rLoop Battery Test Plan

Battery Test Requirements
Each test shall have the following supporting documentation prior to execution:

- Up to date circuit diagrams
- Step by step procedures for all systems involved
- List of all risks and mitigation strategies
- Printed out checklists that will be marked by operator
- An OK to proceed from rLoop management & TE management

Each test shall be designed such that two independent test system failures are required to create a condition in which an absolute battery limit can be reached. These are the two autonomous layers of safety.

Each test shall be monitored by an operator and a kill switch available to operator to stop test if necessary. Kill switch shall clearly be marked and labeled as "SHUTDOWN”. This is the third layer of safety. Tests should always have two people near the controls monitoring conditions at all times.

Test List
- Tab Clamping Qualification
- Single Cell Low Current Test
- Single Cell High Current Test
- Module Acceptance Test
- 18S String System Integration Test
- Full Pack System Test

Tab Clamping Qualification

<u>Purpose:</u> To validate the quality of the cell to cell interconnect method.

<u>Methods:</u>

Take sample tab material gathered from team members (pure copper, nickel coated copper, and pure aluminium), clamp it onto sample copper bus bar elements 2.5” long. Perform following tests:

- Low current resistance: use 4-probe measurement device
- High current resistance with temperature rise measurement: Use power supply to apply 75A through the weld for three minutes. Measure voltage drop through the weld and temperature rise.

Take sample tab material from Revolectrix cell and use the expected resistance weld process to connect the tab material to a sample of the expected copper bus bar. Perform tests as above.

<u>Success criteria:</u> Voltage drop and temperature rise limits to be determined.

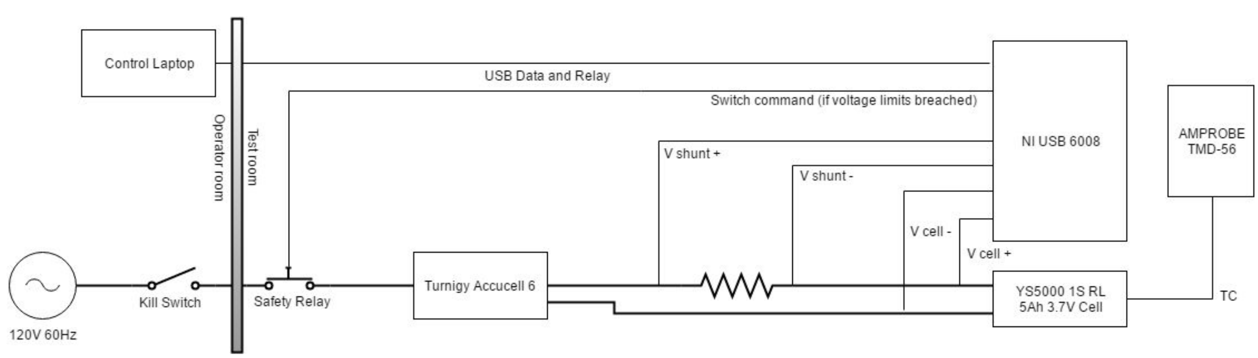
Single Cell Low Current Test

Purpose: To validate the cell's capacity, internal resistance, voltage, and temperature rise when charged and discharged slowly.

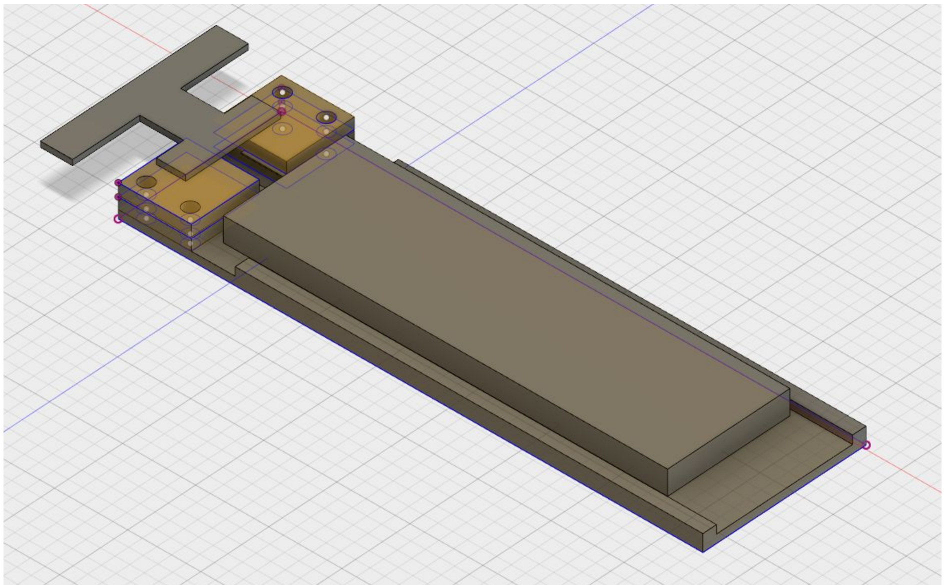
Items needed:

