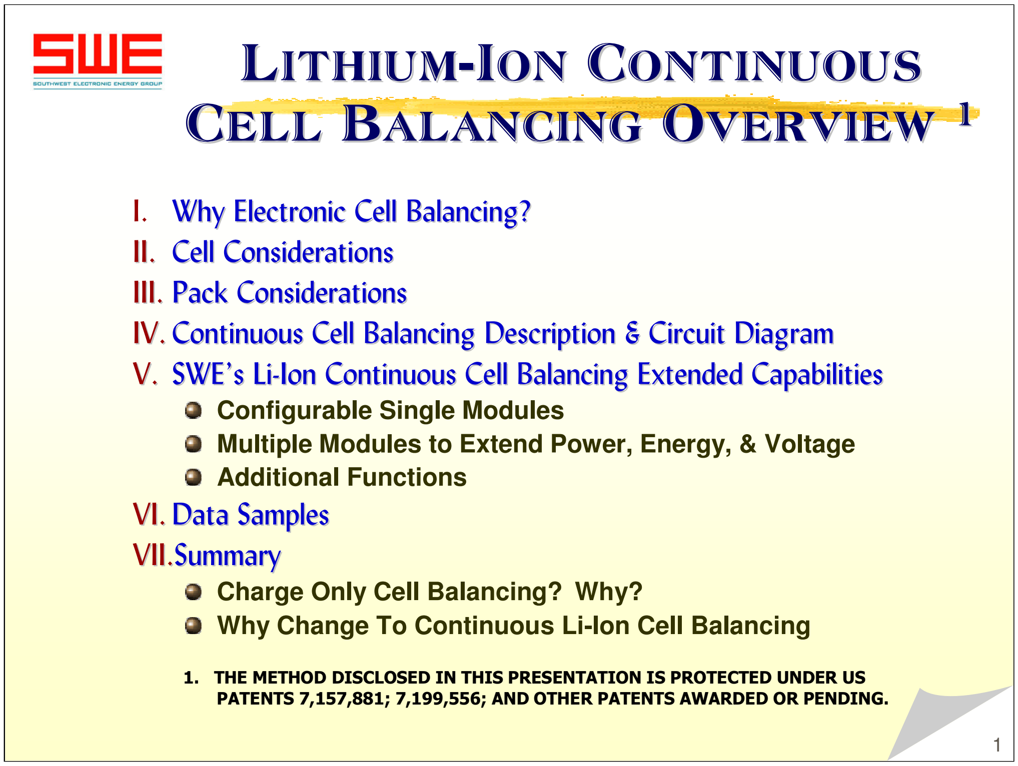


LITHIUM-ION CONTINUOUS CELL BALANCING OVERVIEW [1]

I. Why Electronic Cell Balancing?
II. Cell Considerations
III. Pack Considerations
IV. Continuous Cell Balancing Description & Circuit Diagram
V. SWE's Li-Ion Continuous Cell Balancing Extended Capabilities
  - **Configurable Single Modules**
  - **Multiple Modules to Extend Power, Energy, & Voltage**
  - **Additional Functions**

VI. Data Samples
VII. Summary
  - **Charge Only Cell Balancing? Why?**
  - **Why Change To Continuous Li-Ion Cell Balancing**

1. THE METHOD DISCLOSED IN THIS PRESENTATION IS PROTECTED UNDER US PATENTS 7,157,881; 7,199,556; AND OTHER PATENTS AWARDED OR PENDING.

OVERVIEW: This presentation will disclose a new method of balancing Li-Ion battery packs we call Continuous Cell Balancing. The method disclosed in this presentation is protected by US Patents already awarded or pending.

This presentation will cover the following:

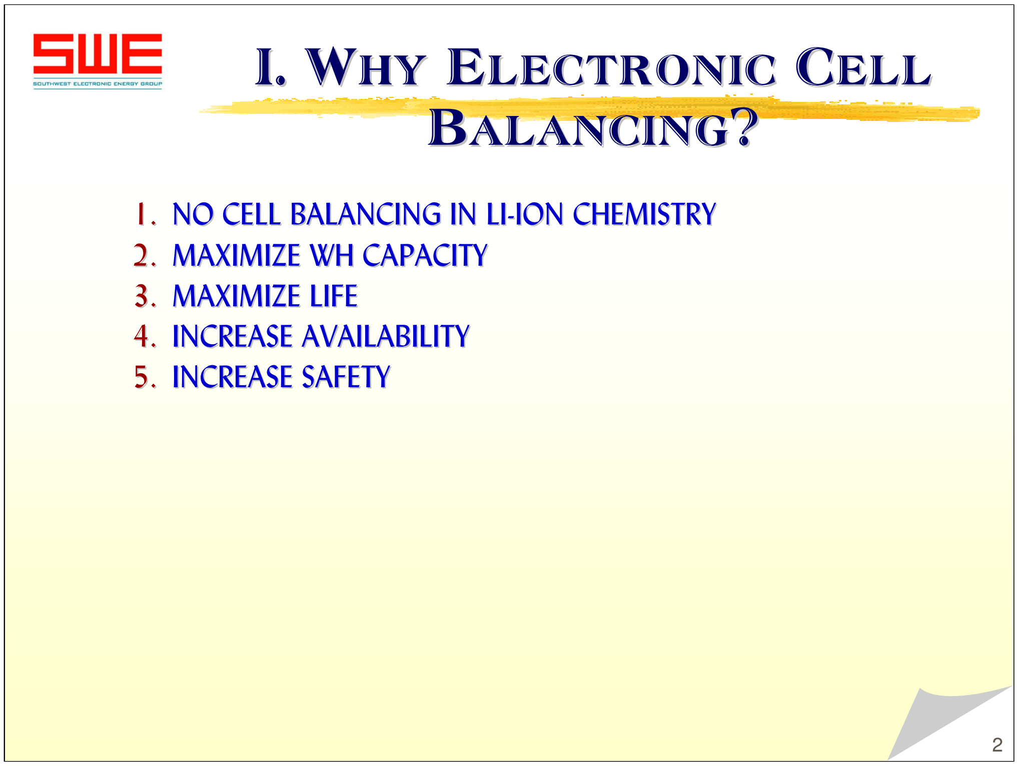
I. The presentation will begin with a review of the need for balancing a Li-Ion battery pack.

II. & III. The pack manufacturer and user need to understand their cells, their pack design, and their particular application to make sure that the cell balancing design being implemented will be effective. We'll review some of the cell and pack features that should be considered when evaluating the potential effectiveness of a particular cell balancing implementation.

IV. & V. We'll show a simple, modular, circuit design to implement continuous discharge cell balancing and show how this approach can be used in single module applications and how multiple modules can be combined to extend battery pack energy, power, and voltage while retaining cell balancing capability. The modular implementation lends itself to functionality expansion as well and we will discuss a few of these.

VI. We'll take a look at several data samples that show development and successful implementation of the continuous balancing concept using the modular design approach. - The data will show that limiting cell balancing to a charge-only activity is so restrictive that it poses risks to pack life, mission success, battery availability, and safety.

VII. In summary, we will discuss why charge-only cell balancing has been used. Then we will discuss why it's needed to make a paradigm shift to continuous cell balancing.



