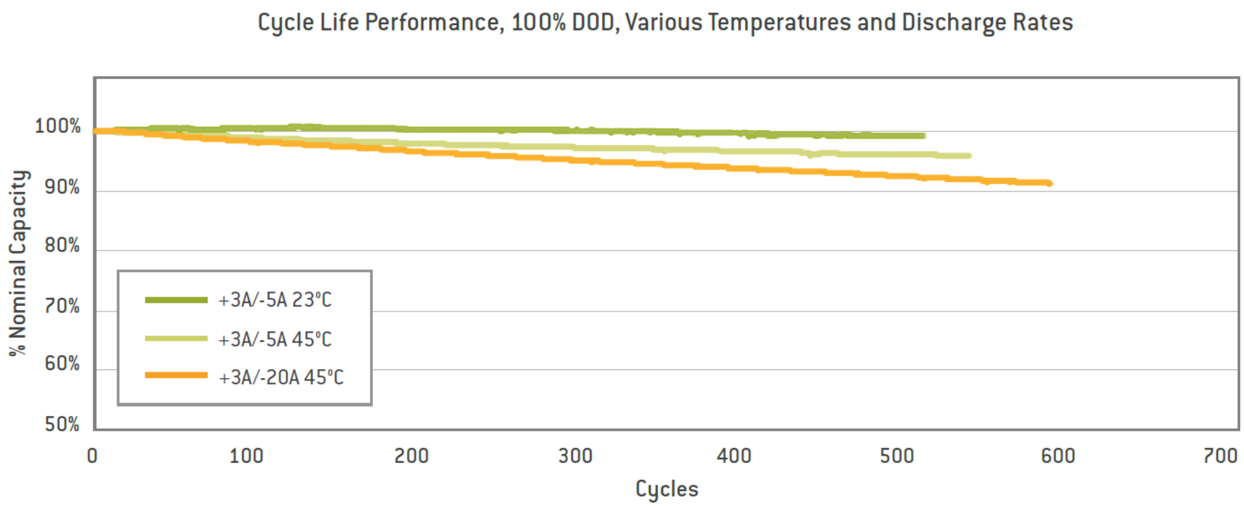


Figure 3 26650 Cycle Life

This information has been prepared solely for general information and illustration purposes and should not be used for any other purpose. While A123 Systems believes the information to be correct as of its publication/release date, the user must rely on its own skill and judgment when making use of the information contained herein. Notwithstanding anything to the contrary herein or in any other document, this information is being provided as-is without warranty, undertaking or guarantee (implied or express) of any kind, including without limitation all warranties of accuracy or completeness, merchantability, and fitness for any particular purpose. A123 Systems assumes no liability for any loss or damage caused by any error or omission in the contents of this document, whether due to negligence or any other cause. Any and all such liability is disclaimed.

Chapter 5

Applications

A123 Systems' cells can be used in many different applications, ranging from Hybrid Electric Vehicles (HEVs) to embedded systems to backup storage devices. This guide cannot cover all possible uses, pack designs and conditions for these cells; therefore, you must make sure the pack design is suitable for your application, and then design and test accordingly.

This chapter includes the following sections:

Voltages and Capacity

Cells can be combined together either in series or in parallel to achieve higher operating voltages and capacities, respectively. When connecting cells, consider the principles of basic pack design discussed in Chapter 6 Basic Pack Design.

Series Strings

Cells combined in series strings can 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 4.

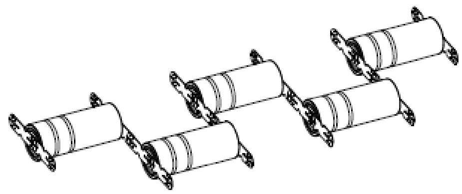


Figure 4 Cells Connected in Series

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

Three cells in series: 3 x 3.3V = 9.9V (nominal)

Parallel Strings

Cells combined in parallel strings can achieve higher operating capacities by connecting like-polarity terminals of adjacent cells to each other. Connect strings of parallel cells using their current collection tabs in a manner similar to that illustrated in Figure 5.

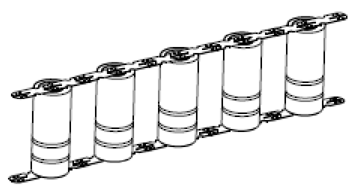


Figure 5 Cells Connected in Parallel

Two cells in parallel: 2 x 2.5Ah = 5Ah (nominal for 26650 cells)

Three cells in parallel: 3 x 2.5Ah = 7.5Ah (nominal for 26650 cells)

Charging Cells

Charging or Recharging Cells or Strings

⚠WARNING When charging or recharging Nanophosphate cells, the charger should apply a constant current (CC) charge followed by a constant voltage (CV) charge.

To achieve maximum life, reliability, and safety, A123 Systems recommends using cell balancing circuitry during cell charging to prevent an increasing spread between highest and lowest battery voltages. Refer to Cell Balancing on page 41 for more information.

Stop the charging process when either:

- The string voltage across the pack has exceeded the recommended maximum charging voltage for the string, or
- 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 charing.

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. 1 *(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. 1 *(Number of cells in series) x (Recommended Charge Voltage, Cell) = Charge Voltage, String*

Refer to Table 1 for recommended charge currents and voltage.

Table 1 Recommended Charge Current and Voltage

Example 1	If the cell string has 10 cells in parallel (10P), and the recommended charge current per cell is 3A, then the charge current for this string is 30A: (10 cells, parallel) x (3A) = 30A
Example 2	If the 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
Example 3	If the cell string has 10 cells in series and 3 cell strings in parallel (10S-3P), the recommended charge voltage per cell is 3.6V, and the recommended charge current per cell is 3A, then the charge current and charge voltage for the string is 9A and 36V: (10 cells, series) x (3.6V) = 36V (3 cells, parallel) x (3A) = 9A

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 6 for an illustration.

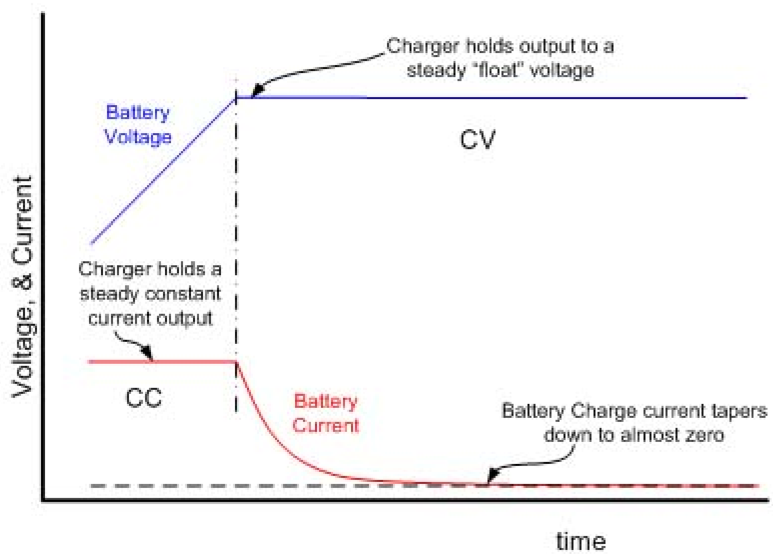


Figure 6: Battery Voltage and Current During Recharge

Recommended Fast Charge Method for Strings

The cells can be 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:

1. Increasing the internal wear and tear on the cell electrodes and reduce its capacity faster than normal
2. Increase the internal temperatures in the cells which increase degradation rates of the cell's capacity and impedance over time.