- YS5000 cell
- Cell holder
- Li Ion safe bag
- Turnigy Accucell 6
- NI USB-6008
- AMPROBE TMD-56
- Laptop with battery DAQ software installed
- Current shunt and amplifier circuit
- Relay safety circuit
- ABC Fire Extinguisher
- Heat resistant gloves
- Face shield
- Ceramic tray for cells
- GoPro
- Power cutoff switch for relay circuit

Method: Set up Turnigy Accucell 6 Charger and YS5000 cell as shown in the diagram below. The connection to AC power will be gated by a normally open contactor/relay controlled by a data acquisition and control computer. The power cabling coming out of the charger will have a current shunt. The DAQ computer will record cell voltage and shunt voltage. Body temperature will be measured by the AMPROBE TMD-56. If the voltages reach a limit (Max 4.25V and min 2.95V) then the contactor will go open. Charge the cell to 4.2V up to 5A and discharge the cell up to 2A until voltage reaches 3.0V. Operator kill switch will be power to DAQ controlled relay drivers. This will immediately stop current flow. All wiring coming out of cell holder will be minimum 2 meters away from other equipment.



The cell will be held by the single cell fixture, as shown below:



<u>Success Criteria:</u> Cell outputs minimum 5Ah as measured by integrating the current shunt data over time. Cell voltage profile matches model OCV curve within 50mV. Cell temperature rise is less than 10°C.

Risks:

Overcharge: Cell above 4.5V can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.
Mitigation:
- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Turnigy controller is programmed to stop charge at 4.2V (first autonomous layer).
- Data acquisition software is programmed to open controller power relay if 4.25V detected (second autonomous layer)
- Operator can switch off auxiliary power supply to relay if voltage above 4.2V (third operator layer)

Overdischarge: Cell under 2.5V can hard short. This will irreversibly damage cell and cause a resistive current path inside cell. Resistive path can lead to high temperature rise and thermal event.
Mitigation:
- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Turnigy controller is programmed to stop discharge at 3.0V (first autonomous layer).
- Data acquisition software is programmed to open controller power relay if 2.95V detected (second autonomous layer)
- Operator can switch off auxiliary power supply to relay if voltage below 3.0V (third operator layer)

Temperature rise: Cell above 100°C can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.
Mitigation:
- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Operator can switch off auxiliary power supply to relay if temperature above 40°C. GoPro will be facing the AMPROBE TMD-56.
- Although no autonomous layer exists, the low current nature of this test makes pure temperature rise an extremely unlikely scenario. Internal resistance high enough to cause high temperature rise will be stopped by voltage limits.

Procedure:

Date ___________________

Print procedure and check off all steps. Note any changes required and add them to follow up procedures. Two personnel required to be present during test: operator and safety. Operator should be familiar with circuitry and software. Safety should follow along all steps, be familiar with test limits, and know the location of the “SHUTDOWN” switch.

1. Check off items:
    a. YS5000 cell
    b. Cell holder
    c. Li Ion safe bag
    d. Turnigy Accucell 6
    e. NI USB-6008
    f. AMPROBE TMD-56
    g. Laptop with battery DAQ software installed
    h. Current shunt and amplifier circuit
    i. Relay safety circuit
    j. ABC Fire Extinguisher
    k. Heat resistant gloves
    l. Face shield
    m. Ceramic tray for cells
    n. GoPro
    o. Power cutoff switch for relay circuit
2. Perform visual inspection of all wiring
3. Apply power to relay circuit, amplifier circuit, and AMPROBE sensor
4. Check that kill switch is off “SHUTDOWN” position
5. Perform the following wire checks
    a. Check continuity between cell holder terminals to Accucel 6
    b. Check continuity between cell holder terminal to DAQ analog input
    c. Check continuity between shunt terminals to amplifier circuit
    d. Check continuity between amplifier circuit and DAQ analog input
    e. Check continuity between DAQ digital output to relay circuit
    f. Check 12V applied to relay circuit
    g. Check 5V applied to amplifier circuit
    h. Check ambient temperature reading on TC
6. Perform functional relay test
    a. Check that relay is currently open circuit
    b. Open NIMax on laptop, open test panels, apply bit to digital output 1
    c. Check that relay is closed
    d. Restore bit to 0
7. Install cell

    a. Ensure terminal nuts are loose
    b. Note down cell serial number ______________________________
    c. Remove isolation cap from positive terminal
    d. Insert cell into cell holder. **Warning! Do not short terminals**
    e. Tighten nuts
    f. Measure cell voltage with a DMM ____________________
    g. Tape TC to cell
8. Start up GoPro display
9. Turn kill switch to “ARMED” position
10. Start up DAQ programs
    a. Open AMPROBE software and check connection to TC
    b. Start temperature logging
    c. Start BatteryDAQ program and close relay
    d. Check that voltage matches DMM reading
11. Document test limits
    a. Voltage upper limit _______________
    b. Voltage lower limit _______________
    c. Temperature max _______________
12. Set Acucell to desired setting and start current flow. **Warning! Personnel to exit room immediately after current flow begins**
    a. Write start time __________________
    b. Write current flow ___________________
13. Check that current reading matches expected
14. Actively monitor test and set kill switch to “SHUTDOWN” if limits are violated
15. Test ending
    a. Set kill switch to “SHUTDOWN” to end test, press “k” to stop DAQ
    b. Save file on computer, label with serial number and date
    c. Log into test matrix
    d. Loosen cell terminal nuts. **Warning! Do not short terminals**
    e. Remove cell from holder
    f. Place isolation cap on positive terminal
    g. Return cell to storage.
16. Record additional portions of tests below

Start time	Start voltage	Current	Notes

Single Cell High Current Test

<u>Purpose:</u> To validate the cell's capacity, internal resistance, voltage, and temperature rise when exposed to expected flight loads.

<u>Items needed:</u>

- YS5000 cell
- Cell holder
- Li Ion safe bag
- Turnigy Accucell 6
- NI USB-6008
- Adafruit TC amplifier
- Laptop with battery DAQ software installed
- Current shunt and amplifier circuit
- Charge safety relay safety circuit
- Discharge relay circuit
- Power resistor assembly
- Fans for resistor assembly
- Stand-alone protection circuit
- ABC Fire Extinguisher
- Heat resistant gloves
- Face shield
- Cinder blocks to cover cells
- GoPro
- Power cutoff switch for relay circuit
- Isolated driver to install cell
- Extension cords
- Fan
- Handheld digital multimeter

<u>Method:</u> Set up Turnigy Accucell 6 Charger and YS5000 cell as shown in the diagram below. The connection to AC power will be gated by a normally open contactor/relay controlled by a data acquisition and control computer. The power cabling coming out of the charger will have a current shunt. The DAQ computer will record cell voltage, shunt voltage, and body temperature. Body temperature will be measured by Adafruit TC amplifier. Additional temperature TCs from will be used as auxiliary data. If the voltages reach a charge limit (Max 4.25V) or discharge limit (Min 3.0V), then the relays will go open. If the temperature reaches a limit (Max 55°C), then relays will go open. DAQ computer will then control two relays: one to provide power to charger (charge safety relay), and one to expose cell to resistive load.

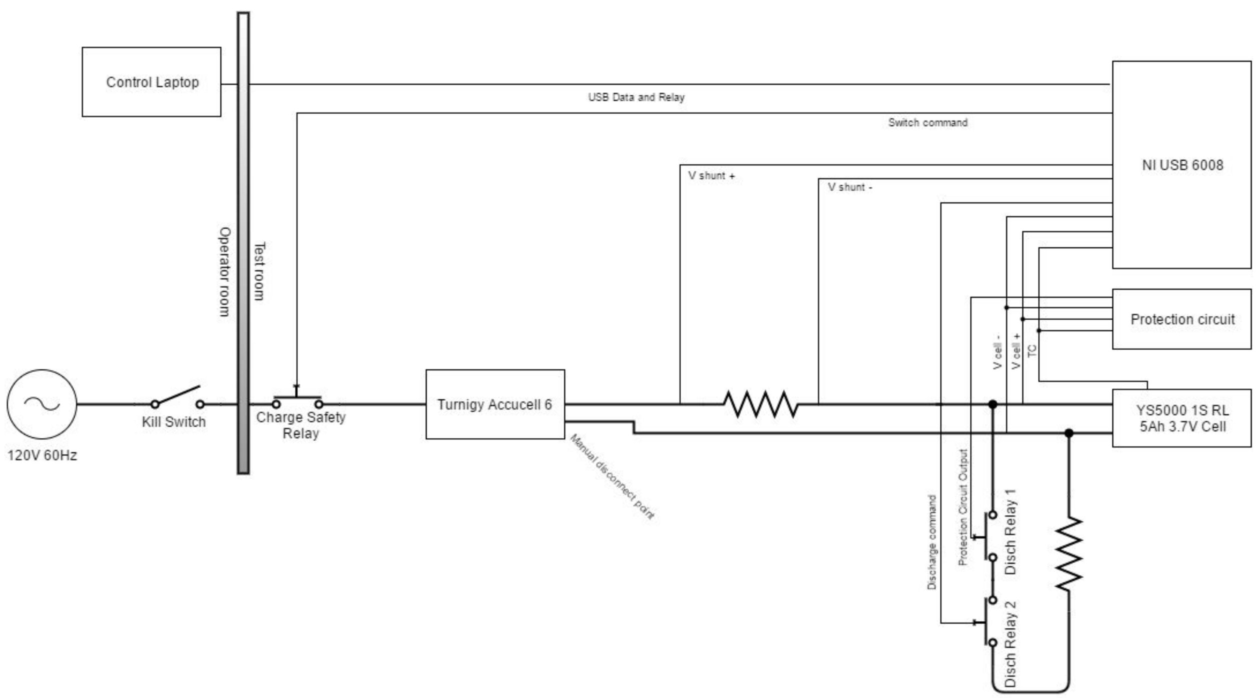
The resistive load will be large power resistors placed in a proper thermal environment to control heat rise. The power resistors are bolted to a large aluminum heat sink and will have a fan blowing ambient air on them. There are three resistors available and can be placed in any parallel number to control discharge:

- 1 resistor = 0.1 ohm = 30A to 42A
- 2 resistor = 0.05 ohm = 60A to 84A
- 3 resistor = 0.033 ohm = 90A to 126A

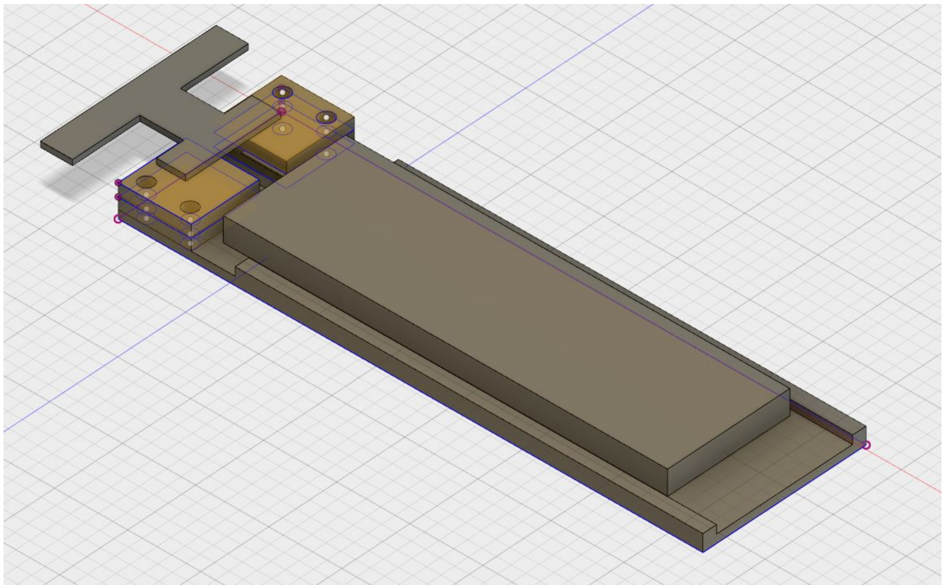
Additionally, a separate protection circuit will measure voltage and body temperature and can also shut down relay. Discharge resistor will be active only if both DAQ computer and protection circuit agree.

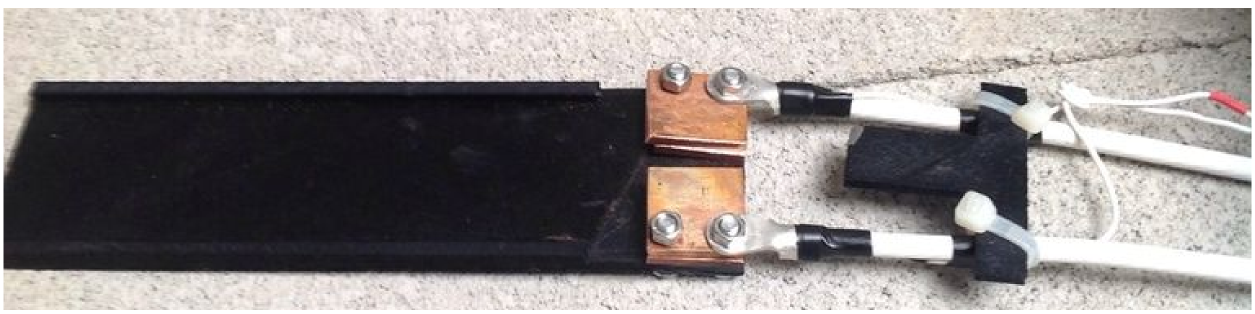
Operator kill switch will be power to DAQ controlled relay drivers by unplugging USB connection. This will immediately stop current flow. Data from auxiliary TC will still be available.

All wiring coming out of cell holder will be minimum 2 meters away from other equipment.



The cell will be held by the single cell fixture, as shown below:





<u>Success Criteria:</u> Cell capacity at end of discharges is greater than 4.5Ah. Temperature rise is less than 10°C for cell body.

<u>Risks:</u>

Overcharge: Cell above 4.5V can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.
Mitigation:

- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Turnigy controller is programmed to stop charge at 4.2V (first autonomous layer).
- Data acquisition software is programmed to open controller power relay if 4.25V detected (second autonomous layer)
- Operator can switch off power supply to relay driver if voltage above 4.2V (third operator layer)

Overdischarge: Cell under 2.5V can hard short. This will irreversibly damage cell and cause a resistive current path inside cell. Resistive path can lead to high temperature rise and thermal event.

Mitigation:

- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Protection circuit programmed to open discharge relay if 3.0V detected (first autonomous layer).
- Data acquisition software is programmed to open discharge relay if 3.0V detected (second autonomous layer)
- Operator can switch off power supply to relay driver if voltage below 3.0V (third operator layer)

Temperature rise: Cell above 100°C can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.

Mitigation:

- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Protection circuit programmed to open discharge relay if 55°C detected (first autonomous layer).
- Data acquisition software is programmed to open discharge relay if 55°C detected (second autonomous layer)
- Operator can switch off power supply to relay driver if temperature above 55°C (third operator layer)

Procedure:

Date ___________________

Print procedure and check off all steps. Note any changes required and add them to follow up procedures. Two personnel required to be present during test: operator and safety. Operator should be familiar with circuitry and software. Safety should follow along all steps, be familiar with test limits, and know the location of the "SHUTDOWN" switch.

1. Check off items needed
2. Perform visual inspection of all wiring
3. Perform the following wire checks
    a. Check continuity between cell holder terminals to Accucel 6 (if charging, negative terminal should be connected, if discharging, negative terminal should be disconnected)
    b. Check continuity between cell holder terminals and discharge relays.
    c. Check continuity between cell holder terminal to DAQ analog input
    d. Check continuity between shunt terminals to amplifier circuit
    e. Check continuity between amplifier circuit and DAQ analog input
    f. Check continuity between DAQ digital output to relay circuit
    g. Check ambient temperature reading on TCs
4. Open NI MAX program on laptop to reset digital outputs
    a. Find "Devices and Interfaces", "NI USB-6008", "Test Panels"
    b. Go to "Digital Input/Output"
    c. Set "All to Output"
    d. Press "Start"
    e. Set DI Pin 0 and 1 to zero.
    f. Press "Stop" and close the program.
5. Apply power to circuits
    a. Ensure Turnigy Accucel is not turned on. If Accucel turns on, remove power to circuits and repeat step 4.
    b. Check 12V applied to relay circuits
    c. Check 5V applied to amplifier circuit
    d. Check protection circuit online (slow short blink on LED)
6. Set discharge load
    a. Write down desired discharge load in ohm _______________________
    b. Ensure resistor load matches desired
        i. For 3.5C discharge, 0.2Ω, two resistors in series
        ii. For 7.4C discharge, 0.1Ω, one resistor
        iii. For 14.8C discharge, 0.05Ω, two resistors in parallel
7. Install cell
    a. Inspect all wiring to terminals and ensure no risk of shorting negative/positive exists

b. Ensure terminal nuts are loose
c. Note down cell serial number ____________________________
d. Remove isolation cap from positive terminal
e. Insert cell into cell holder. **Warning! Do not short terminals**
f. Tighten nuts
g. Measure cell voltage ___________________
h. Tape Amprobe TC1 to cell body
i. Tape Adafruit Yellow TC (AI2) to center cell body
j. Tape Protection Circuit Thermistor to center cell body
k. Tape Adafruit Blue TC (AI3) near positive cell terminal

8. Start up GoPro display
9. Start AMPROBE program on the computer and start logging
   a. Check that both TC readings read ambient temp
   b. Press the graph window
   c. Press “Record” then “OK”
   d. Check that a new reading is placed into the table once per second

For charging the cell:

10. Ensure accucel negative terminal is connected to cell
11. Ensure discharge relay 1 & 2 is open
12. Start Matlab r2007 and find battery DAQ folder
13. Run “setup” into command line
14. Open “batteryDAQv2.m” program and document test limits, defined in first four lines of program.
    a. Voltage upper limit ______________
    b. Voltage lower limit ______________
    c. Yellow TC (AI2) temperature max ______________
    d. Blue TC (AI3) temperature max ______________
15. Run “batteryDAQv2” in command line
    a. Set 5 second delay
    b. Set relay to 1 (charge relay)
    c. Press any key to start
    d. After 5 seconds, Turnigy unit should turn on.
16. Set Acucell to desired setting and start current flow. **Warning! Personnel to exit room immediately after current flow begins**
    a. Cycle using left-right keys to get to “Li-Ion Charge”
    b. Press enter
    c. Set charge current to desired, press enter
    d. Set to 1S charge, press enter
    e. Hold Enter key for 5 seconds to start
    f. Write start time _________________
    g. Write current flow __________________
17. Check that current reading matches expected in DAQ.

18. Actively monitor test
    a. To stop relays, click on Matlab figure and press “s” key
    b. To stop logging, click on Matlab figure and press “k” key
    c. Stop relays or set kill switch to “SHUTDOWN” if limits are violated.
19. When complete, save file
    a. Click “File” “Save workspace as” in Matlab window.
    b. Save file name as SN*XXXX*C*NN*CF*YY*.mat where
        i. SN stands for serial number
        ii. XXXX is the last four digits of the cell serial number (example 0394)
        iii. C stands for cycle count
        iv. NN is the cell cycle count. Simply increment from last cycle count as logged in the test matrix.
        v. C is charge, D is for discharge
        vi. F stands for file index.
        vii. YY is a file index. If two files were needed to capture charge or discharge, increment YY.
        viii. Example file name: “SN0394C06CF02.mat” Serial number 0394, cycle 6, charge, file index 2.

For discharging the cell:

20. Ensure accucel negative terminal is disconnected from cell.
21. Ensure fan is aimed at load and running at highest setting.
22. Ensure TC2 is taped on an active resistor.
23. Ensure GoPro feed is being monitored.
24. Activate protection circuit by holding down the button for 5 seconds. If successful, the blinking will be faster and the relay will close. **Warning! Personnel to exit room once this relay has been closed.**
25. Start Matlab r2007 and find battery DAQ folder
26. Run “setup” into command line
27. Open “batteryDAQv2.m” program and document test limits, defined in first four lines of program.
    a. Voltage upper limit _______________
    b. Voltage lower limit _______________
    c. Yellow TC (AI2) temperature max _______________
    d. Blue TC (AI3) temperature max _______________
28. Run “batteryDAQv2” in command line
    a. Set 30 second delay
    b. Set relay to 2 (discharge relay)
    c. Press any key to start
    d. Ensure cell voltage is at expected level
    e. Ensure TC outputs are all near ambient temperature
    f. After 20 seconds, Turnigy unit should turn on and discharge will start.
29. Actively monitor test

a. To stop relays, click on Matlab figure and press “s” key
b. To stop logging, click on Matlab figure and press “k” key
c. Stop relays or set kill switch to “SHUTDOWN” if limits are violated.

30. When complete, save file
    a. Click “File” “Save workspace as” in Matlab window.
    b. Save file name as SN*XXXX*C*NN*DF*YY*.mat where
        i. SN stands for serial number
        ii. XXXX is the last four digits of the cell serial number (example 0394)
        iii. C stands for cycle count
        iv. NN is the cell cycle count. Simply increment from last cycle count as logged in the test matrix.
        v. C is charge, D is for discharge
        vi. F stands for file index.
        vii. YY is a file index. If two files were needed to capture charge or discharge, increment YY.
        viii. Example file name: “SN0394C06DF02.mat” Serial number 0394, cycle 6, discharge, file index 1.

For ending test:

31. Set kill switch to “SHUTDOWN” to end test, press “k” to stop DAQ if running.
32. Log into test matrix, report on #mfg-testing channel
33. Loosen cell terminal nuts. **Warning! Do not short terminals**
34. Remove cell from holder
35. Place isolation cap on positive terminal
36. Return cell to storage.

Single Module High Current Test

Purpose: To validate a single module's capacity, internal resistance, voltage, and temperature rise when exposed to expected flight loads.

Items needed:

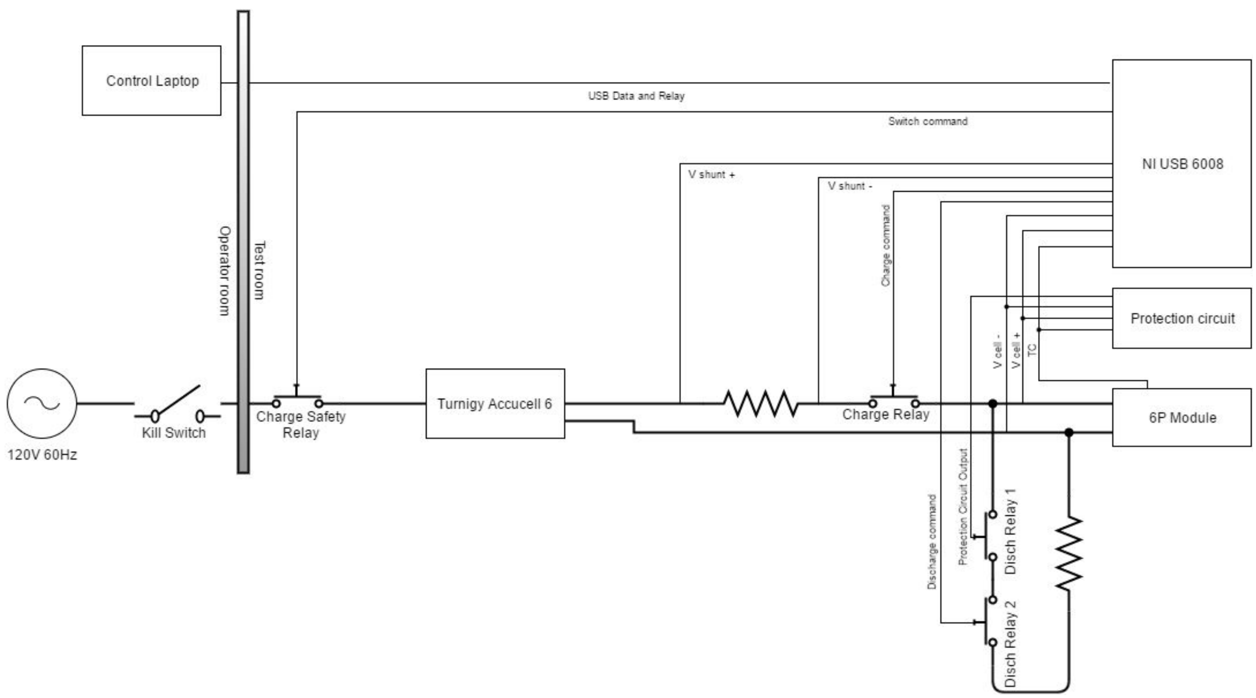
- Module assembly (6 cells, 6 PCM)
- Module test rig (copper wiring to resistive load)
- Li Ion safe bag
- Turnigy Accucell 6
- NI USB-6008
- Adafruit TC amplifier
- Laptop with battery DAQ software installed
- Current shunt and amplifier circuit
- Charge safety relay safety circuit
- Discharge relay circuit
- Power resistor assembly
- Fans for resistor assembly
- Stand-alone protection circuit
- ABC Fire Extinguisher
- Heat resistant gloves
- Face shield
- Cinder blocks to cover cells
- GoPro
- Power cutoff switch for relay circuit
- Isolated driver to install bus bars
- Extension cords
- Fan
- Handheld digital multimeter

Method: Set up Turnigy Accucell 6 Charger and 6P Module as shown in the diagram below. The connection to AC power will be gated by a normally open contactor/relay controlled by a data acquisition and control computer. The power cabling coming out of the charger will have a current shunt. The DAQ computer will record cell voltage, shunt voltage, and body temperature. Body temperature will be measured by Adafruit TC amplifier. Additional temperature TCs from will be used as auxiliary data. If the voltages reach a charge limit (Max 4.25V) or discharge limit (Min 3.0V), then the relays will go open. If the temperature reaches a limit (Max 55°C), then relays will go open. DAQ computer will then control two relays: one to provide power to charger (charge safety relay), and one to expose cell to resistive load.

The resistive load will be large power resistors placed in a proper thermal environment to control heat rise. The power resistors are bolted to a large aluminum heat sink and will have a fan blowing ambient air on them. There are six resistors in parallel, 0.1Ω each, totaling 0.017Ω. This will output a total current of 218A. This results in 36A per cell.

Additionally, a separate protection circuit will measure voltage and body temperature and can also shut down relay. Discharge resistor will be active only if both DAQ computer and protection circuit agree.

Operator kill switch will be power to DAQ controlled relay drivers by unplugging USB connection. This will immediately stop current flow. Data from auxiliary TC will still be available.



<u>Success Criteria:</u> Cell capacity at end of discharges is greater than 27Ah. Temperature rise is less than 20°C.

<u>Risks:</u>

Overcharge: Module above 4.5V can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.
Mitigation:

- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Turnigy controller is programmed to stop charge at 4.2V (first autonomous layer).

- Data acquisition software is programmed to open controller power relay if 4.25V detected (second autonomous layer)
- Operator can switch off power supply to relay driver if voltage above 4.2V (third operator layer)

Overdischarge: Module under 2.5V can hard short. This will irreversibly damage cell and cause a resistive current path inside cell. Resistive path can lead to high temperature rise and thermal event.
Mitigation:
- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Protection circuit programmed to open discharge relay if 3.0V detected (first autonomous layer).
- Data acquisition software is programmed to open discharge relay if 3.0V detected (second autonomous layer)
- Operator can switch off power supply to relay driver if voltage below 3.0V (third operator layer)

Temperature rise: Module above 100°C can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.
Mitigation:
- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Protection circuit programmed to open discharge relay if 55°C detected (first autonomous layer).
- Data acquisition software is programmed to open discharge relay if 55°C detected (second autonomous layer)
- Operator can switch off power supply to relay driver if temperature above 55°C (third operator layer)

Procedure:

Date ___________________

Print procedure and check off all steps. Note any changes required and add them to follow up procedures. Two personnel required to be present during test: operator and safety. Operator should be familiar with circuitry and software. Safety should follow along all steps, be familiar with test limits, and know the location of the “SHUTDOWN” switch.

1. Check off items needed
2. Perform visual inspection of all wiring
3. Perform the following wire checks
    a. Check continuity between cell holder terminals to Accucel 6 (if charging, negative terminal should be connected, if discharging, negative terminal should be disconnected)
    b. Check continuity between cell holder terminals and discharge relays.
    c. Check continuity between cell holder terminal to DAQ analog input
    d. Check continuity between shunt terminals to amplifier circuit
    e. Check continuity between amplifier circuit and DAQ analog input
    f. Check continuity between DAQ digital output to relay circuit
    g. Check ambient temperature reading on TCs
4. Open NI MAX program on laptop to reset digital outputs
    a. Find “Devices and Interfaces”, “NI USB-6008”, “Test Panels”
    b. Go to “Digital Input/Output”
    c. Set “All to Output”
    d. Press “Start”
    e. Set DI Pin 0 and 1 to zero.
    f. Press “Stop” and close the program.
5. Apply power to circuits
    a. Ensure Turnigy Accucel is not turned on. If Accucel turns on, remove power to circuits and repeat step 4.
    b. Check 12V applied to relay circuits
    c. Check 5V applied to amplifier circuit
    d. Check protection circuit online (slow short blink on LED)
6. Check isolation between test rig positive and negative bus bars.
7. Install cell
    a. Inspect all wiring to terminals and ensure no risk of shorting negative/positive exists
    b. Ensure terminal nuts are loose
    c. Note down module serial number _____________________________
    d. Note down cell serial numbers inside module
        i. _________
        ii. _________

iii. __________
iv. __________
v. __________
vi. __________

e. Remove isolation cover from module. **WARNING: Do not short module terminals, keep conductive tools away from exposed module terminals.**
f. Attach module to test rig.
g. Measure module voltage ____________________
h. Tape Amprobe TC1 to cell body
i. Tape Adafruit Yellow TC (AI2) to cell body
j. Tape Protection Circuit Thermistor to cell body
k. Tape Adafruit Blue TC (AI3) near positive cell terminal

8. Start up GoPro display
9. Start AMPROBE program on the computer and start logging
   a. Check that both TC readings read ambient temp
   b. Press the graph window
   c. Press “Record” then “OK”
   d. Check that a new reading is placed into the table once per second

For charging the cell:

10. Ensure accucel negative terminal is connected to cell
11. Ensure discharge relay 1 & 2 is open
12. Start Matlab r2007 and find battery DAQ folder
13. Run “setup” into command line
14. Open “batteryDAQv2.m” program and document test limits, defined in first four lines of program.
    a. Voltage upper limit _______________
    b. Voltage lower limit _______________
    c. Yellow TC (AI2) temperature max _______________
    d. Blue TC (AI3) temperature max _______________
15. Run “batteryDAQv2” in command line
    a. Set 5 second delay
    b. Set relay to 1 (charge relay)
    c. Press any key to start
    d. After 5 seconds, Turnigy unit should turn on.
16. Set Acucell to desired setting and start current flow. **Warning! Personnel to exit room immediately after current flow begins**
    a. Cycle using left-right keys to get to “Li-Ion Charge”
    b. Press enter
    c. Set charge current to desired, press enter
    d. Set to 1S charge, press enter
    e. Hold Enter key for 5 seconds to start
    f. Write start time __________________

    g. Write current flow ___________________

17. Check that current reading matches expected in DAQ.
18. Actively monitor test
    a. To stop relays, click on Matlab figure and press “s” key
    b. To stop logging, click on Matlab figure and press “k” key
    c. Stop relays or set kill switch to “SHUTDOWN” if limits are violated.
19. When complete, save file
    a. Click “File” “Save workspace as” in Matlab window.
    b. Save file name as MSN*XX*C*NN*CF*YY*.mat where
        i. MSN stands for module serial number
        ii. XX is the module serial number (example 04)
        iii. C stands for cycle count
        iv. NN is the cell cycle count. Simply increment from last cycle count as logged in the test matrix.
        v. C is charge, D is for discharge
        vi. F stands for file index.
        vii. YY is a file index. If two files were needed to capture charge or discharge, increment YY.
        viii. Example file name: “MSN04C06CF02.mat” Serial number 04, cycle 6, charge, file index 2.

For discharging the cell:

20. Ensure accucel negative terminal is disconnected from cell.
21. Ensure fan is aimed at load and running at highest setting.
22. Ensure TC2 is taped on an active resistor.
23. Ensure GoPro feed is being monitored.
24. Activate protection circuit by holding down the button for 5 seconds. If successful, the blinking will be faster and the relay will close. **Warning! