Application Note

A passion for performance.

An Introduction
Cell Balancing and Monitoring
Lithium Ion Batteries

Table of Contents

Section

I Introduction

Lithium-Ion batteries were introduced in 1991, and have become the preferred technology for many applications. This is primarily due to their outstanding energy density, the ratio of stored energy per unit weight which is higher than that of other commonly used battery technologies as shown in the following table:

Energy Density of Batteries

Battery Type	Watt-Hours/Kilogram
Lithium-Ion	128
Alkaline Long-life	110
Nickel Metal Hydride (NiMH)	95
Lead-Acid	41
Nickel-Cadmium (NiCd)	39
Carbon-Zinc	36

In many applications, achieving the greatest possible energy density is critical, because the weight saved by a lighter battery can be allocated to other equipment. For example, in a typical satellite application, a Lithium-Ion battery may save hundreds of pounds by replacing a NiMH unit with the same energy (watt-hours) capacity. This weight saving can translate to a direct increase in payload capacity.

Lithium-Ion cells are designed to provide a voltage in the range of approximately 3.0 to 4.3 volts. It is EXTREMELY IMPORTANT to maintain the cell voltage between its design limits at all times, or the cell will be irreparably damaged. If a cell's voltage is allowed to drop below 3.0 volts, the cell will go into a state known as *deep discharge*, from which it may take hours or even days to recover. In fact, a deep discharge may cause the cell to short circuit, an event from which it will not recover. Overcharging to a voltage greater than 4.3 volts can be even worse because this can cause the cell to destruct, possibly with severe overheating or other catastrophic results. In simple applications using only a single Lithium-Ion cell, the electronic control circuit must protect the cell by shutting off the load when the cell voltage drops below 3.2 volts, and limiting the voltage during charging to less than 4.1 volts.

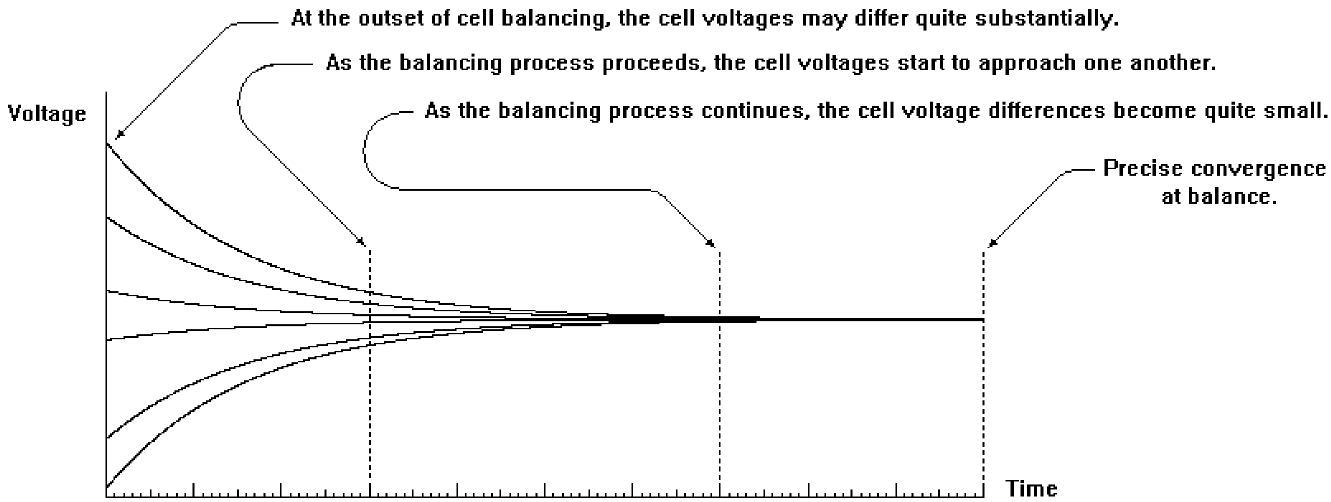
A Lithium-Ion battery may be constructed by connecting two or more cells in series. In this configuration, the battery voltage is equal to the sum of the individual cell voltages. For example, a 96-volt battery is obtained by connecting 24 Lithium-Ion cells in series. When a load is applied, the load current flows out of all 24 series cells. When the battery is being charged, the charger supplies charging current to the series string of cells. In both cases, the discharging and charging currents in all the cells are equal. Over the life of the battery, the battery may be charged and discharged for hundreds or even thousands of cycles. As this occurs however, the individual cells may age differently. Some cells may become slightly (or more than slightly) mismatched with respect to the others. If this phenomenon is not corrected, one or more cells may become undercharged or overcharged, either of which can lead to failure of the battery.

The methodology for correcting this condition is called *balancing*. Balancing is the process of forcing all of the cells to have identical voltages. This is accomplished by a balancing circuit. The Aeroflex balancing circuit creates a Share Bus, which has a voltage equal to the average voltage of all the cells (24 in this example). The balancing circuit takes charge from all of the cells that are above the Share Bus voltage and injects that charge into the cells that are of lower voltage. The charge transfer is facilitated by the Share Bus.

Each cell's own part of the balancing circuit is a transformer-coupled bilateral DC-AC converter, operating at a frequency of approximately 100 kHz. Pairs of DC-AC converters form bilateral DC-DC converters between the various cells. The balancing circuit takes charge from the Share Bus, and forces that charge into those cells that are below the Share Bus voltage. By this process, the high cell voltages become lower, and the low cell voltages become higher.

The Aeroflex Battery Electronics Unit (BEU) performs balancing using a proprietary circuit that is covered by several patents. Each cell in the battery is connected to the Share Bus by a bilateral DC-AC converter, causing current to flow from the side with higher voltage to the side with lower voltage. The magnitude of the current is proportional to the voltage difference, i.e. as the cells become closer to being perfectly balanced, the balancing current approaches zero.

Note that balancing is not an instantaneous process, but requires some period of time for its completion as sketched below. Eventually all the cell voltages become equal, and no further current flows into or out of the Share Bus, but there is a time requirement to achieve this.



Balance represents a state of equilibrium for the battery and balancing circuit. Balancing occurs continuously throughout the life of the battery, while the battery is charging, discharging, or inactive. The Aeroflex BEU works directly with the Lithium-Ion battery and in harmony with an external battery charger.

Bear in mind that the balancing circuit is not a battery charger. Balancing is a process that consumes some small fraction of the battery's total energy, energy which must be replenished by an external battery charger.

The second major function performed by the BEU is *monitoring*. In this process, the individual cell voltages are measured with an accuracy of approximately 10 millivolts, digitized and transmitted by telemetry over a serial data bus, MIL-STD-1553B, to a remote device. In addition, the BEU continuously compares the individual cell voltages to preset limits and sends out cautionary or alarm signals if any of these limits are exceeded. These limits are typically programmed as follows:

Typical Preset Cell Voltage Limits

Nomenclature	Voltage Limit
Low Cell	$<$ 3.20 volts
High Cell	$>$ 4.20 volts
Overvoltage Protect (OVP)	$>$ 4.40 volts

The Low Cell limit may be used as a signal to the user to remove the load from the battery to prevent the cell voltage from dropping further. The High Cell limit or the OVP may be used as a signal to the user to halt any further charging of the battery.

In addition to monitoring the individual cell voltage, the BEU also monitors the full battery voltage. This may be used as a check, to be compared with the sum of the individual cell voltages.

Studies have shown that cell balancing can significantly prolong the life of Lithium-Ion batteries by preventing cell mismatch over the life of the battery. Without balancing, two types of mismatch may occur: State-of-Charge (SOC) and capacity/energy (C/E). By providing continuous on-line balancing during charging, discharging and inactive periods, the Aeroflex BEU will allow a Lithium-Ion battery to achieve its maximum possible life while also ensuring battery safety.

II Handling Battery Failure Mechanisms with Bypass Relay Option

In a battery, individual cells may fail in different ways.

If one cell of a battery short circuits, that battery can continue to operate in a degraded mode. For example, a 24-cell (96 volt) battery would become a 23-cell (92 volt) battery. In most applications, this degradation may be acceptable and the system may continue to perform acceptably.

However, if a cell fails open, the battery becomes non-functional because the cells are in series. To address this problem, some systems utilize bypass relays with which a failed cell is replaced by a set of closed relay contacts. Such relays are specially designed to serve in this application. Such a relay contains a mechanical mechanism similar to a fuse or a squib which once energized, is permanently latched closed and cannot be reset.

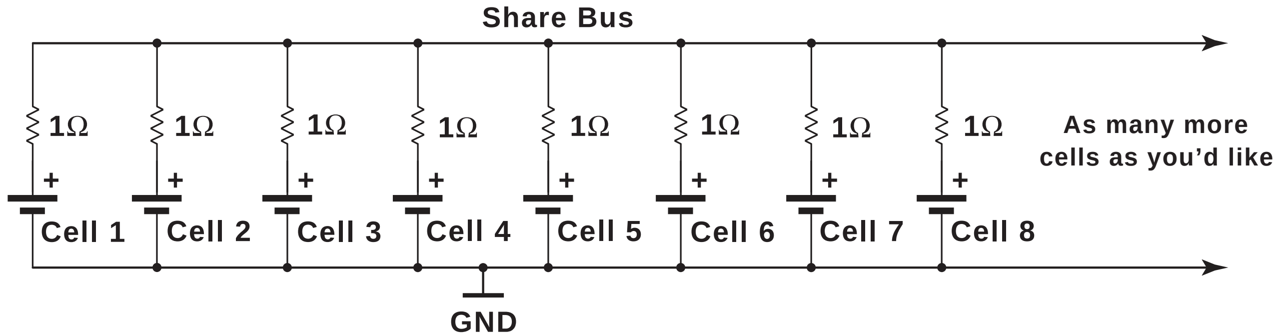
In a system that utilizes bypass relays, the relays are located in the battery while the relay's driver circuits are located in the BEU. To energize a bypass relay, a series of three valid commands must be received through the MIL-STD-1553B serial data bus. This causes the bypass relay to energize, permanently bypassing the designated failed cell and allowing the battery to continue to operate.

The decision to energize a bypass relay is very critical. This decision is not made by the BEU. Instead, the cell voltage monitor measurements are sent by telemetry to a control location where the data is analyzed using algorithms developed by the battery user. If and when it is decided by the user that a particular cell should be bypassed, the three MIL-STD-1553B commands are sent to the BEU and the relay is energized.

The relay driver circuit is a very special circuit in the sense that it is designed to be *two-fault tolerant*. This means that no two failures can inadvertently cause a bypass relay to be energized. This includes any failure in the BEU's internal ASIC, its power supply, its voltage regulators and all other components in the BEU.

III Theory of Operation

The theory of operation is best understood by first considering a collection of lithium-Ion cells placed in the following arrangement.

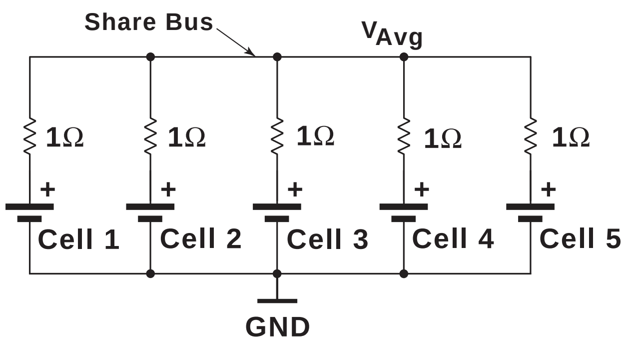


With a group of cells connected to the Share Bus through the current limiting resistors, the stronger cells with slightly higher voltage will transfer charge to the weaker cells with slightly lower voltage until finally all of the cells arrive at the same voltage and no currents flow in any cells.

This arrangement requires all of the cells to have a common ground. However, we need to do this sharing function with cells that do not share a common ground, but which are arranged instead in a series stack. This is done with bilateral converters as shown below:

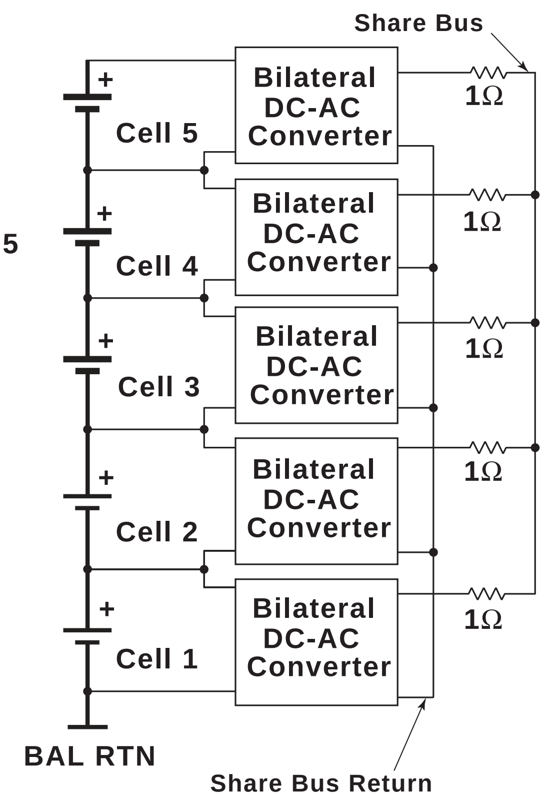
Cell Balancing by Share Bus

Cells Connected in Parallel



$$I_{Cell} = \frac{V_{Cell} - V_{Avg}}{1\Omega}$$

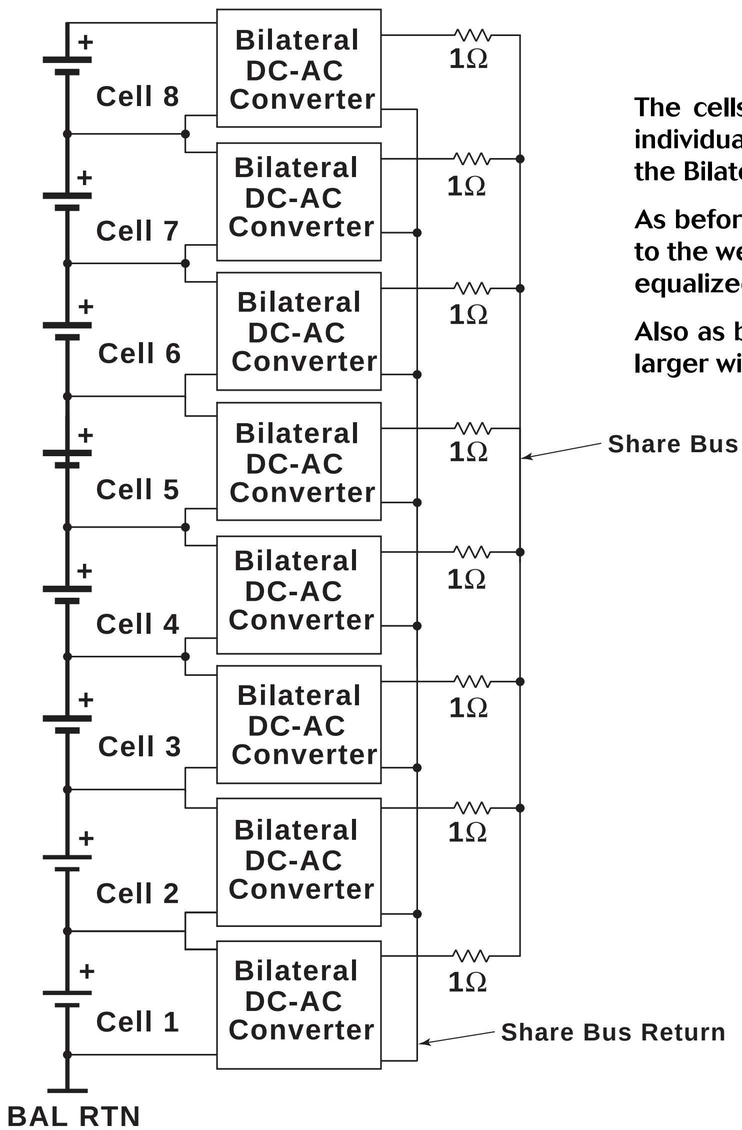
Cells Connected in Series



$$I_{Cell} = \frac{V_{Cell} - V_{Avg}}{1\Omega}$$

Any cell which has a voltage higher than the others will discharge into the lower cells via the Share Bus. The process will continue until all of the cells have the exact same voltage level and all of the circulating currents have become zero. This condition is called cell balance.

To form a battery, however, the cells must be arranged in a series stack. In that condition, the individual cells are treated as follows.



The cells shown this way form a battery whose individual cells are coupled into the Share Bus by the Bilateral DC-AC converters.

As before, each stronger cell will transfer charge to the weaker cells until all of the cells have been equalized.

Also as before, the number of cells can be made larger with no inherent limitations.

Each cell is connected to a bilateral DC-AC converter for connection to a Share Bus. Between any two cells, a pair of DC-AC converters operates as a bilateral DC-DC converter.

Each DC-AC converter is transformer-coupled to provide isolation between the battery cells and the Share Bus. This allows the Share Bus and the monitor circuits (which are connected to the Share Bus) to be connected to the ASIC and the logic circuits and the logic ground. Thus, the transformers also provide isolation between the battery and the logic circuits.

IV Glossary

A/D	Analog to Digital
BAL_RTN	Balance Return, the negative end of the lowest cell at the bottom of a battery.
BEU	Battery Electronics Unit (BEU) used for balancing cells within a battery.
Bilateral DC-AC Converter	A type of DC-AC converter in which energy transfer can be from inputted at one side (A) and outputted at the other side (B) or inputted at one side (B) and outputted at the other side (A).
Bilateral DC-DC Converter	A pair of bilateral DC-AC converters joined to each other at a Share Bus.
Bypass	A circuit provision made for removing from service a defective cell within a battery consisting of a stack of cells.
Cell Balance	The condition in which a collection of individual cells have been all brought to the same voltage.
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
MIL-STD-1553B	A dual redundant serial data bus operating at 1MHz. A military standard that defines the mechanical, electrical and functional characteristics of a serial data bus.
MUX	Multiplexer
Share Bus	A circuit node common to all of the cell circuits where a voltage is established that is equal to the average voltage of the individual cells serviced by the Share Bus.
SHARE_B_RTN	Share Bus Return. The common node to which the cell voltages, as reflected via the bilateral DC-DC converter, are referenced.
Triaxial	A specialized coaxial conductor arrangement, circular in cross-section and consisting of a center conductor separated by an insulating material from a concentric conductor which is in turn separated by an insulating material from a third conductor, concentric with the first two.

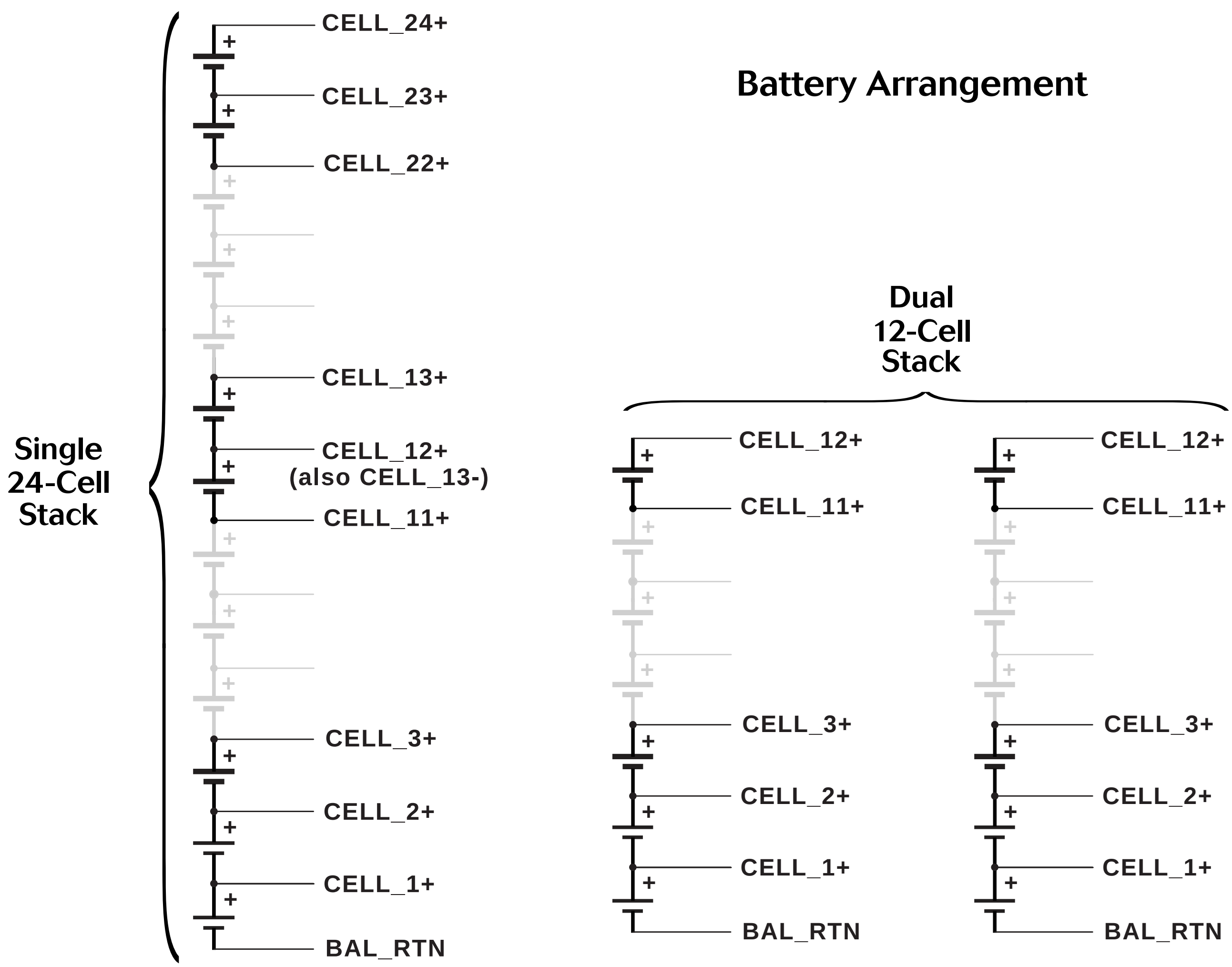
V Requirements

A Battery Configuration

The battery arrangement being serviced may be:

a) A single stack of up to twenty-four Lithium-Ion cells.
b) A pair of stacks of up to twelve Lithium-Ion cells each.
c) A single stack of up to twelve Lithium-Ion cells.

The first two of these arrangements are illustrated below:



A single stack can be made up of any number of cells up to the twenty-four cell maximum while the dual stacks can be made up of any number up to the twelve cell maximum.

Also, the two stacks of the dual arrangement can be a combination of different numbers such as nine cells in one stack and eleven cells in the other, six cells and ten cells, etc.

B Balancing

In operation, the cell balancing process acts on any one cell to bring that cell to equality with the average of all of the other cells in the battery. For a twenty-four cell battery, any one cell is acted upon to make its voltage equal to the average of the voltages of the other twenty-three cells. Each of the cells in the subject battery finds itself being drawn to equality with the average of all of the other cells.

The directions and the magnitudes of the individual currents are proportional to the deviations of the cell voltages from the average cell voltage. The transfer ratio of the difference between an individual cell's voltage and the average voltage of the remaining cells divided by the current into the individual cell is 1.0 ohm nominal and is satisfied for cell voltages of up to 4.2 volts.

C Monitoring

Each cell voltage is monitored by an A/D conversion process. Actual cell voltages are determined by comparison to a precise internal voltage reference of +4.000 volts. The voltage measurements of specific cells are available as data via the MIL-STD-1553B bus.

D Telemetry

a) MIL-STD-1553B

The MIL-STD-1553B dual redundant communications bus provides telemetry service which allows the user to read the values of the raw +4.000 volt BEU internal reference, the zero volt reference, total battery voltage with triple redundancy, each of the individual cell voltages, the highest cell voltage, the lowest cell voltage and the status of the Overvoltage (OVP) latch.

b) Digital Discrete

Three discrete logic outputs are provided for dedicated telemetry as follows.

1) OVP = Overvoltage protection, NPN open collector, active low.

   If any of the battery's cells exhibits a voltage in excess of a user specified overvoltage threshold, the OVP goes to active low saturation of its NPN open collector via 10 ohms and remains latched in that condition until reset by the user through the MIL-STD-1553B communications bus.

2) HIGH_CELL = High Cell, Controller Logic Output via 8.5 kohms.

   If any of the battery's cells exhibits a voltage greater than a user specified upper threshold, the HIGH_CELL goes to active high and remains there only for as long as the cell voltage remains above that threshold. It returns to active low if the responsible cell returns to below the upper threshold.

3) LOW_CELL = Low Cell, Controller Logic Output via 8.5 kohms.

   If any of the battery's cells exhibits a voltage lower than a user specified lower threshold, the LOW_CELL goes to active high and remains there only for as long as the cell voltage remains below that threshold. It returns low if the responsible cell returns to above the lower threshold.

E Power

a) Input Power From Mains

A single positive DC input is required of +22VDC to +36VDC with current requirements that vary from model to model.

b) Battery Power

BEU consumption of battery power is approximately 10 mA times the full battery voltage for each battery stack.

F Environmental

a) Temperature

Operating Temperatures

Space Grade: -34°C to +71°C.

Commercial Flow: 0°C to +70°C

Storage Temperatures: -34°C to +71°C.

b) Humidity

Operating Humidity is a maximum of 95% RH, non-condensing.

c) Positioning

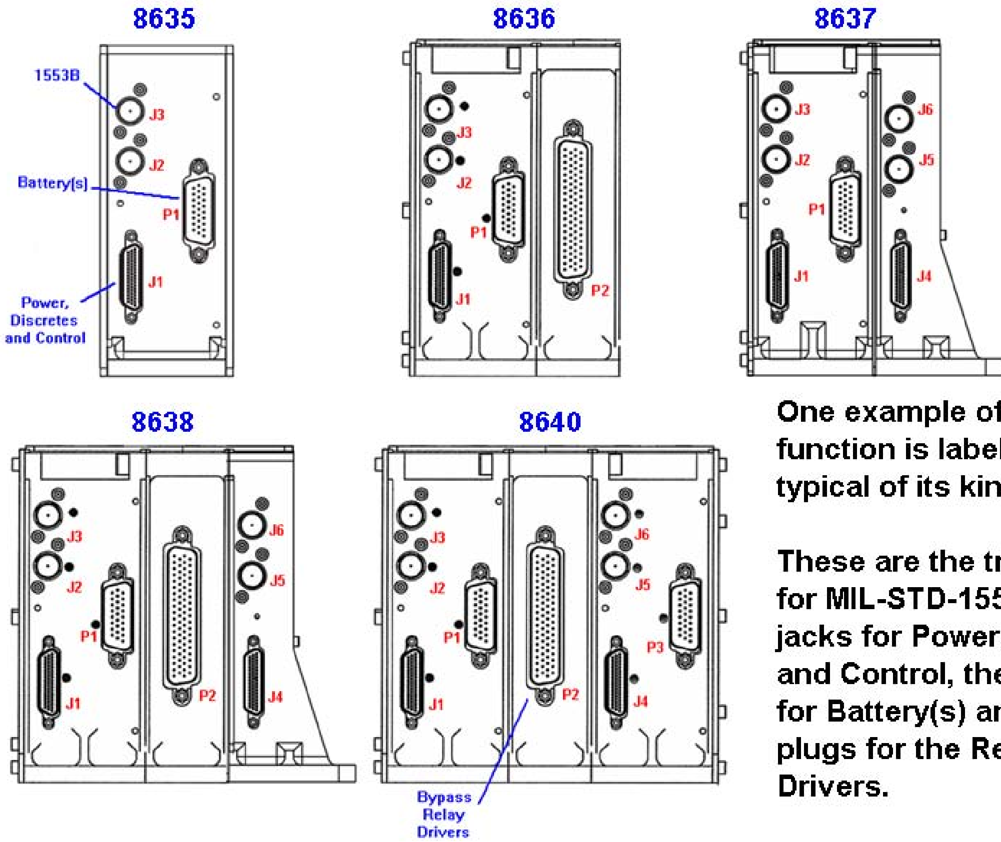
Operation is permitted in any position or orientation on any cold-plate surface within the specified range of operating temperatures.

d) Radiation

Operation is specified for up to 100 kRad(Si) total dose. Contact factory for further information.

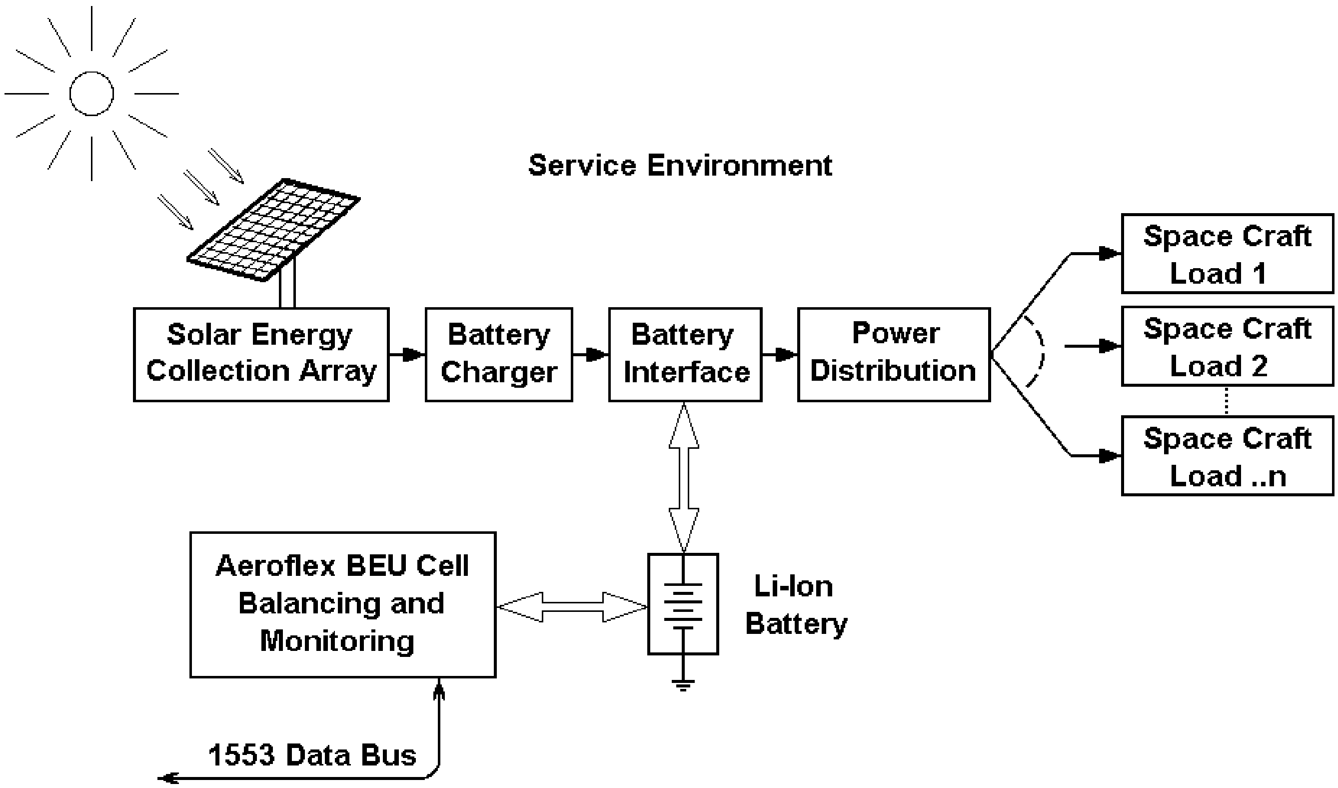
VI Input / Output Descriptions

The connector arrangements for each series are viewed as follows:



Each BEU uses a group of connectors for MIL-STD-1553B interface, battery connections, input power, discrete signals for control and monitoring and for the relay bypass function. In the above illustration, each annotation of those connectors is typical and is therefore shown only once for each type.

VII Typical Electrical Power Subsystem Architecture



Note that the BEU Cell Balancing and Monitoring is not a battery charger, but rather it redistributes charge among the cells of the Li-Ion Battery to bring those cells into voltage equality with each other.

As the BEU accomplishes that balance, the total energy of the Li-Ion battery is slightly depleted and must be eventually replenished with energy derived from the Battery Charger and the Battery Interface which are seen above as being a part of the Service Environment.

VIII Frequently Asked Questions (FAQ's)

a) How are Lithium-Ion batteries constructed?

Lithium-Ion batteries may be constructed in many different series-parallel arrangements. For example, one user constructs a 96-volt battery as follows:

Three (3) basic Lithium-Ion cells are connected in parallel to form a *Module*.

Two (2) Modules are connected in parallel to form a *Virtual Cell (VC)*.

Twelve (12) VC's are connected in series to form a *Pack*.

Two (2) Packs are connected in series to form the *Battery*.

The output voltage of a Cell, or a Module, or a VC is 4 volts

The output voltage of a Pack (12 VC's) is 48 volts.

The voltage of the Battery (2 Packs) is 96 volts.

This seems to be a complex arrangement, with a lot of terminology. Are all these terms necessary? The manufacturer of the cells fabricates the modules, and delivers them to the user. The user connects the modules to form VC's and packs, and then connects two Packs to form the battery. The terminology is their terminology, and we have to work with it.

b) So are we really balancing a cell, a module, a VC, or what?

Actually, in the above example, we are really balancing 24 groups of 6 cells (or 2 VC's). In other words, what we commonly refer to as "a cell" is really 6 *basic cells* in parallel. The key point to remember is that electrically, from the point of view of the balancing circuit, this composite is equivalent to a single 4-volt cell. We assume that the 6 basic cells are well matched and that they will eventually distribute their total charge among themselves because they are connected in parallel. Being in parallel, those 6 cells each effectively have their own local DC Share Bus that brings their own 6 basic cells into balance with each other which justifies thinking of the basic cells as "well matched".

c) What is the key point in matching a BEU to a battery?

The most important point is to determine how many cells are to be balanced among themselves. Or, how many cells should be connected to the same Share Bus? (A *cell*, in this sense, may be a single basic cell, or it may be a group of parallel basic cells.)

d) What is the relationship of Balancing and Monitoring and Telemetry?

Balancing is transferring charge between cells to equalize the cell voltages. *Monitoring* refers to *measuring* the voltage of each cell. Monitoring uses an internal A/D converter, and is similar to measuring each cell voltage with a DVM. In the BEU, the accuracy of this measurement is approximately 10 millivolts. *Telemetry* is the process of sending the monitor data to a remote location. In the BEU, the data is transferred on a MIL-STD-1553B serial data bus.

e) Some customers would like telemetry, but do not want MIL-STD-1553B. What can we do?

The present BEU was designed for MIL-STD-1553B applications, and takes advantage of our MIL-STD-1553B SμMMIT chip. However, many other data bus architectures are commonly used in various industries. If a new application is presented, Aeroflex can configure the telemetry portion of the BEU Control Card to work with any data bus architecture.

f) What about redundancy?

Two BEUs can be used on the same battery at the same time. If either one of the BEUs gets turned off for some reason, the other one will continue as before to provide cell balancing, monitoring and telemetry.

g) Is balancing a good idea for other types of batteries, such as NiCd (Nickel Cadmium) or NiMH (Nickel Metal Hydride) or even Lead-Acid?

Cell balancing will extend the life of any battery. It is particularly important for Lithium-Ion batteries, because Lithium-Ion batteries do not recover from overcharging (they may destruct catastrophically) or deep discharge (they may take days to recover, or they may permanently short). However, while other types of batteries do not exhibit these catastrophic failure mechanisms, there seems to be no doubt that their operating lifetimes would be significantly extended. The BEU can be used with any type of battery technology, even though the cell voltages may be 1.5 volts, 2.0 volts, or any other voltage.

h) If a BEU is designed to operate with 24 cells, can I use it with smaller batteries, such as 16 cells?

Yes. To use the 24-cell BEU with a 16-cell battery, just connect the battery to the lowest sixteen cell positions of the BEU and leave the eight remaining BEU cell positions open, that is, unconnected. The BEU will balance the battery's sixteen cells and at the same time, the BEU will bring those leftover cell positions to the same voltage as the average of those sixteen that are connected. Seventeen cells? Same thing. Leave the remaining seven BEU cell positions open and the BEU will balance everything in just the same way. Thirteen cells? Same thing. Twenty-three cells? Same thing. You can connect anywhere from two to twenty-four cells and balancing will be accomplished.

i) Does the BEU take its power from the battery that it is balancing?

Yes. The BEU does drain the battery with approximately 10 mA per stack. It does not charge the battery. The BEU takes current from cells that are above the average voltage to supply current to the cells that are below average. When all the cell voltages become equal, the cell currents are almost zero except for the aforementioned 10 mA. However, the BEU does require power from a source other than the battery, to operate the ASIC, the A/D, the MIL-STD-1553B telemetry, and other circuitry. This power varies somewhat, depending primarily on the duty cycle of the MIL-STD-1553B transmissions, but is typically a few watts. This power is taken from a 28 volt or 30 volt bus.

j) Are bypass relays a good idea?

The answer to this question is somewhat controversial. In general, manufacturers of cells maintain that bypass relays are unnecessary, because their cells are very reliable and are unlikely to fail in an open circuit condition. End users, however, tend to be more conservative, and may desire the protection provided by a bypass relay.

Another issue is the possibility that the bypass relay or its driver circuit may fail, and the bypass relay may become energized accidentally, e.g. by a circuit failure or an improper telemetry command. The BEU can be supplied with or without bypass relay drivers. If relays are used, the relays are located in the battery, and the driver circuits are located in the BEU. These relay driver circuits are *2-fault tolerant*, which means that no two component failures can possibly cause a bypass relay to turn on when it is not intentionally commanded to do so.

k) When the BEU is connected to a battery, in which the cells are initially out of balance, how long will it take for the battery to become balanced?

The time required for the battery to achieve balance depends on four factors:

The ampere-hour rating of the battery (measured in ampere-hours/volt)

The Transfer Ratio (RT) of the BEU (measured in ohms)

The initial imbalance voltage

The definition of "balance voltage" (typically 25 mV)

<u>Step 1</u>

The first step is to calculate the balance time constant τ. The balance time constant is the product of the ampere-hour rating and the Transfer Ratio. For example, a typical large battery may have an ampere-hour rating of 240 Ah for a change of 1.4 volts, or 171.4 Ah/volt. The BEU has a nominal RT of 1 ohm (the specified range of RT is 0.8 ohms to 1.39 ohms). Therefore,

$$\tau = (171.4 \text{ Ah/volt})\ (1 \text{ ohm}) = 171.4 \text{ hours}$$

This is interpreted as follows:

The time constant τ is the time required for the voltage to get to within approximately 36.8% of its final value, because this is an exponential function. As the time increases, the voltage gets closer and closer to its final value, as shown in the following table (assuming an initial imbalance voltage of 100 mV):

Number of Timte Constants (τ)	Elapsed Time	Imbalance Voltage
0	0 hours	100 mV
1	171.4 hours	36.8 mV
2	342.8 hours	13.5 mV
3	514.3 hours	4.98 mV
4	685.7 hours	1.83 mV
5	857.1 hours	0.67 mV

Step 2

The second step is to calculate the ratio of the starting voltage (V_{START}) to the desired balance voltage (V_{BAL}).

Step 3

We now enter τ and V_{START}/V_{BAL} into equation (1), which is as follows:

$$T_{BAL} = \tau \ln [V_{START}/V_{BAL}] \qquad (1)$$

where

T_{BAL} is the time to achieve the defined balance voltage
V_{START} is the initial imbalance voltage
V_{BAL} is the defined balance voltage
ln is the natural logarithm operator

Example 1

Let $V_{START} = 100$ mV
Let $V_{BAL} = 25$ mV
Let $\tau = 171.4$ hours

Then

$$T_{BAL} = (171.4 \text{ hours}) \ln 4 = (171.4 \text{ hours})(1.386) = 237.6 \text{ hours}$$

This means that it will take 237.6 hours for the cell voltage to drop from 100 mV (the initial imbalance voltage) to 25 mV (the defined balance voltage). Of course, as time goes on, the cell imbalance voltage will continue to drop exponentially. After an additional 237.6 hours, the imbalance voltage will be 6.25 mV.

Example 2

Now let us calculate T_{BAL} for a much smaller battery, in which the ampere-hour rating is 1 ampere-hour for a voltage drop of 1.2 volts.

Let $V_{START} = 100$ mV
Let $V_{BAL} = 25$ mV

Then

$$\tau = (1 \text{ ampere-hour}/1.2 \text{ volt})(1 \text{ ohm}) = (0.83 \text{ Ah/volt})(1 \text{ ohm}) = 0.83 \text{ hours}$$

$$T_{BAL} = \tau \ln [V_{START}/V_{BAL}]$$

$$T_{BAL} = (0.83 \text{ hours})(\ln 4) = 1.15 \text{ hours}$$

This demonstrates that the time to reach balance is directly related to the size (capacity) of the battery.

Example 3

What if we have a single battery, being balanced by two BEU slices (primary and redundant)? In this case, the Transfer Ratio of each slice is 1 ohm, so the parallel RT is 0.5 ohm.

Then

$$T_{BAL} = \tau \ln [V_{START}/V_{BAL}]$$

$$T_{BAL} = (171.4 \text{ Ah/volt})(0.5 \text{ ohm}) \ln (100 \text{ mV}/25 \text{ mV})$$

$$T_{BAL} = 118.8 \text{ hours}$$

Therefore, the balancing time is halved (see Example 1), which is to be expected.

Notes:

PLAINVIEW, NEW YORK
Toll Free: 800-THE-1553
Fax: 516-694-6715

INTERNATIONAL
Tel: 805-778-9229
Fax: 805-778-1980

NORTHEAST
Tel: 603-888-3975
Fax: 603-888-4585

SE AND MID-ATLANTIC
Tel: 321-951-4164
Fax: 321-951-4254

WEST COAST
Tel: 949-362-2260
Fax: 949-362-2266

CENTRAL
Tel: 719-594-8017
Fax: 719-594-8468

www.aeroflex.com info-ams@aeroflex.com

AEROFLEX
A passion for performance.

Our passion for performance is defined by three attributes represented by these three icons: solution-minded, performance-driven and customer-focused