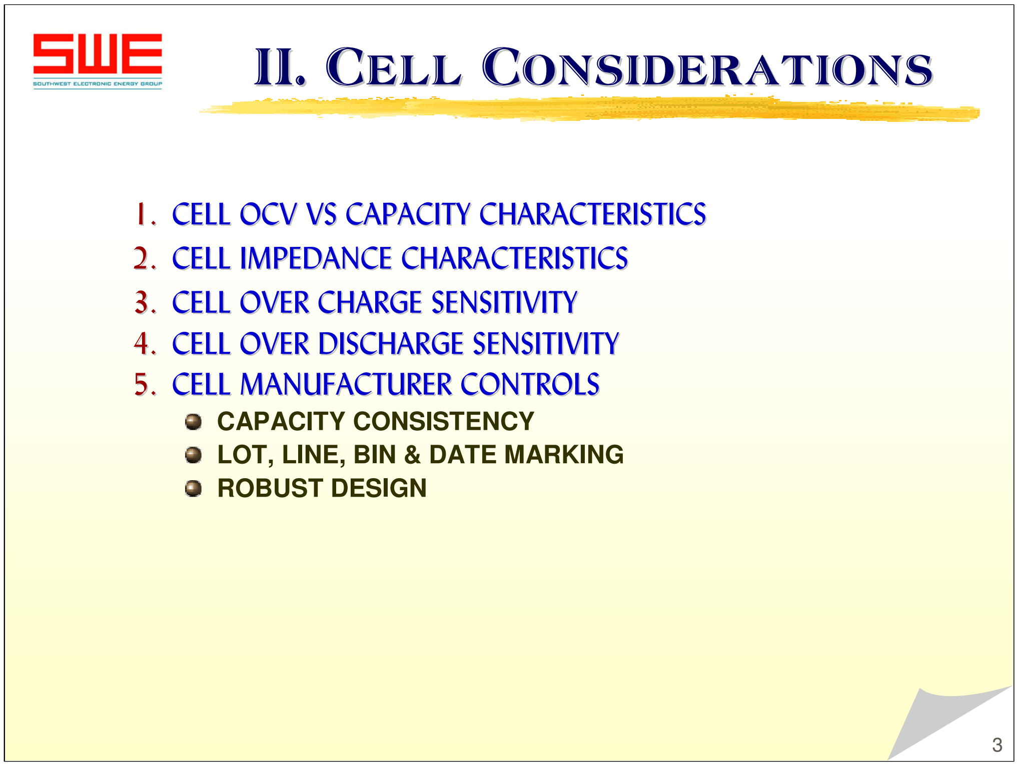
I. WHY ELECTRONIC CELL BALANCING?

1. NO CELL BALANCING IN LI-ION CHEMISTRY
2. MAXIMIZE WH CAPACITY
3. MAXIMIZE LIFE
4. INCREASE AVAILABILITY
5. INCREASE SAFETY

1. Most rechargeable cell chemistries have cell balancing built into their chemistry. When you charge the conventional cell, it will charge up to full capacity then it will convert additional charge energy to heat. If a battery pack made up of several series connected cells is charged, the pack automatically balances at the end of the charge cycle when given an overcharge. This capability is not built into the Li-Ion cell chemistry. When it is overcharged, the cell can be damaged, resulting in a potential safety hazard.

Other reasons to balance a battery pack consisting of series connected cells are pretty obvious:

2. Balancing a battery pack will result in maximizing its capacity.
3. A balanced battery pack is less likely to expose cells to damage at the end of discharge and at the end of charge; thus, maximizing its life.
4. A balanced battery pack means that, with one single charge, the pack is always available to deliver its expected amount of energy - every time - all the time.
5. For Li-Ion, a balanced pack means that unbalanced cells are not continuously overcharged; thus, the safety hazards associated with continuous over charge - even slight continuous overcharge - are reduced.



II. CELL CONSIDERATIONS

1. CELL OCV VS CAPACITY CHARACTERISTICS
2. CELL IMPEDANCE CHARACTERISTICS
3. CELL OVER CHARGE SENSITIVITY
4. CELL OVER DISCHARGE SENSITIVITY
5. CELL MANUFACTURER CONTROLS
    - CAPACITY CONSISTENCY
    - LOT, LINE, BIN & DATE MARKING
    - ROBUST DESIGN

When designing a cell balancing system, the choice of cells used will affect the setting of balancing parameters, constraints, and effectiveness.

1. As will be shown later, Li-Ion OCV can be used to determine charge capacity and relative cell balance. The relationship of OCV VS Capacity is different for different Li-Ion chemistries. New Li-Ion chemistries are continually being developed. It is important that the OCV VS capacity of these new chemistries is understood and can be incorporated into the balancing algorithm.

2. As the data will show, cell impedance, especially differential Diffusion and Charge Transfer impedances will determine the limit of charge or discharge current that can be flowing through the battery for valid differential balancing measurements.

3. Cell sensitivity to overcharge affects safety circuit settings, system balancing current requirements, and balancing parameter settings. Continuous overcharge on sensitive cells can become a safety concern.

4. Cell sensitivity to over discharge also affects safety circuit settings and balancing parameter settings. Excessive over discharge on sensitive cells can result in dendrite growth near cell separator which can become a safety concern should the dendrite puncture the cell separator.

5. Good cell manufacturer quality controls are important for cell selection and are usually evidenced by:

•Cell to cell capacity matching & binning and capacity consistency

•Lot, line, bin, and date marking & tracking

•Design robustness as evidenced by qualification tests such as UL1642 or the like

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III. PACK CONSIDERATIONS

1. DESIGN AND USE
   - CURRENT PATH SYMMETRY
   - DIFFERENTIAL LEAKAGE PATHS
   - ENVIRONMENT
   - CAPACITY (AH & VOLTAGE)
   - POWER
   - LONGEVITY REQUIREMENTS
   - AVAILABILITY REQUIREMENTS
   - SAFETY
   - COST
   - DEVELOPMENT TIME
2. MANUFACTURING QUALITY
   - CELL SORTING/MATCHING
   - WELD & SOLDER QUALITY CONTROLS
   - HANDLING & TESTING

1. Battery pack design is usually a collaborative effort between the pack supplier engineers and their customers. The need for, and effectiveness of, the cell balancing system should factor in design constraints such as:

•Current path symmetry.

•Potential differential leakage paths -> which can lead to cell imbalance.

•Environment -> hot, cold, humidity/condensation, and differential heat & cooling – which can also lead to cell imbalance.

•Capacity - A higher capacity pack will typically require more balancing capability.

•Power - As we will see, high power charge and discharge can affect the ability to obtain needed balancing parameters.

•Longevity - Balancing increases pack longevity.

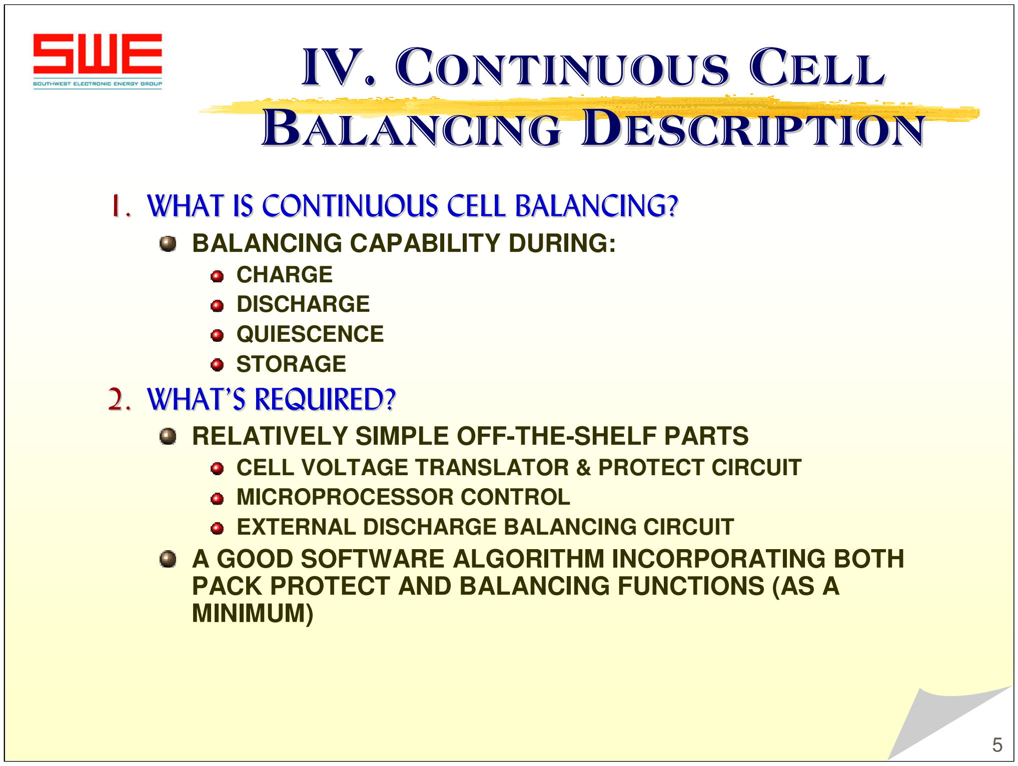
•Availability -> How you do balancing is critical to this! Continuous cell balancing maximizes pack availability.

•Safety - A balanced pack is a safer pack. The longer the pack is out of balance during charge/discharge cycles the more likely overcharge risks can happen.

•Cost - This is always a trade-off.

•Development time - Time is money and time to market can mean gaining or losing opportunity. The cell balancing method needs to be easily customized to different battery pack designs.

2. Pack manufacturers are concerned with Quality and how to get there. A well designed balancing system should consider and support this.



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IV. CONTINUOUS CELL BALANCING DESCRIPTION

1. WHAT IS CONTINUOUS CELL BALANCING?
   - BALANCING CAPABILITY DURING:
     - CHARGE
     - DISCHARGE
     - QUIESCENCE
     - STORAGE
2. WHAT'S REQUIRED?
   - RELATIVELY SIMPLE OFF-THE-SHELF PARTS
     - CELL VOLTAGE TRANSLATOR & PROTECT CIRCUIT
     - MICROPROCESSOR CONTROL
     - EXTERNAL DISCHARGE BALANCING CIRCUIT
   - A GOOD SOFTWARE ALGORITHM INCORPORATING BOTH PACK PROTECT AND BALANCING FUNCTIONS (AS A MINIMUM)

We are proposing that continuous cell balancing is a better system than what is predominantly in use - which appears to be balancing only during charge.

1.What do we mean when we say continuous cell balancing?

Simply, Continuous cell balancing is the ability to perform cell balancing during all battery modes including:

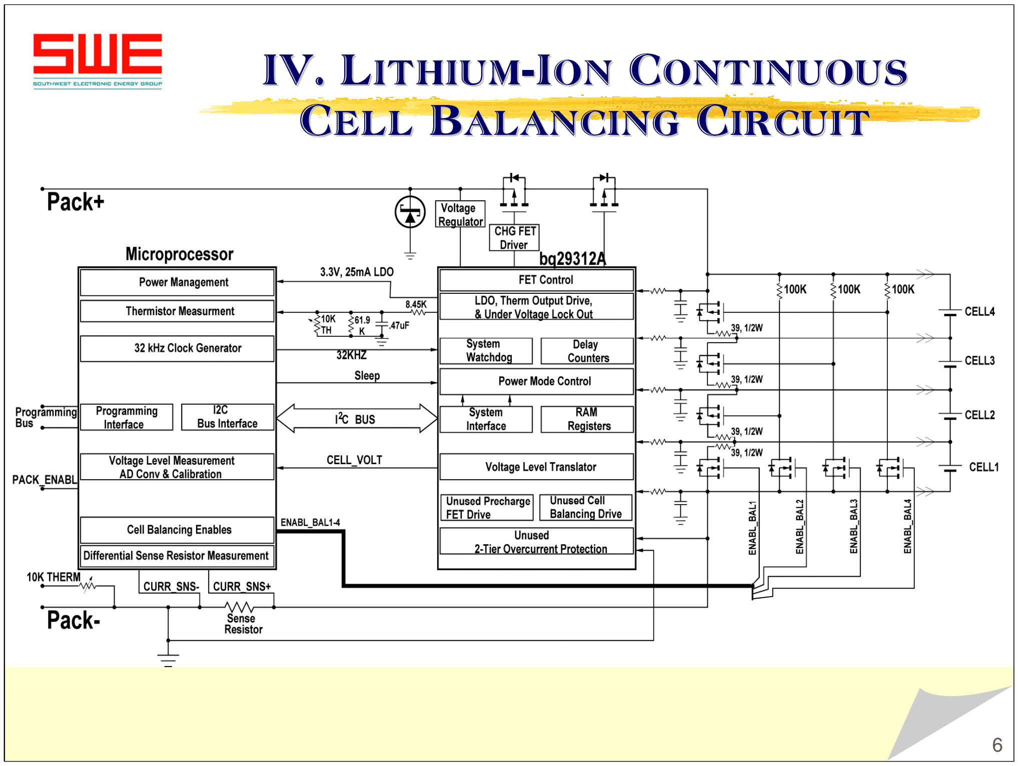
a. Charge

b. Discharge

c. Quiescence - When the battery is installed but is drawing or being supplied little or no current.

d. Storage - When the battery is not installed but is being stored and needs to be ready for use immediately when installed.

2.What's required to implement continuous cell balancing? - > <Read slide item # 2>



IV. LITHIUM-ION CONTINUOUS CELL BALANCING CIRCUIT

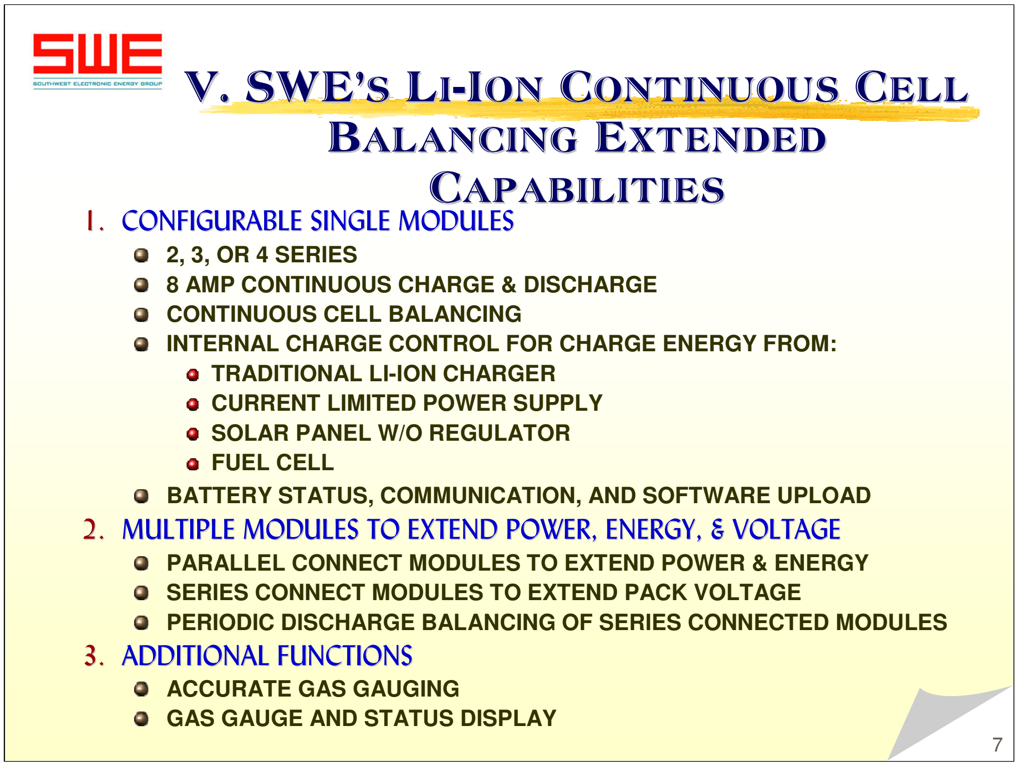
The following makes up a basic battery pack module:

Point out basic features:

- Microprocessor
- Voltage Translator
- External Discharge Balancing Circuit
- Charge & Discharge FETs
- Cells -> 2, 3, or 4 series (4 series is shown)

Point out additional features:

- Back biased diode to allow maintenance balancing of multiple series connected modules.
- Voltage regulator to allow high voltage packs using multiple series connected modules.



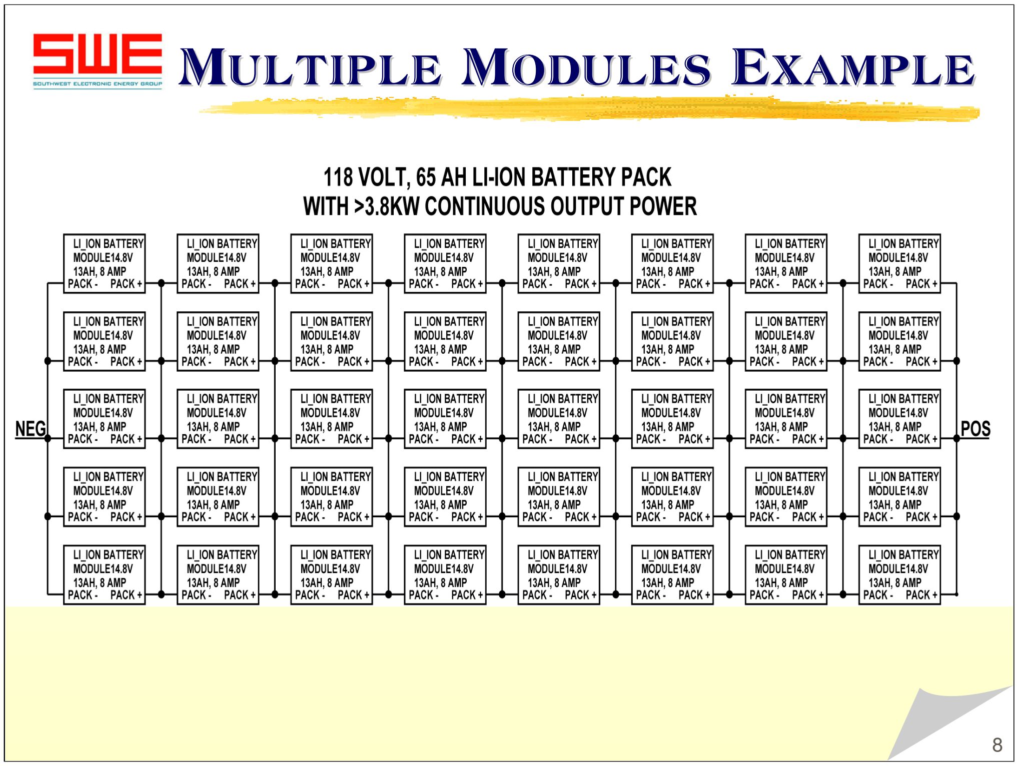
V. SWE's Li-Ion Continuous Cell Balancing Extended Capabilities

1. CONFIGURABLE SINGLE MODULES
   - **2, 3, OR 4 SERIES**
   - **8 AMP CONTINUOUS CHARGE & DISCHARGE**
   - **CONTINUOUS CELL BALANCING**
   - **INTERNAL CHARGE CONTROL FOR CHARGE ENERGY FROM:**
     - **TRADITIONAL LI-ION CHARGER**
     - **CURRENT LIMITED POWER SUPPLY**
     - **SOLAR PANEL W/O REGULATOR**
     - **FUEL CELL**
   - **BATTERY STATUS, COMMUNICATION, AND SOFTWARE UPLOAD**
2. MULTIPLE MODULES TO EXTEND POWER, ENERGY, & VOLTAGE
   - **PARALLEL CONNECT MODULES TO EXTEND POWER & ENERGY**
   - **SERIES CONNECT MODULES TO EXTEND PACK VOLTAGE**
   - **PERIODIC DISCHARGE BALANCING OF SERIES CONNECTED MODULES**
3. ADDITIONAL FUNCTIONS
   - **ACCURATE GAS GAUGING**
   - **GAS GAUGE AND STATUS DISPLAY**

Basic Module capabilities of an implementation of the circuit previously shown: <read slide> add -> Configuration tables allow pack customization speeding development time.

Extended capabilities using multiple modules: <read slide> . SHOW PCB ASSY.

Coming: <read slide> add -> This design is complete and checkout has started.



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MULTIPLE MODULES EXAMPLE

118 VOLT, 65 AH LI-ION BATTERY PACK
WITH >3.8KW CONTINUOUS OUTPUT POWER

This slide shows an example of how multiple modules can be connected to increase power, capacity, and voltage.

A prototype of this battery pack has been constructed and tested with the listed characteristics.

Other characteristics of this battery pack include:

A. Inherent redundancy – if a module fails, 80% capacity is retained; it is possible that failure of as many as 8 modules would still result in 80% capacity retention.

B. Internal Charge Control – The battery pack modules have internal charge control and can be connected to

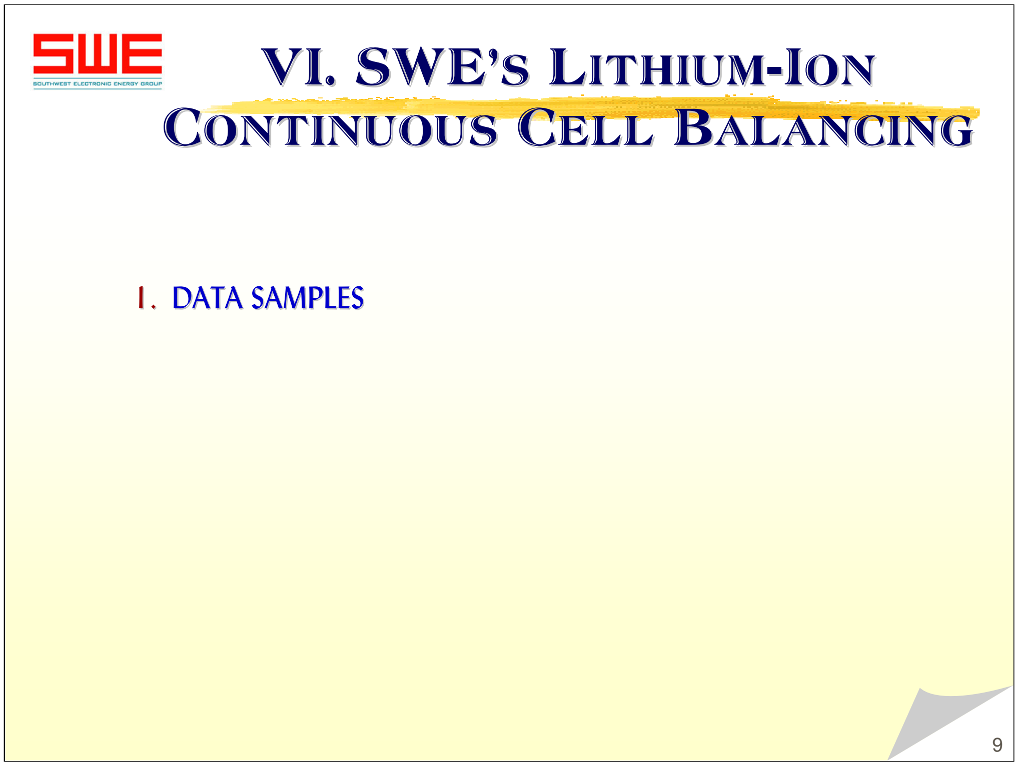
1) a current limited power supply,
2) a current limited fuel cell, or
3) a diode protected solar panel

and it will charge itself without the need for a special Li-Ion charger.

C. Charge and Discharge Safety Redundancy – Since safety circuits are series connected, there is inherent redundancy in ability to shut down the battery pack due to over charge, over discharge, or over current.

D. Automatic Module Balancing of parallel connected sections.

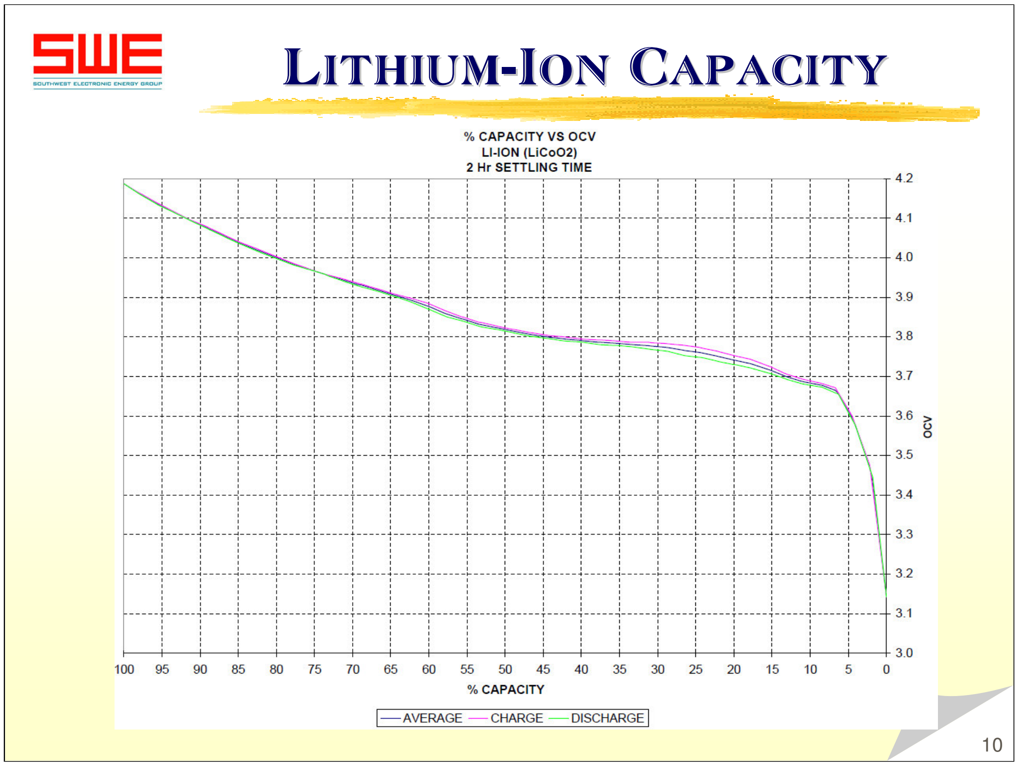
E. Module Balancing of series connected sections via a maintenance discharge of the battery pack recommended every 6 months to 1 year.



VI. SWE’S LITHIUM-ION CONTINUOUS CELL BALANCING

1. DATA SAMPLES

Data Samples taken before, during, and at end of the continuous cell balancing development process.

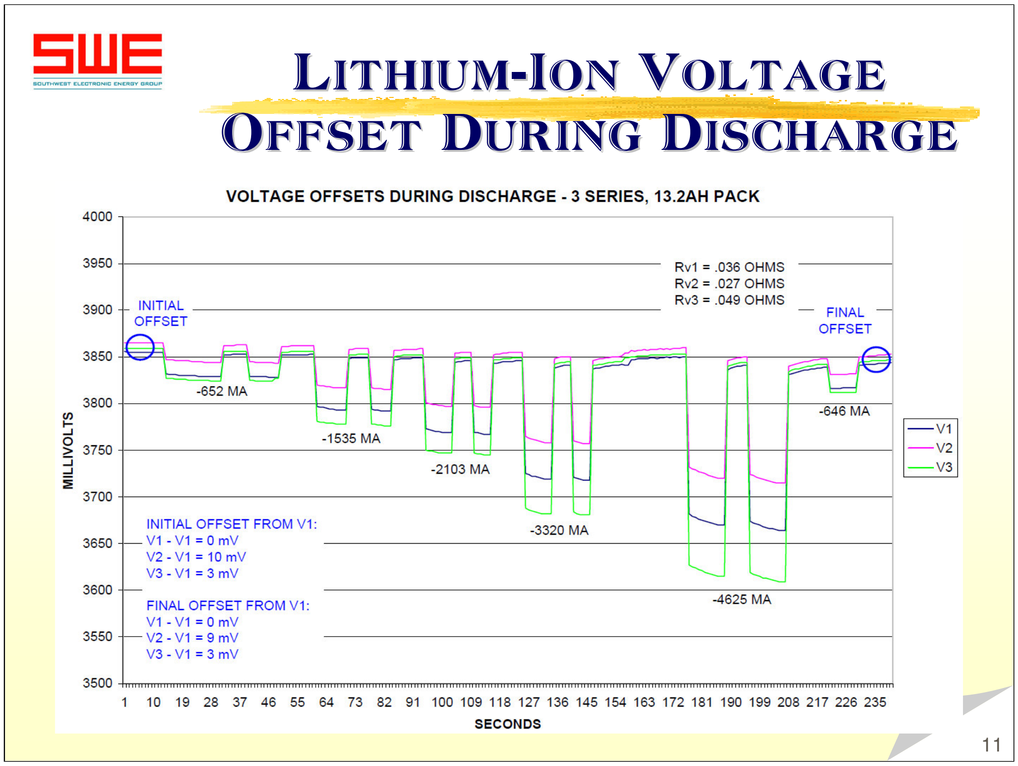


LITHIUM-ION CAPACITY

Early on in the project, data was taken to characterize a Li-Ion, LiCoO2, cell’s relative capacity VS OCV. This is the result of that characterization.

Notice that data was taken as the cell was charged and also as it was discharged. Charging and discharging was done in equal value current pulses each followed by a 2 hour wait time before recording the data.

It was verified over many different packs that OCV very accurately represents capacity.



LITHIUM-ION VOLTAGE OFFSET DURING DISCHARGE

This slide shows a fairly large 13.2AH, 3 series battery pack module at about a 60% charge level.

The initial voltages of the cells are OCV readings taken prior to the discharge experiment shown.

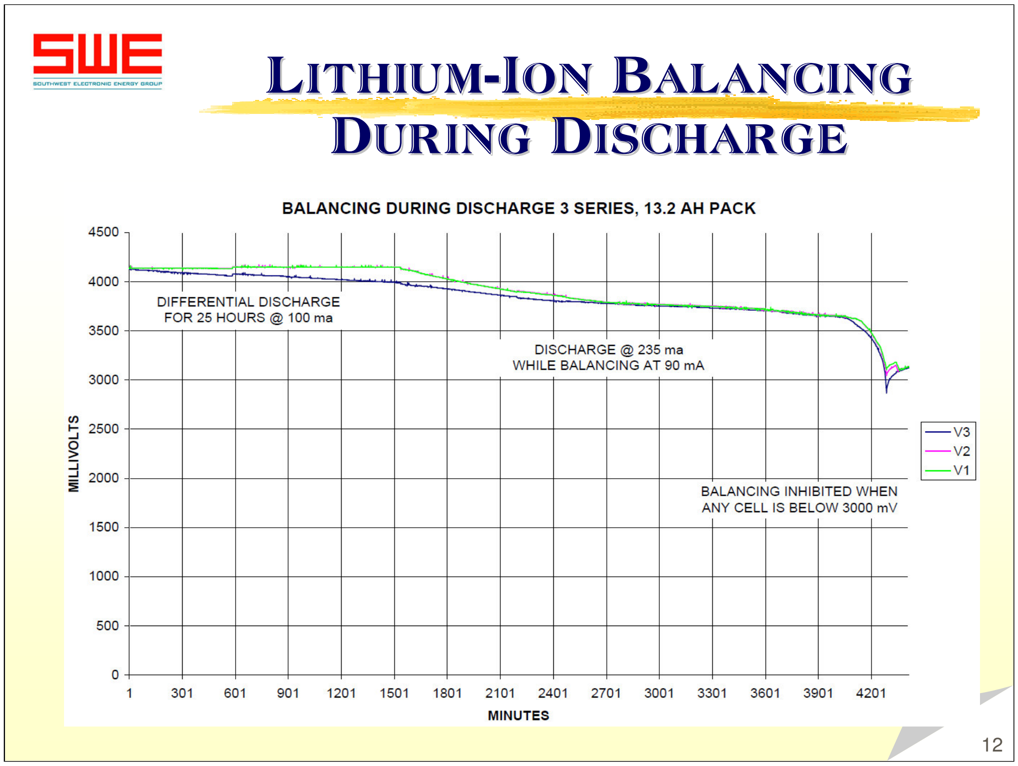
Notice that there is an initial offset difference in the cell voltages that represents an imbalance of these cells. The voltage difference at this level of charge is very small and illustrates the accuracy needed to obtain imbalance measurements.

This battery pack is shown being pulsed with varying amounts of discharge current.

Notice that, due to internal resistance associated with the diffusion and charge transfer impedances, voltage offsets are significantly larger as current increases. These voltage offsets are associated with the differing diffusion and charge transfer rates of the series connected cells NOT the cells' relative state of balance. During high discharge currents, relative state of balance is overwhelmed by these impedances. Relative state of balance information is lost and can even be misleading -> Notice voltage difference reversal of V1 and V3 during discharge that could lead to incorrect cell balancing information.

Also notice that relative state of balance information is accurately available almost immediately after the current pulse is turned off.

Never-the-less, at low enough discharge currents, it may still be possible to obtain useful relative state of balance information as shown on the next slide.



LITHIUM-ION BALANCING DURING DISCHARGE

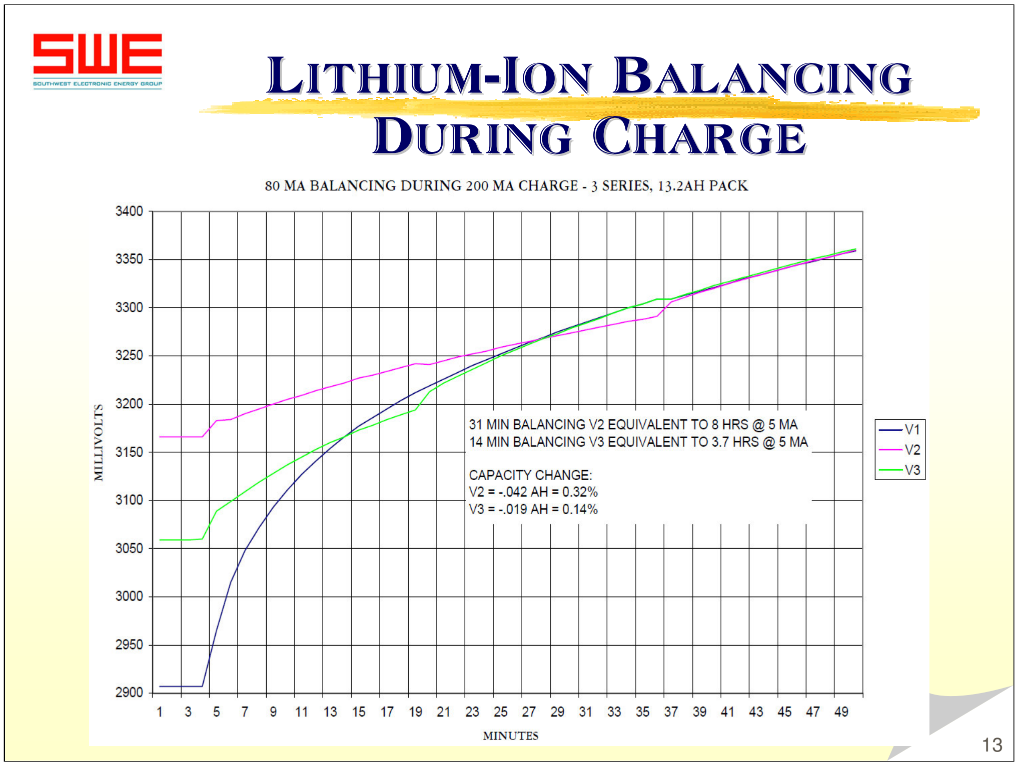
Shown is the same previous battery pack at an earlier time when we seriously differentially discharged V3 by 2.5 AH (about 20% of the capacity of the other series connected cells). Balancing was turned off during this discharge.

At the end of the 25 hour unbalancing operation, we turned balancing on and simultaneously began discharging the battery pack at 235 mA. Balancing of V1 and V2 began immediately at about 100mA balancing current for each.

Notice that even during this discharge, the pack is noticeably able to come into balance - but not perfectly. Once obtaining balance, balancing stops and the pack cells discharge together.

Notice that near the end of discharge where voltage VS capacity differences are large, a slight imbalance is still observed. At this point, balancing of V1 & V2 starts again but is terminated automatically when V3 goes below 3V.

The discharge current was turned off and the pack voltage began to relax with all cell voltages going above 3V. At this point notice that cell balancing began again until the pack was balanced.



LITHIUM-ION BALANCING DURING CHARGE

80 MA BALANCING DURING 200 MA CHARGE - 3 SERIES, 13.2AH PACK

31 MIN BALANCING V2 EQUIVALENT TO 8 HRS @ 5 MA
14 MIN BALANCING V3 EQUIVALENT TO 3.7 HRS @ 5 MA

CAPACITY CHANGE:
V2 = -.042 AH = 0.32%
V3 = -.019 AH = 0.14%

Remember the 2nd data slide where we showed a slightly unbalanced pack whose balance voltage differences were 3mV and 10mV for V3 and V2, respectively?

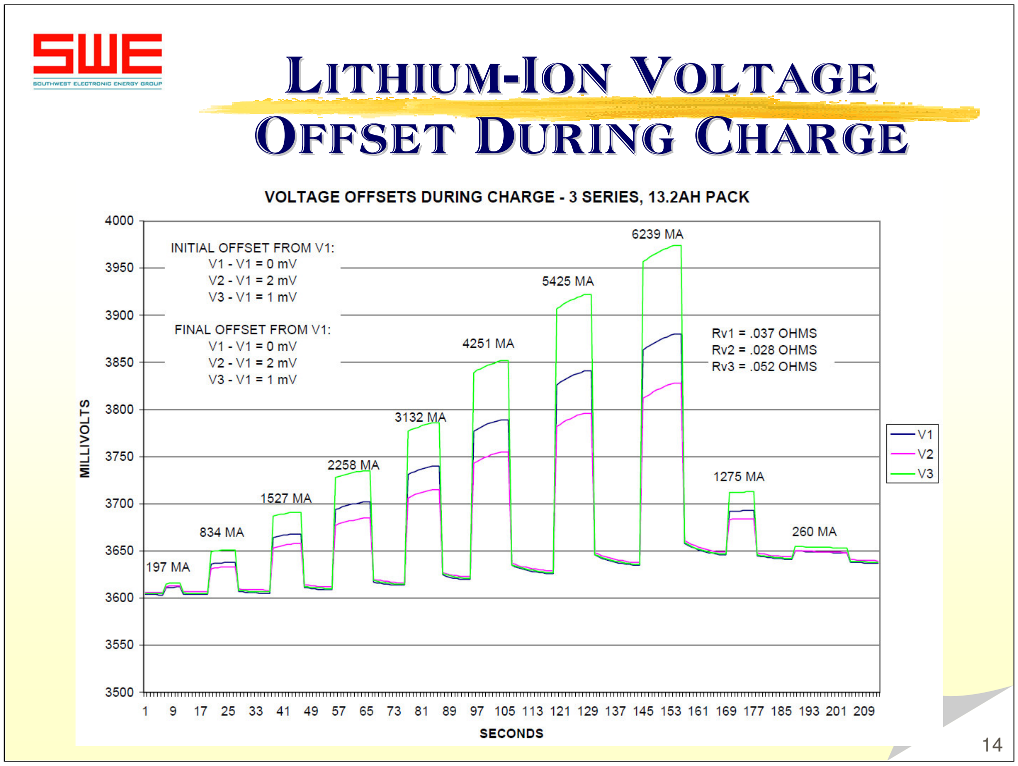
This is the same pack at a later time after discharging it to almost 0% capacity with balancing turned off.

Notice how the 3mV & 10mV voltage differences of the unbalanced cells has spread to over 100 mV and 250mV for V3 and V2, respectively.

At the 4 minute mark on this slide the discharged battery pack begins to charge at 200 mA with balancing now enabled. You can see first, V3 coming into balance with V1, and finally, V2 coming into balance with both V1 and V3. The balancing took 14 minutes and 31 minutes, respectively, using 80mA discharge balancing current. The imbalance was only 19mAh and 42mAh, respectively.

Notice in the comments on the graph that if one was doing internal balancing at 5mA, the time to correct this small amount of imbalance would have been 8 hours if the balancing were active 100% of the time. However, it is more typical of some charge balancing algorithms that balancing is not active 100% of the time but only 30% of the time resulting in a correction of this small amount of unbalance requiring more than 26 hours to correct the imbalance that was accomplished here in 31 minutes!

Putting this in perspective and assuming a full charge time of 2.6 hours, the low current, internal balancing only during charge would have required over 10 full charge/discharge cycles (about 50 charge/discharge cycling hours) to obtain balance of even this very small amount of imbalance.



LITHIUM-ION VOLTAGE OFFSET DURING CHARGE

The same battery pack as the previous slide was subsequently charged to about 5% capacity and then pulses of charge current were delivered to it at gradually increasing current levels.

Notice that both initial and final voltage offsets are very small indicating that this pack is virtually perfectly balanced.

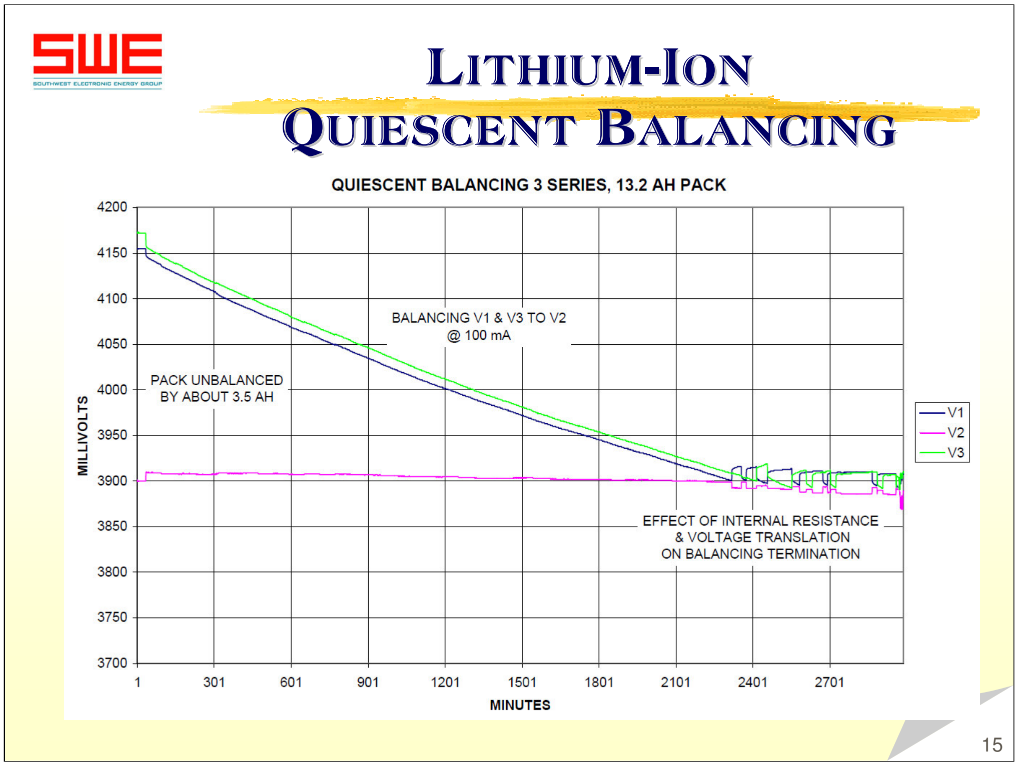
Also notice that when increasingly larger charge currents are delivered to the battery pack, there is an increasingly larger voltage difference in the cells. This voltage differential is not imbalance but is almost solely a result of the diffusion and charge transfer impedance differences.

The highest charge rate shown is 6.24A which is about a C/2 rate - a normal charge current for a pack of this size.

The information needed for controlling balancing during a normal level of constant charge of the battery pack is virtually swamped out by the diffusion and charge transfer impedances whose relative values are not related to the state of balance of the battery pack.

It appears that the only way to obtain information related to state of balance is to reduce or stop the charge current. When current is stopped you can see that relative state of balance is almost immediately available from the cells' relative voltage readings.

On a pack of this size, normal charge current would be about 6.6 Amps and charge termination current would be about 300 to 600 mA. The majority of charge time at 6.6 Amps provides little direct relative balance information from reading cell voltage. It appears that unless charge current is really very low, it is not a very good idea to be balancing during charging!



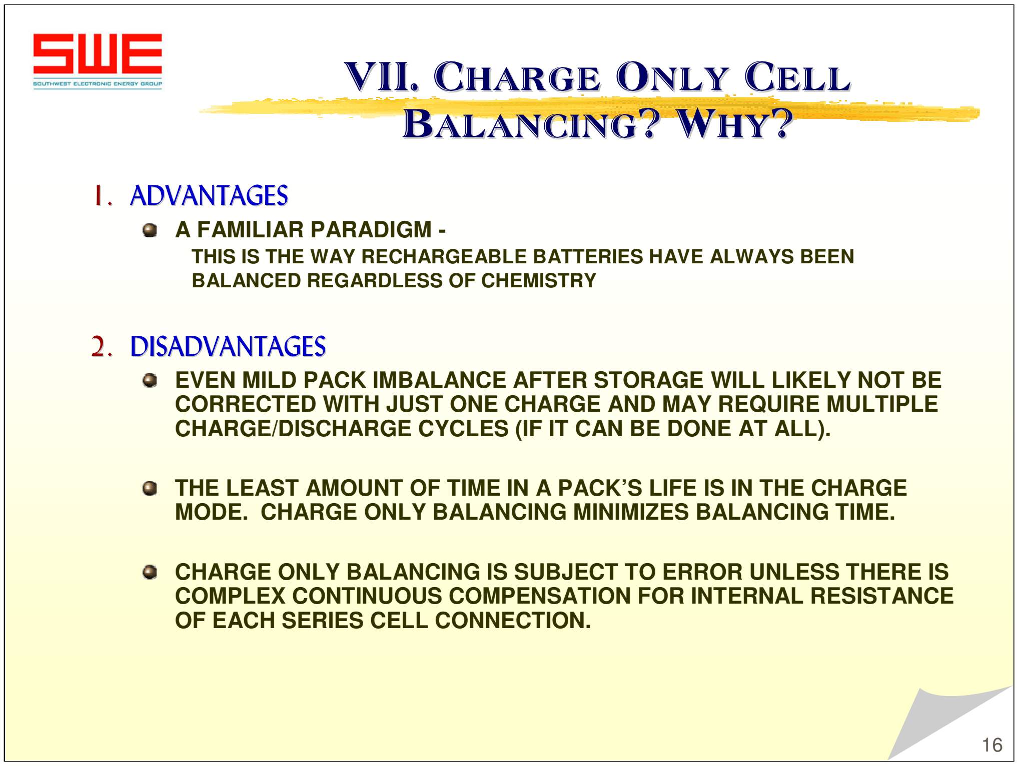
LITHIUM-ION QUIESCENT BALANCING

QUIESCENT BALANCING 3 SERIES, 13.2 AH PACK

The previous pack at an earlier time was fully charged and then V2 was differentially discharged with balancing turned off to severely unbalance the battery pack by a little more than 3.5AH. - Over 25% of pack capacity!

Balancing was turned on and the pack was rebalanced at about 100 mA of balancing current. This large amount of unbalance required over 35 hours but would have been virtually impossible using any other method.

Notice at the end of the balancing experiment that balancing was stopped when the voltage of the cell being discharged was equal to the voltage of the cell it was being balanced to. Notice the effect of cell internal resistance combined with effects of the voltage translation circuit prevents the cell from coming fully into balance. This problem has been solved. Recall that on a previous slide showing cell balancing during charging, when balancing was stopped, the result was almost a perfect balance. The data for that slide was obtained at a later time in algorithm development after this balancing termination problem had been solved.



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VII. CHARGE ONLY CELL BALANCING? WHY?

1. ADVANTAGES
   - A FAMILIAR PARADIGM -
     THIS IS THE WAY RECHARGEABLE BATTERIES HAVE ALWAYS BEEN BALANCED REGARDLESS OF CHEMISTRY
2. DISADVANTAGES
   - EVEN MILD PACK IMBALANCE AFTER STORAGE WILL LIKELY NOT BE CORRECTED WITH JUST ONE CHARGE AND MAY REQUIRE MULTIPLE CHARGE/DISCHARGE CYCLES (IF IT CAN BE DONE AT ALL).
   - THE LEAST AMOUNT OF TIME IN A PACK'S LIFE IS IN THE CHARGE MODE. CHARGE ONLY BALANCING MINIMIZES BALANCING TIME.
   - CHARGE ONLY BALANCING IS SUBJECT TO ERROR UNLESS THERE IS COMPLEX CONTINUOUS COMPENSATION FOR INTERNAL RESISTANCE OF EACH SERIES CELL CONNECTION.

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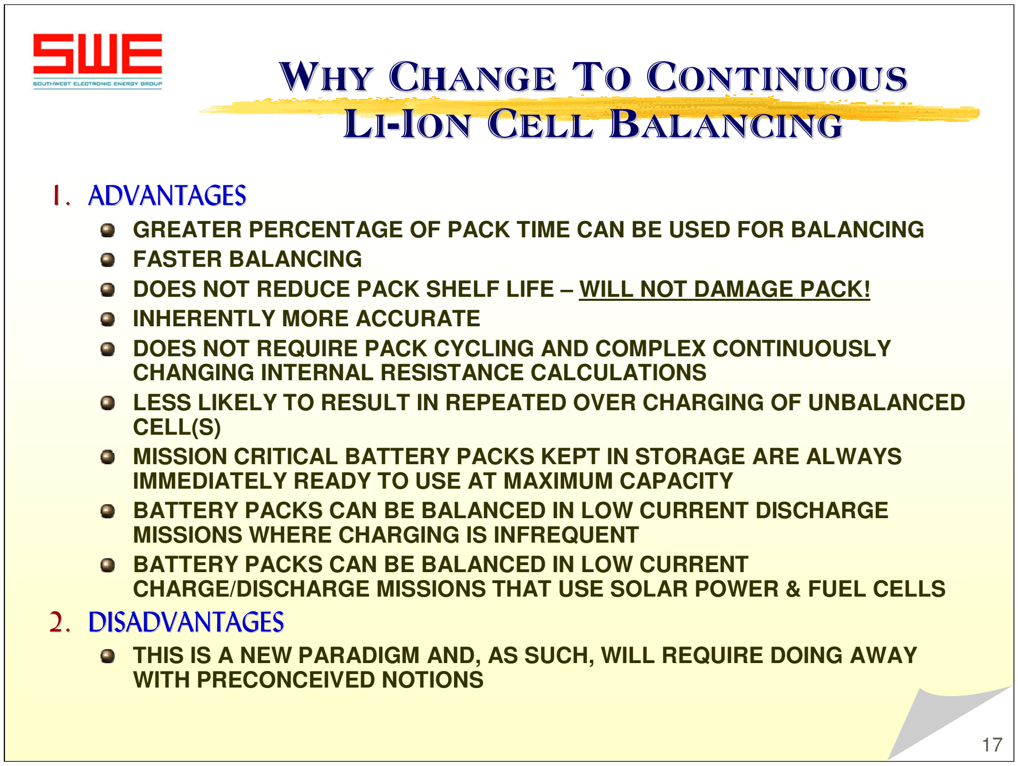
1. Given the data on the previous slides it is hard to understand why cell balancing only during charging or, in earlier implementations, only at the very end of charging, has so easily been accepted. The only reasonable explanation for the perception of any kind of advantage of this scheme seems to be that balancing only during charge is a familiar paradigm from other cell chemistries that is difficult to give up.

2. Disadvantages of charge-only balancing paradigm:

- A charge-only electronic balancing method is just barely effective for the smallest packs and can be ineffective for large battery packs, especially if, during storage, or due to external differential discharge, the pack becomes out of balance by more than a few tenths of one percent. In these instances, low current balancing only during charge may never catch up with imbalance that happened over months of storage.

- For most battery packs, the least amount of time during the pack's life is spent in the charge mode. Thus, charge only balancing typically minimizes the balancing time.

- As was seen from the data, charge only balancing is subject to error unless there is complex continuously modified compensation for internal resistance – especially diffusion and charge transfer impedances - of each series cell connection. The operative word here is "continuously modified compensation" because as a battery ages, the diffusion and charge transfer impedances change and may change at different rates for the different series sections within the same battery pack.



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WHY CHANGE TO CONTINUOUS LI-ION CELL BALANCING

1. ADVANTAGES
   - **GREATER PERCENTAGE OF PACK TIME CAN BE USED FOR BALANCING**
   - **FASTER BALANCING**
   - **DOES NOT REDUCE PACK SHELF LIFE – <u>WILL NOT DAMAGE PACK!</u>**
   - **INHERENTLY MORE ACCURATE**
   - **DOES NOT REQUIRE PACK CYCLING AND COMPLEX CONTINUOUSLY CHANGING INTERNAL RESISTANCE CALCULATIONS**
   - **LESS LIKELY TO RESULT IN REPEATED OVER CHARGING OF UNBALANCED CELL(S)**
   - **MISSION CRITICAL BATTERY PACKS KEPT IN STORAGE ARE ALWAYS IMMEDIATELY READY TO USE AT MAXIMUM CAPACITY**
   - **BATTERY PACKS CAN BE BALANCED IN LOW CURRENT DISCHARGE MISSIONS WHERE CHARGING IS INFREQUENT**
   - **BATTERY PACKS CAN BE BALANCED IN LOW CURRENT CHARGE/DISCHARGE MISSIONS THAT USE SOLAR POWER & FUEL CELLS**
2. DISADVANTAGES
   - **THIS IS A NEW PARADIGM AND, AS SUCH, WILL REQUIRE DOING AWAY WITH PRECONCEIVED NOTIONS**

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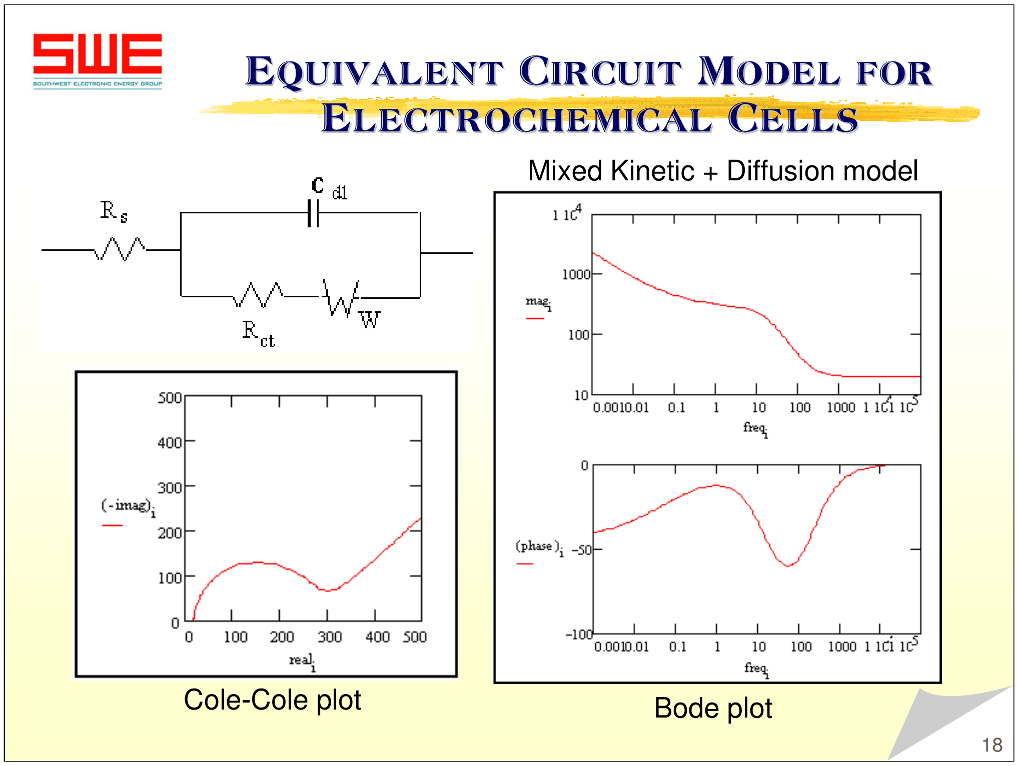
Read advantages on slide emphasizing especially the last 3 bullets which are more typical of large battery packs not currently being mass produced.

END OF PRESENTATION. <ANY QUESTIONS?>



EQUIVALENT CIRCUIT MODEL FOR ELECTROCHEMICAL CELLS

Mixed Kinetic + Diffusion model

Cole-Cole plot

Bode plot

This slide is a relatively simple model of an electrochemical cell.

R_S represents the resistivity of both the electrolyte Solution and the interconnection wiring of the cell. It is typically, very small.

R_{CT} represents Charge Transfer or kinetic resistance which is related to the speed at which charge can be transferred i.e., the speed at which ions can be released from one electrode and transferred to the other.

W is the diffusion or Warburg impedance. It is related to the distance diffusing reactants have to move. At high frequencies this is a short distance, at low frequencies this distance is larger. The Warburg impedance is not a pure resistance but exhibits a phase shift of -45°.

C_{dl} is the double layer capacitance that is created between charges in the electrolyte surrounding an electrode and the charge on the electrode. This thin electrical double layer forms a capacitor whose value is about 20 to 60 uF for every cm^2 of electrode area.

- Notice on the Bode plot that the lowest internal resistance of the cell is at a frequency of 1000 Hz or more. This is the frequency that the cell manufacturers use when specifying their internal resistance. It doesn't change much with age.

- Notice on the Bode plot that the highest internal resistance of the cell is at the lower frequencies and is associated with both the Warburg and the Charge Transfer impedances. These impedances dominate at the lowest frequencies. Both Warburg and Charge Transfer impedances can change dramatically with cell age or cell damage.

- The Cole-Cole plot is more often called a Nyquist plot by electrical engineers. The plot begins at the highest frequencies to the left and proceeds to the lowest frequencies to the right.