Determine the fast charge current for a string of cells by multiplying the number of parallel elements in the string by the maximum continuous charge current for a single cell. Determine the maximum recommended charge voltage by multiplying the number of series elements in the string by the recommended charge voltage of a single cell.

Charge the string at its maximum continuous charge current until the string or any one cell within the string has reached its maximum recommended charge voltage. Apply a constant voltage hold at the maximum recommended charge voltage, not exceeding the recommended charge voltage of any series cell, until the total charge time reaches the fast charge time. Do not attempt a fast charge outside the recommended temperature range, and stop if any individual cell voltage or temperature exceeds the maximum allowable limits.

Eq. 1 *(Number of cells in parallel) x (Max Continuous Charge Current, Cell) = Fast Charge Current, Strings*

Recommended Float Charge Method for Strings

The charge current shall be limited whenever any one cell in the string reaches its maximum recommended float voltage.

Eq. 1 *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 elements in the string by the recommended float-charge voltage of a single cell.(Number of cells in series) x (Recommended Float Charge Voltage, Cell) = Float Charge Voltage, String*

Refer to the appendix for recommended float charge voltages.

Discharging Cells

Recommended Discharge Method 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. 1 *(Number of cells in parallel) x (Max Discharge Current, Cell) = Max Discharge Current, String*

Additionally, correctly size the cell-to-cell current collection tabs to carry the maximum design current. Discharges at currents higher than the tab design limit risks damaging these tabs, as well as possibly overheating cells.

Discharge Cell Temperature Limits

For optimum life, do not continuously discharge the strings of cells faster than the maximum continuous discharge current. Do not allow the string of cells to self-heat beyond the maximum recommended cell temperature of 70^{o}C for discharge or 60^{o}C for recharge. 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.

Discharge String/Cell Cut-Off Voltage Limits

Discharge should be cut off whenever any one cell in the string reaches its lowest recommended discharge cutoff voltage.

Stop discharges when any of the following occurances happen:

- 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 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. 1 *(Number of cells in series) x (Recommended discharge cutoff voltage, Cell) = Cutoff Voltage, string*

While the string 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 string voltage can safely fall below the recommended discharge cut-off voltage. Although it is safe to temporarily discharge the string 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.

DANGER Under no conditions should the voltage of the cells be allowed to go under 0.5V. Under such conditions, it is unsafe to continue to operate the cell in its application.

Chapter 6

Basic Pack Design

This chapter includes the following sections:

- Overview
- Mechanical Connection and Protection
- Thermal Management

Overview

Battery Packs (also known as Energy Storage Systems (ESS) and battery modules) should be designed to protect and replicate the individual cell performance of multiple cells in the pack. This means providing mechanical protection and integrity, thermal stability, and electrical protection and performance.

Mechanical Connection and Protection

Design mechanical interconnects to prevent accidental short circuits. Size these mechanical interconnects to carry the expected maximum rated current for both the maximum time and ambient temperature in which the pack is expected to operate.

Cell Interconnects

Size cell interconnects for the expected maximum current carrying capability. Improperly sized tabs could heat up excessively, resulting in even higher resistivity. For reliable welded connections at the terminals, A123 Systems recommends either pure nickel tabs or nickel-clad copper tabs. In addition, other alloys afford both the weldability, strength and low resistance, which are all desirable features of a good interconnection. Cell interconnects (tabs) should be neither soldered on the end caps nor attached using extreme heat. A123 Systems recommends tabs be resistance or laser-welded to both ends of the cells. Resistance welding provides a constant current for a specified period of time through a salient feature in the weld tab. These parameters can be specified and regulated for a consistent high-quality weld every time.

Allowing the Cell to Vent in a Fault Condition

The cell vents, located on the end cap(s) of the cells (on the POSITIVE side of the cell), should not be blocked by any mechanical means. Blocking the cell vent and then sufficiently abusing the cell so as to build up pressure in the cell prevents the cell from properly venting. An ESS designed to install cells end-to-end needs at least 1 mm of space between the cells to allow the vent to open under fault conditions. Refer to Figure 7 as an example.

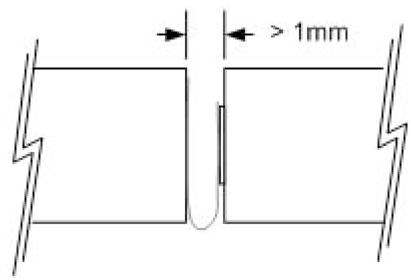


Figure 7 End-to-End Cell Spacing

Cell Insulation

The outside case of the 26650 and 32113 is electrically connected to the positive end (cathode) of the cell. Take care to keep this surface electrically-isolated from any electrical bus bar or mechanical support that may be of different voltage potential. Insulation, such as tapes, shrink wraps, or sleeves, must have at least a 150 °C melting point. This helps ensure that the cells do not short circuit to each other in a high temperature fault condition, which could cause even more widespread damage.

Cell Support

Secure the cells in place by supporting their outside cases, not their terminal ends. The vibration induced between the terminal ends and the rest of the case has been shown to be detrimental to the life of the cell, causing internal and external cell damage. The intercell terminations must be light enough not to cause vibration-induced damage to the cell.

Cell Protection

In addition to being supported, 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. An ESS 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. 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.

Thermal Management

A123 Systems' cells operate throughout 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 implies a cooling system. There are certain applications - such as HEV vehicles operating in cold climates - where a heater is beneficial to keeping the cells operating in their optimal range.

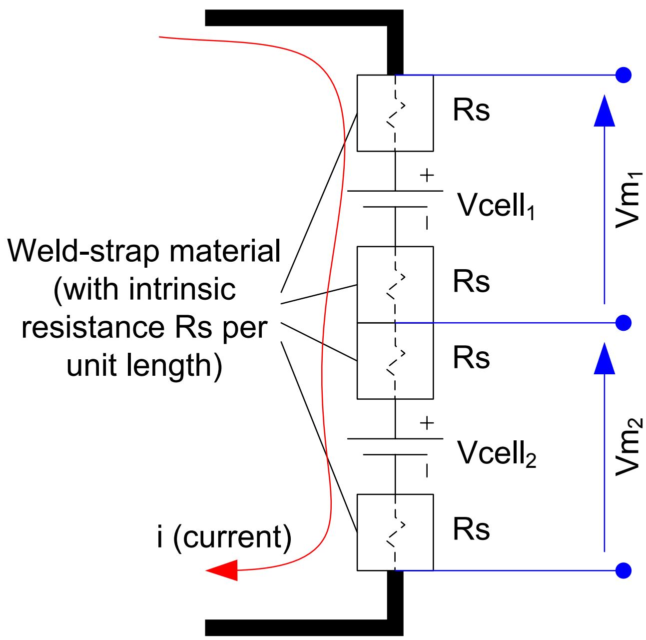
Electrical

When joining cells together, A123 recommends using a Battery Management System responsible for carefully monitoring cell voltage, current, and impedance. The BMS may be implemented as discrete circuitry or through a microcontroller.

Cell Monitoring

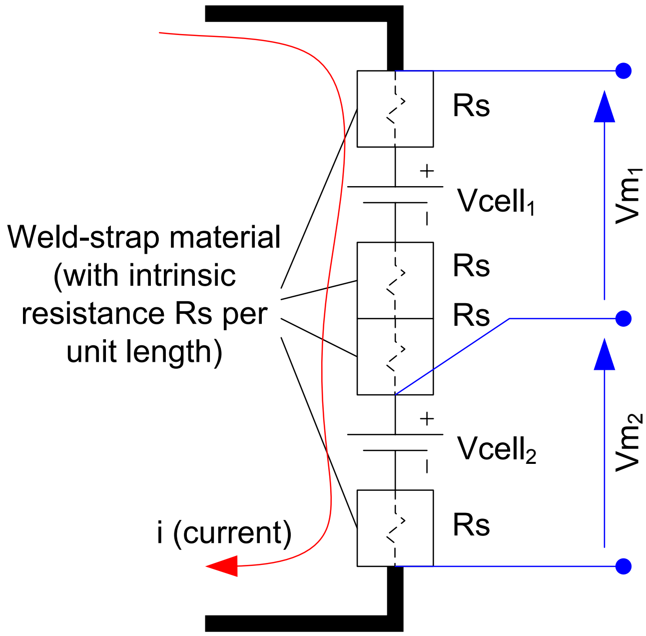
To ensure optimal performance, safety, and durability of the pack, the Battery Management System must monitor the voltage of each individual series cell in a battery string.Take care to place the voltage monitoring connections in such a place that they are not affected by high currents going through 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.

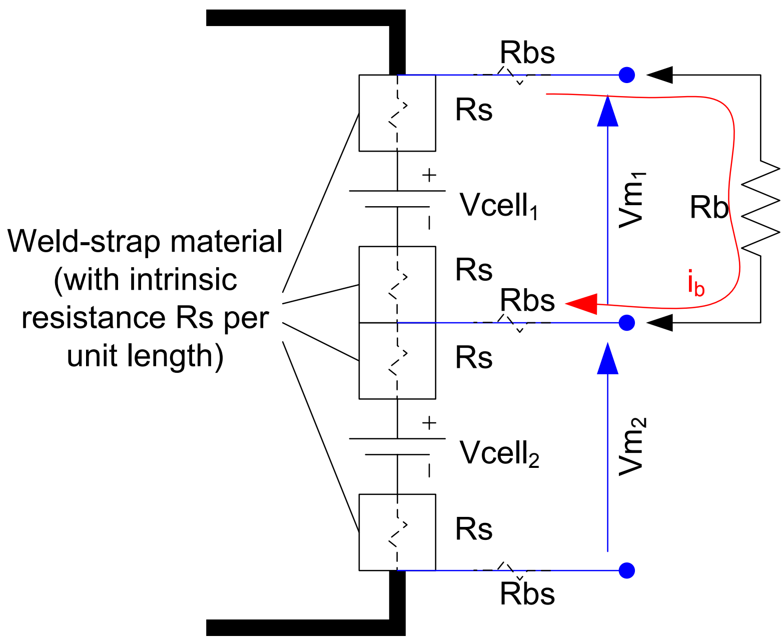
If the contact points are placed asymmetrically, such as shown below:



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 + i x Rs where Voffset = 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 balance some of the cells, and while it is recharging, the BMS would balance the others. This results in a great deal of wasted heat and energy that contributes to a reduced performance and sevice lifetime of the battery. Ensure that balancing currents do not share 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 affect 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:

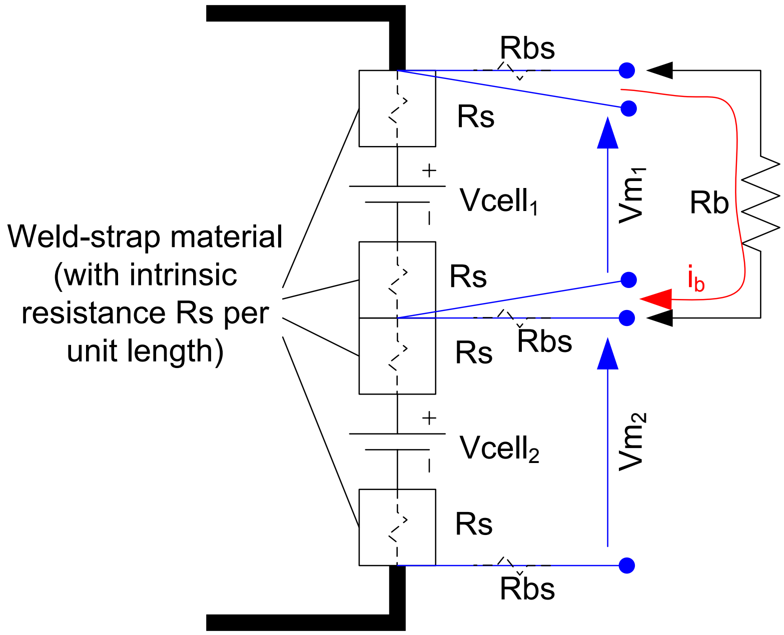


Figure 8 ESS Sample Block Diagram

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

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 ESS is adequate for proper ESS 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 ESS Behavior

The circuitry that monitors the cells in an ESS should also be used to supervise the ESS environment and use, to preserve the safety and life of the ESS by protecting it from external fault conditions such as overcharge, overdischarge, overvoltage, undervoltage, overcurrent and undercurrent. Methods of supervising and controlling the battery pack include firmware based controls or special purpose integrated circuits. Regardless of how you choose to supervise the pack's behavior, protection from fault conditions should be a top priority.

When monitoring cell behavior in the pack, histograms should be stored (e.g. saved in non-volatile EEPROM memory) that outline the condtions that the pack saw while in service. Suggested service histograms are as follows:

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

An example of the historgram data that might be stored is shown in the following table:

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, voltages, and currents.

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. This solution requires an integrated circuit monitor connected to each series cell in a string reporting data measurements to a controller via an internal communication bus. Measurements taken on an individual cell level allows connection and measurement close to each individual cell, resulting in improved accuracy. Integrated circuit controllers offer active cell balancing technology, and are fully programmed from the factory – because the firmware is already embedded, no firmware development is required. In addition, the controllers are user-configurable to suit a variety of applications using a supplied graphical user interface.

For example, manufacturers such as TI offer Analog Front Ends (AFEs) that may be suitable for your application. AFEs integrate an I2C compatible interface 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 TI AFEs provide safety protection for various fault conditions such as short circuits and cell overvoltage.

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

Cell Balancing

Reasons for Cell Balancing

A123 Systems 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. Charging or discharging an imbalanced series string of battery cells increases the spread between the highest and lowest cells' voltages. 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. If the string is balanced, every cell can be charged to its maximum voltage during recharge, and every cell can be brought to its minimum allowable voltage 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 voltage 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 in 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

If you do not include cell balancing in your pack design, you must 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

To maximize deliverable energy from a series string, a balancer would ideally work full-time. This keeps the cells balanced no matter how fast they diverge or how fast the pack is cycling up or down. However, this is generally not practical because of the cost and complexity of the required power conversion. Also, the practical limitation of cell voltage sensing error on the flat part of the Open Circuit Voltage over State of Charge curve may serve to drive an imbalance. 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. On the other hand, if the pack is used in an HEV-type 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 opportunistical 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/DOC that the A123 cells exhibit.

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. Layered 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. This is considered best practice in the circuit protection field.

Individual Cell Fusing

You 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, design the module fuse to blow at a higher level than the main pack fuse. Refer to Figure 9 for an illustration of an individual cell fusing strategy.

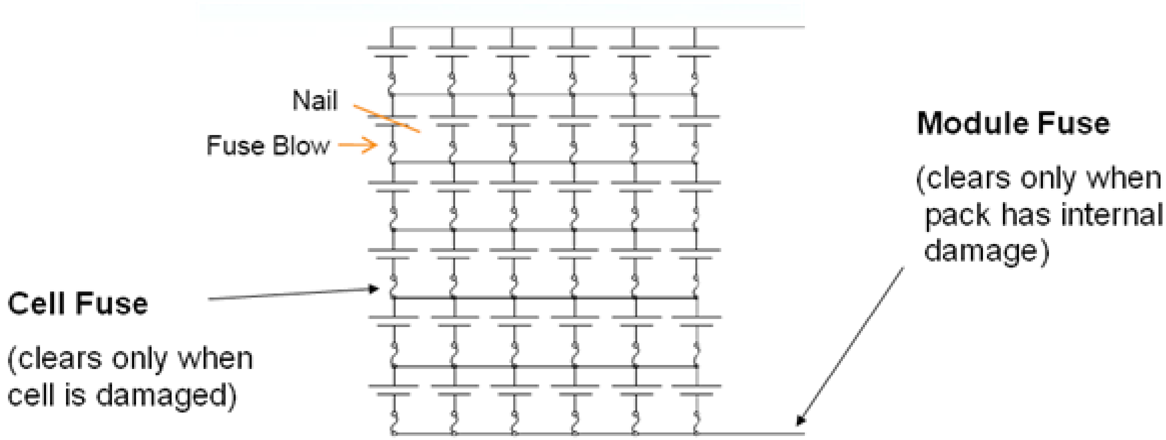


Figure 9 Individual Cell Fusing Strategy

Individual cell fusing can be accomplished by constricting the interconnecting metal material near the cell terminal.

To prevent ignition of the hot vented gasses during a simulateous fusing and venting incident, place the fused tab on the opposite side of the outside casing where the vent is located. In the A123 26650 cells, the vent is located on the positive terminal.

In Figure 10, the 7 mil Nickel strap material is necked down to 3.6 mm, and clears at approximately 2100A in 0.1 sec. This and alternative designs should be verified using modeling software and bench testing prior to design release.

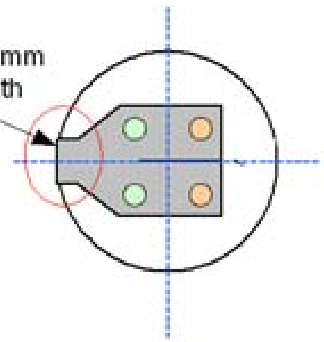


Figure 10 Individual Tab Fuse Example

Module Fuse Rating

Design the module fuse to blow at a lower current than that of the individual cell fuses. This ensures that the module blows before any of the cell fuses do 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 11, a short circuit involving four modules is possible with an internal fault.

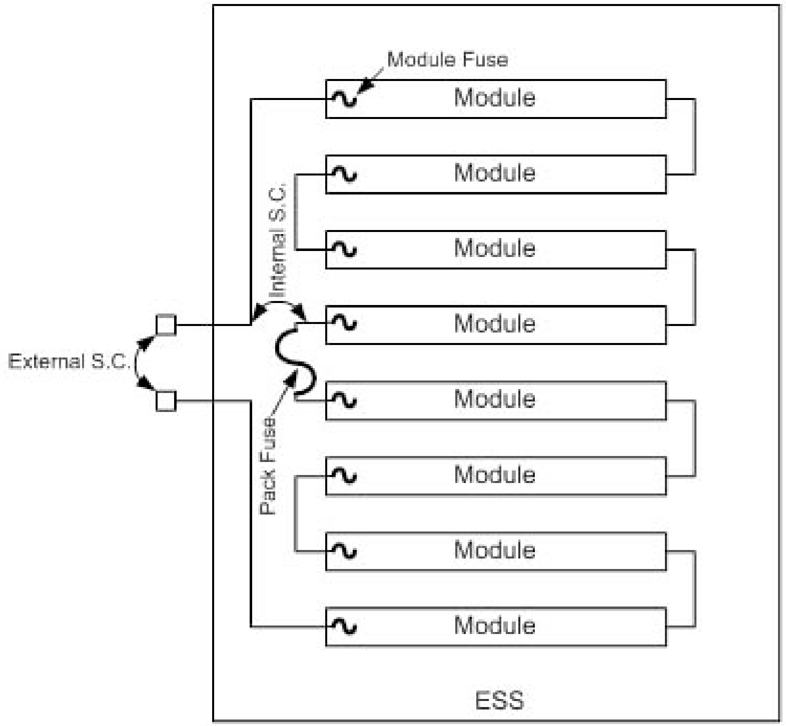


Figure 11 ESS with Representative Short Circuit Faults

Main Fuse Rating and Position

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

Fuse Coordination and Testing

Proper fuse coordination can ensure safe operation of the ESS, even in fault conditions. Once a prototype fusing strategy is in place, **perform the short circuit testing using a variety of cell temperatures and SOC's**, because these can affect the availability of current and the test results.

Overcharge Protection

Using individual series cell voltage monitoring, the BMS can employ a means to protect any cell from being overcharged. Some of these means include opening an input contactor, FET or other switch in series with the battery terminals, or by communicating to a smart external charger to adjust its output appropriately.

Because overvoltage is a sure way to ruin the cells, a best practice technique is to make sure there are redundant methods for monitoring and controlling the cell voltage. For example, if a microprocessor is involved in the decision-making process, employ an analog circuit to watchdog the processor or cell voltages. If an analog circuit is the only method to watch the circuit, use two for redundancy.

Fuel Gauging (Types, Methods)

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 Systems' 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 12 shows the open circuit voltage (OCV) voltage compared to SOC at various temperatures of the 26650 cell.

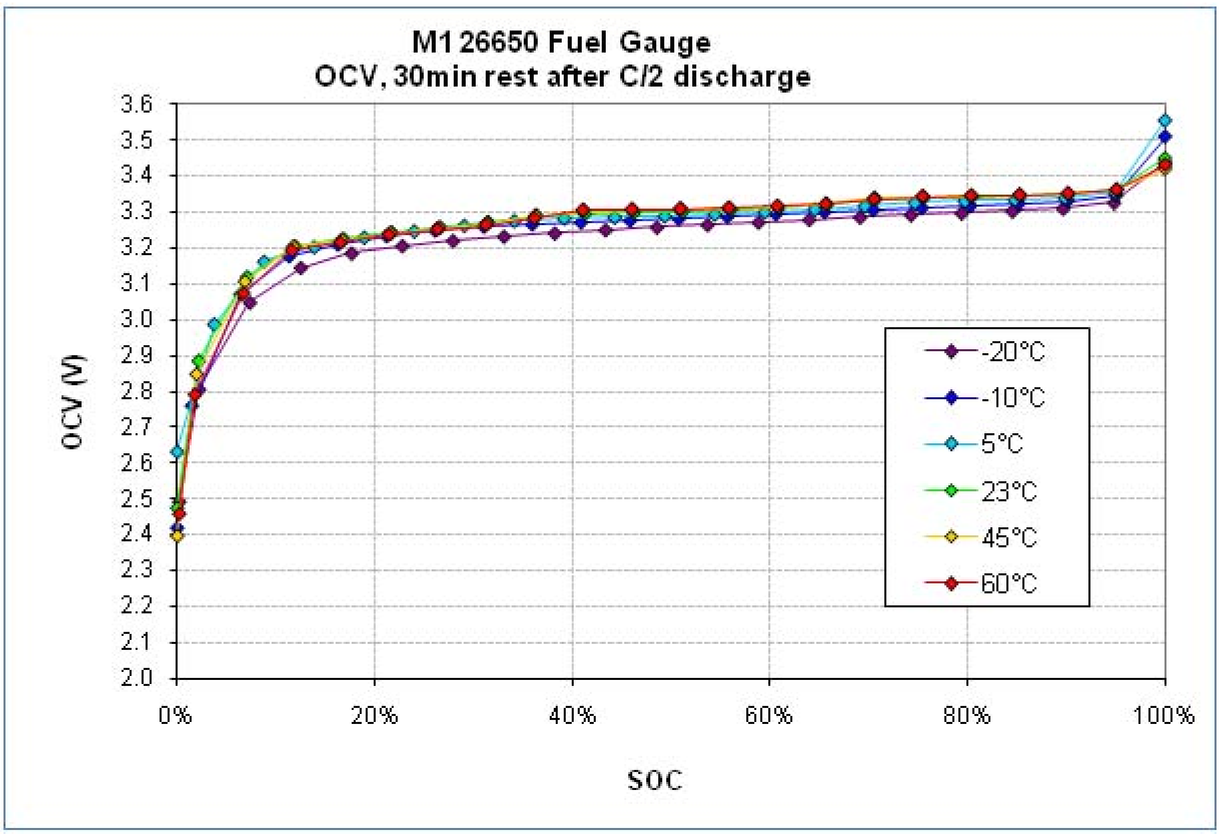


Figure 12 26650 Voltage vs. SOC at Various Temperatures

The middle portion of this plot is extremely flat, roughly equivalent to 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.

There are a number of ways to estimate SOC. Due to an inherent amount of uncertainty in each method, you may need to combine the methods, and periodically reset SOC values, to maintain an 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.

Voltage SOC (vSOC)

One method of determining SOC uses only voltage. The BMS takes a reading of the OCV and correlates it to the SOC using look-up tables based on the chart in Figure 12. The problem with this algorithm is that the voltage readings need to be extremely accurate for the A123 Systems battery technology. Also, 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 13 illustrates the possible range in SOC values resulting from uncertainty measuring OCV.

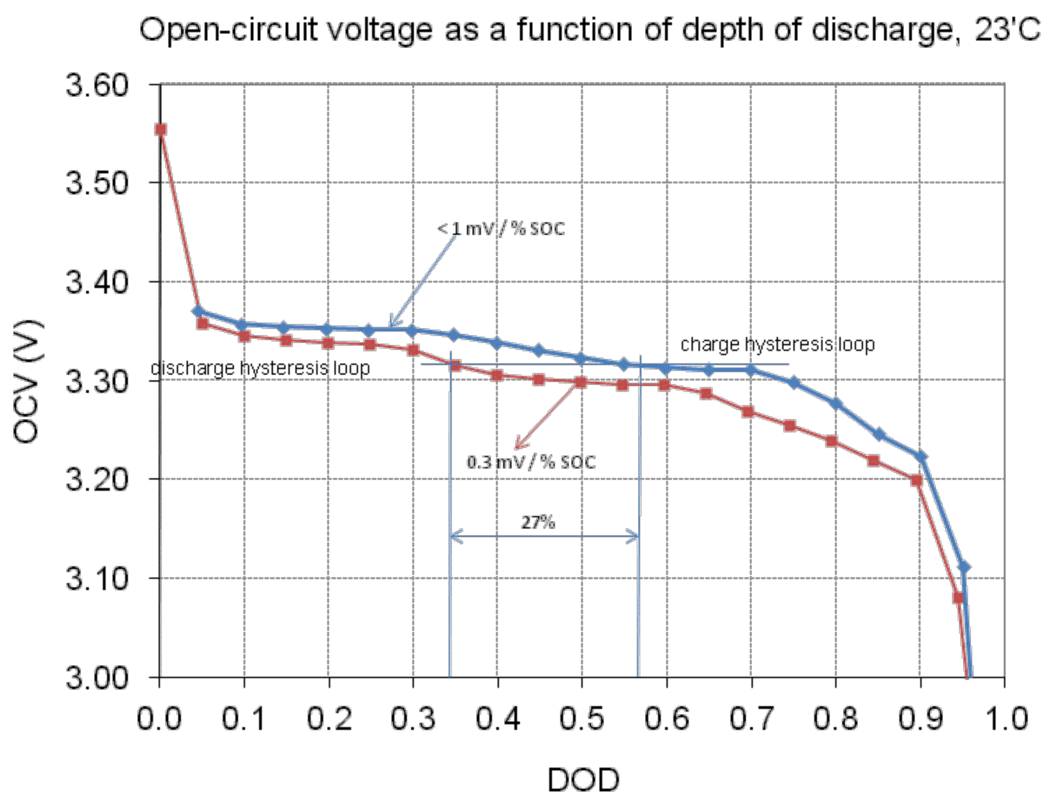


Figure 13 vSOC Sensitivity to OCV Error

For a single voltage of 3.32V, the OCV can represent either 66% SOC or 43% SOC depending on whether the cells were just discharged or charges (See the discussion about hysteresis below). 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.

Coulomb Counting SOC (iSOC)

Another method 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, you can determine the starting SOC point in the iSOC algorithm by taking an OCV reading before discharge/recharge activity starts, and correlate it to an SOC. While the current is strong, the algorithm places a heavy emphasis on the iSOC algorithm. When the current tapers off or settles into a low current idle mode, the vSOC algorithm can take over and keep track of the SOC. Lastly, when the estimated OCV voltage nears the upper or lower range of the cell's voltage range, the vSOC can be used to estimate SOC. The estimated OCV is based on the actual termination voltage minus the current times the estimated battery impedance. The impedance is calculated based on the last known SOC the measured temperature.

Hysteresis

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 14 shows this hysteresis at 23 °C.

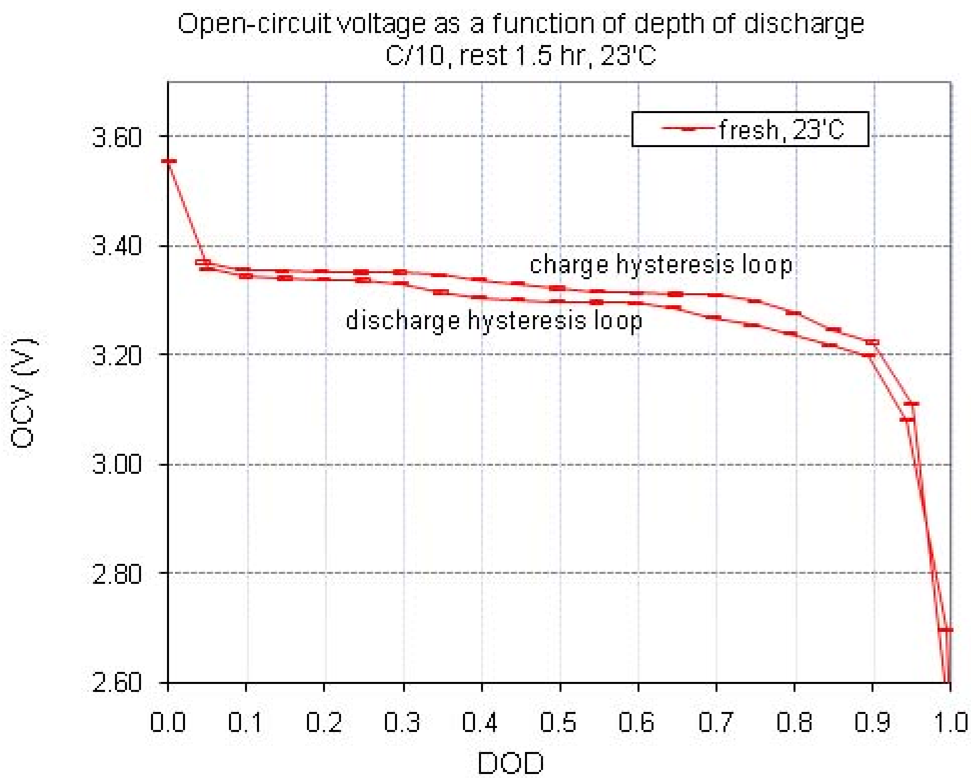


Figure 14 Charge and Discharge Hysteresis

Just as there is some uncertainty in measuring OCV when determining vSOC, there is a range of uncertainty in determining charge hysteresis when the ESS wakes or is reset. This uncertainty also impacts vSOC values, as illustrated in Figure 15.

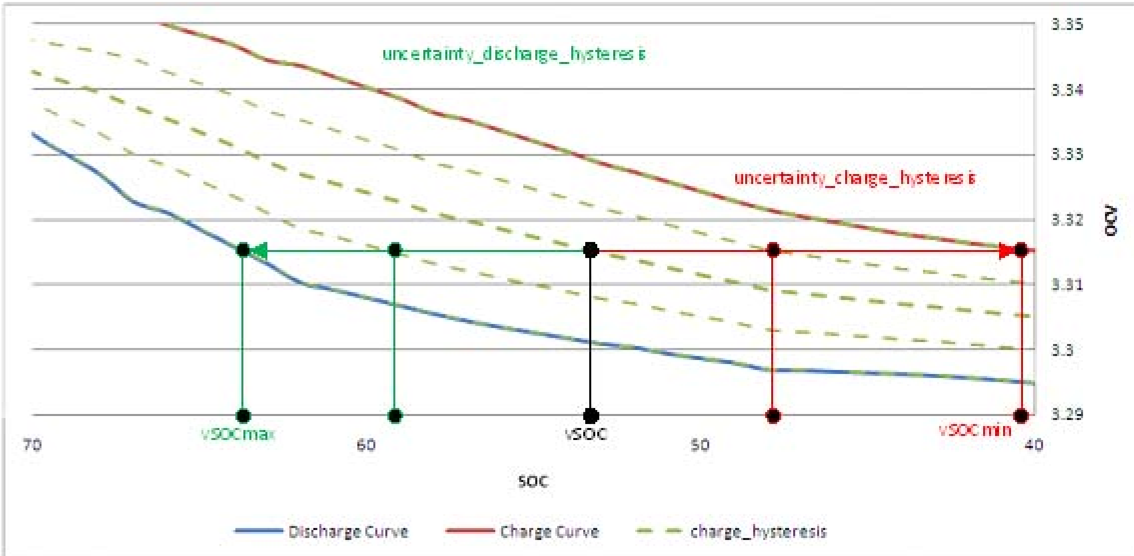


Figure 15 vSOC Sensitivity to Charge Hysteresis Error

Accuracy in determining charge hysteresis improves as the ESS is charged and discharged.

Chapter 7

Summary of ESS Testing

This chapter includes the following sections:

Overview

To ensure safe operating performance of an ESS using A123 Systems' cells, design the ESS to a minimum set of design standards that can pass a minimum set of design validation tests. This chapter summarizes the minimal testing recommended to be performed on an ESS, the performance criteria it must pass, and a set of design guidelines to follow while designing the product.

Performance Testing

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

Table 2 Performance Tests

Name	Description
CC	Constant Current Discharge – Test Capacity of ESS using various constant current loads
PP	Peak Power Discharge – Test Power Capability of ESS 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 ESS using the application's expected cycle profiles. There are two application cycle testing goals. One is to measure short-term ESS performance and 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 ESS while off.
Thermal	Test temperature rise of cells over ambient temperature during worse-case load conditions. Test Temperature gradient from coolest to hottest cell during worse-case load 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.

Table 3 Abuse Tests

Name	Description
Short Circuit	Test the ability of the ESS 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 ESS, such as modules, groups of modules, cells and cell groups.
Overcharge	Test the ability of the ESS to prevent any one of its cells from being overcharged as a result of excessive voltage being applied to the terminals of the ESS
Crush	Understand what happens when the ESS is crushed in a calibrated manner.
Drop	Observe the effects of the ESS being dropped from a specified height.
Shock	Observe the effects of the ESS being subjected to a large shock in three axes.
Immersion	Test the ability of the ESS to seal out liquid water when completely immersed.

Compliance Testing

Compliance or confomance testing verifies whether a product meets a set of defined standards dependent on the product application. The ESS needs to meet standards in areas such as safety, environmental, and electromagnetic compliance. This guide cannot cover all possible applications and uses for A123 Systems' cells. Therefore, you must test your pack design based on the compliance standards appropriate for your intended application.

Chapter 8

Pack Manufacturing

This chapter includes the following sections:

Overview

This chapter discusses inspecting cells prior to assembling into packs and guidelines for creating weld schedules for A123 cells.

Cell Incoming Inspection

Cells are checked for excessive self-discharge at the factory before they are released for sale and shipment. A123 Systems still recommends inspecting cells before assembling them into packs. Cells are shipped at approximately 50% SOC, with a nominal voltage of 3.3V.

Material Handling and Storage

General

Minimize handling of cells to avoid damaging them. Reject any cell dropped from a height of more than 1200 mm. If a cell is dropped from a height of less than 1200 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 either OCV or ACR 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. Any changes in handling, storage or inspection methods must be approved in writing by A123 Systems prior to implementation.

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 from the elements at all times.

Cell Welding

Mechanical Cell Interconnects

WARNING Cell interconnects (tabs) should NOT be soldered on the end caps or attached using extreme heat.

A123 Systems recommends resistance or laser welding tabs to both ends of the cell. Because it is impossible to cover every possible weld schedule, A123 Systems 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/

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 Systems does not endorse or recommend any particular welder or consultant

Appendix A

Cell Specifications

This design guide covers A123 Systems' **ANR26650*m1*B**, **APR18650*m1*A***,* and **AHR32113*m1*** cylindrical cells with the specifications outlined in this section.

Handling/Transportation: Do not open, dissemble, crush or burn cell. Do not expose cell to temperatures outside the range of -40°C to 60°C. Refer to Chapter 3 for more information.

Storage: Store cell 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.

ANR26650m1B

Refer to the table below for specifications for the ANR26650**m1B** for a cell drawing. Note that actual performance of the cells may vary depending on use conditions and application.

Table 4 ANR26650M1B cell specifications

ANR26650m1B	
Nominal Voltage	3.3V
Nominal Capacity	2.5Ah
Maximum discharge current - continuous (A)	70A, with the caveat that the cells do NOT exceed their maximum operating temperature (+60°C)
Pulse discharge at 10 sec	120A
Peak power @ 10 s (watts)	210W
Recommended standard charge	1.5C to 3.6 V
Recommended fast charge	4C to 3.5V
Recommended float charge voltage	3.5V
Recommended end of discharge cutoff	2.0V
Operating Temp Range	-30°C to +60°C
Storage temperature range	-40°C to +60°C
Weight	75 grams
Nanophosphate® Chemistry	m1b
Current Interrupt Device (CID)	No

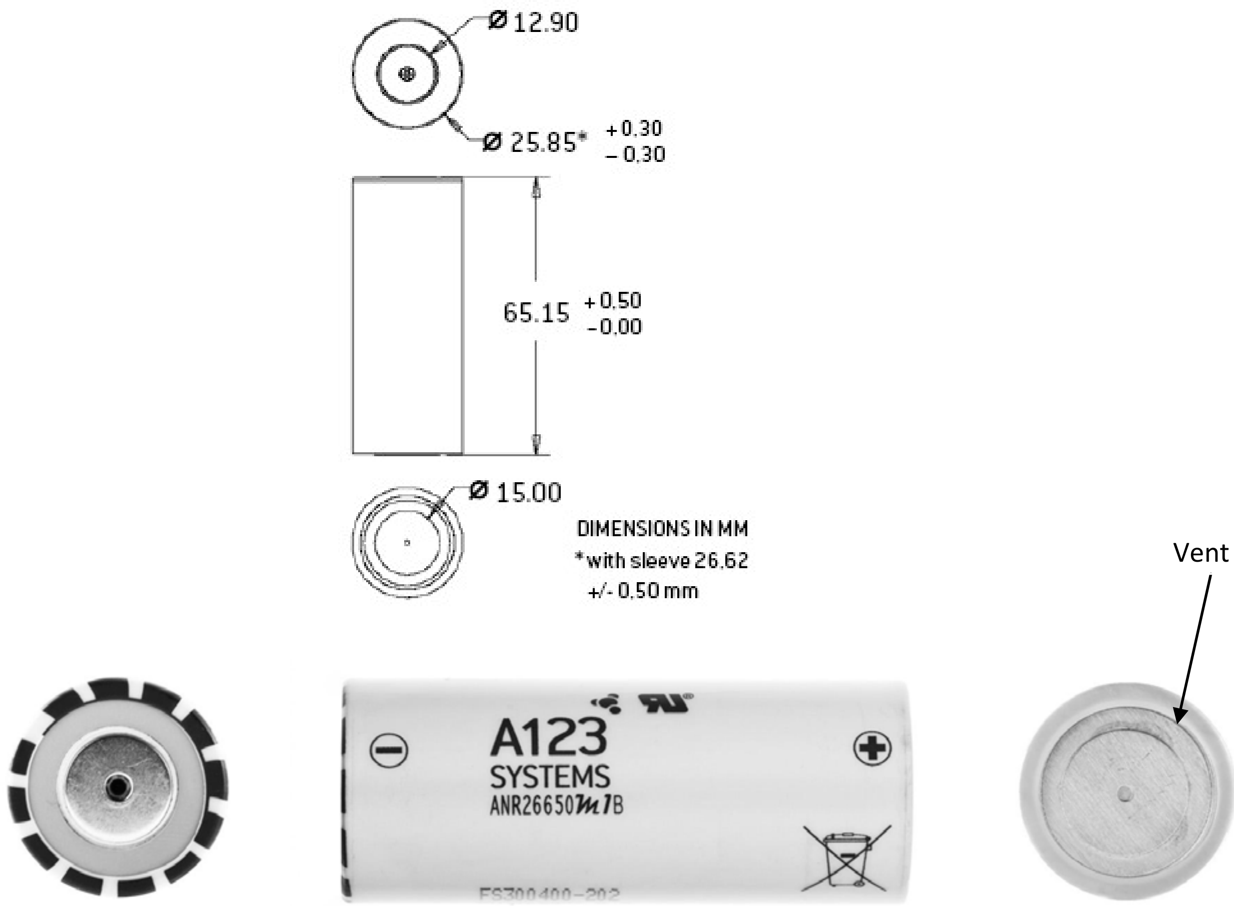


Figure 16 ANR26650m1B

APR18650m1A

Refer to the table below for specifications for the ANR18650m1A and for a cell drawing. Note that actual performance of the cells may vary depending on use conditions and application.

Table 5 APR18650m1A Cell Specifications

Cell Model Number	APR18650m1A
Nominal Voltage	3.3V
Nominal Capacity	1.1 Ah
Maximum discharge current - continuous (A)	30A
Pulse discharge at 10 sec	60A
Peak power (watts)	92W
Internal Impedance (1kHz AC)	18 mΩ typical
Internal Resistance (10A, 1s DC)	27 mΩ typical
Recommended standard charge	1.5C to 3.6V
Recommended fast charge	4C to 3.5V
Recommended float charge voltage	3.5V
Recommended end of discharge cutoff	1.6V
Operating Temp Range	-30°C to +60°C
Storage temperature range	-40°C to +60°C
Weight	39 grams
Nanophosphate® Chemistry	m1A
Current Interrupt Device (CID)	Yes

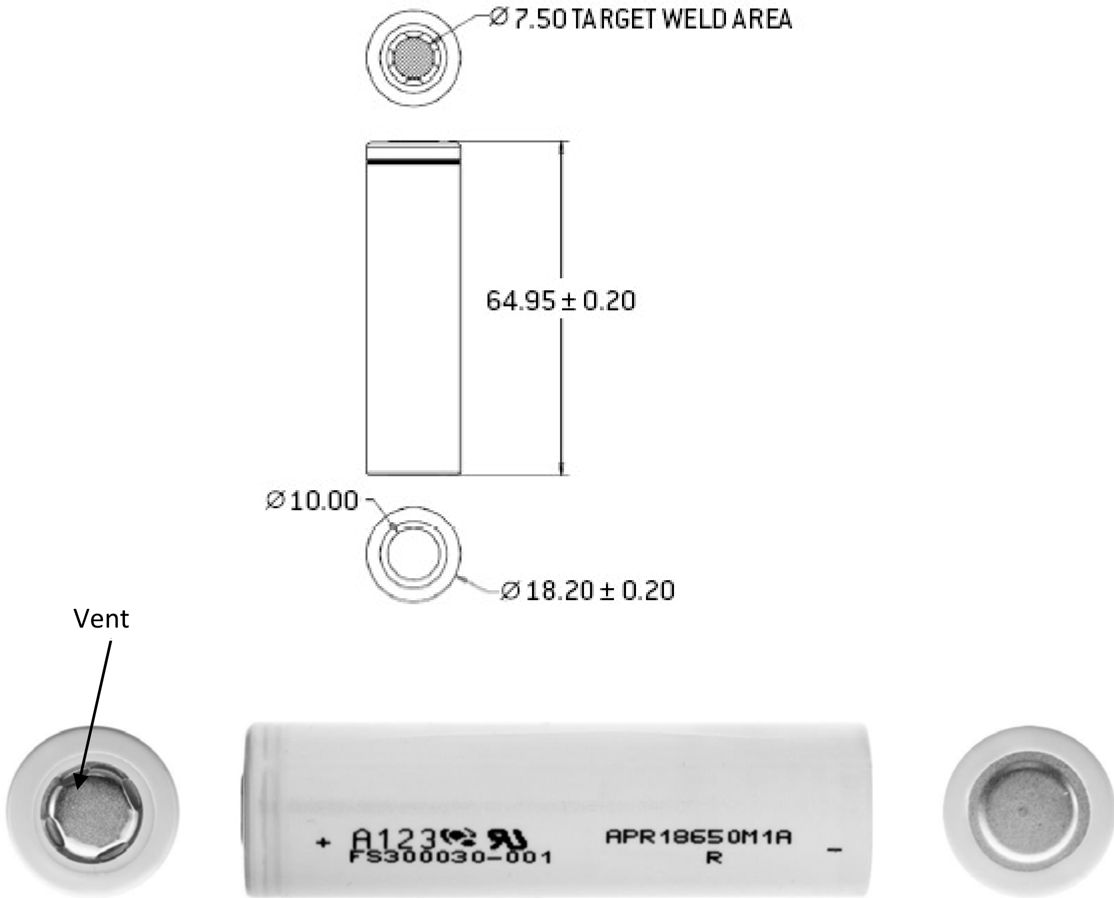


Figure 17 APR18650M1A

AHR32113m1

Refer to the table below for specifications for the AHR32113*m1* and the following graphic for a cell drawing. Note that actual performance of the cells may vary depending on use conditions and application.

Table 6 AHR32113*m1* Ultra-B Cell Specifications

Cell Model Number	AHR32113*m1*
Nominal Voltage	3.3V
Nominal Capacity	4.5 Ah
Maximum discharge current - continuous (A)	200
Pulse discharge at 10 sec @25′C (A)	300
Peak power @ 10 sec (watts)	550W
Recommended standard charge	1.5C to 3.6V
Recommended fast charge	4C to 3.5V
Recommended float charge voltage	3.5V
Recommended end of discharge cutoff	1.6V
Operating Temp Range	-30°C to +60°C
Storage temperature range	-40°C to +60°C
Weight	205 grams
Nanophosphate® Chemistry	*m1* Ultra -B

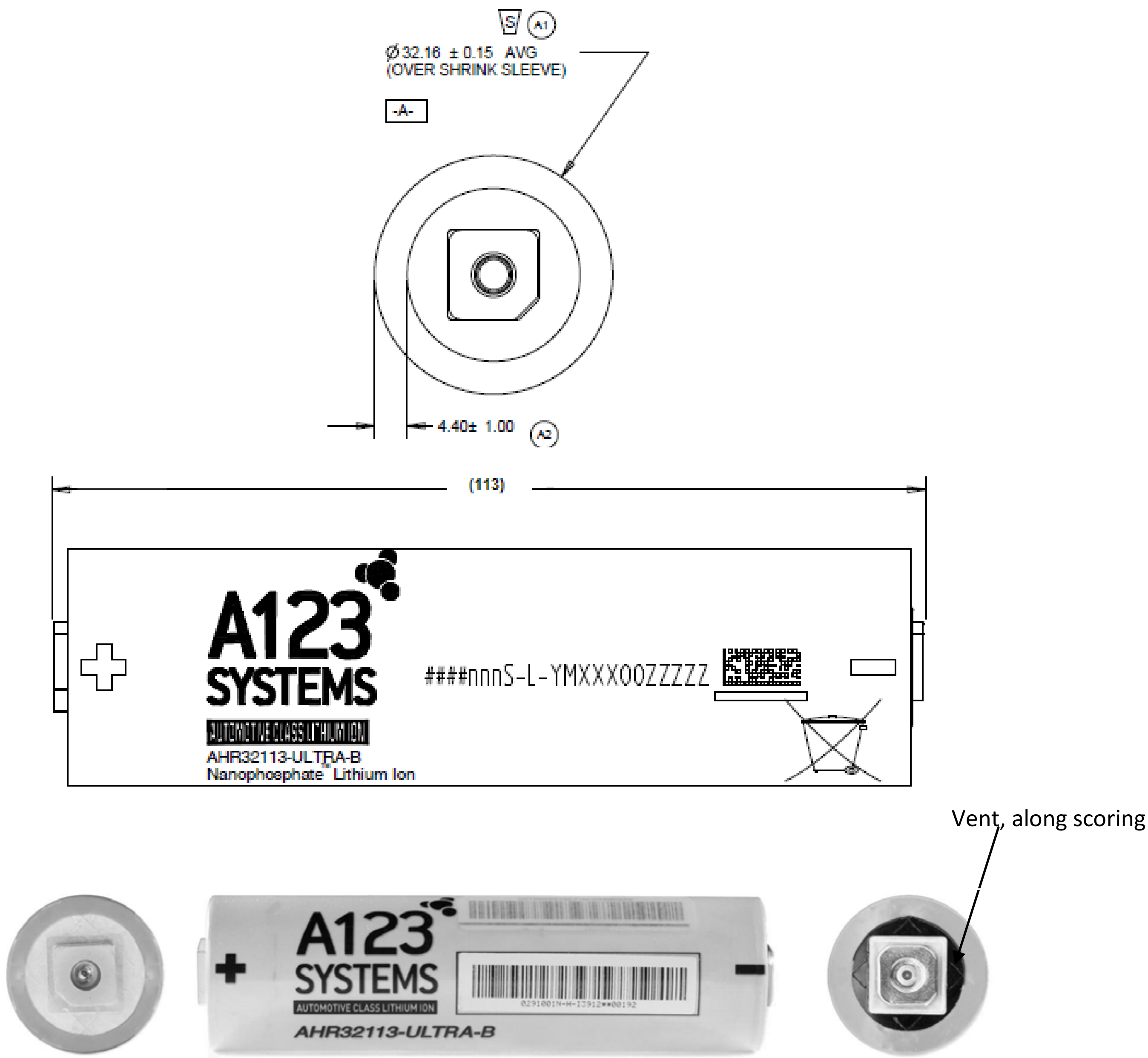


Figure 18 AHR32113m1

This information has been prepared solely for general information and illustration purposes and should not be used for any other purpose. While A123 Systems believes the information to be correct as of its publication/release date, the user must rely on its own skill and judgment when making use of the information contained herein. Notwithstanding anything to the contrary herein or in any other document, this information is being provided as-is without warranty, undertaking or guarantee (implied or express) of any kind, including without limitation all warranties of accuracy or completeness, merchantability, and fitness for any particular purpose. A123 Systems assumes no liability for any loss or damage caused by any error or omission in the contents of this document, whether due to negligence or any other cause. Any and all such liability is disclaimed.

Appendix B

Glossary

This appendix describes the terminology used in this document.

Terminology Table

The following table describes the terminology used in this document.

Table 7 Terminology

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 which 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 ESS.
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.

Term/Acronym	Meaning
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.
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.
vSOC	Voltage based SOC algorithm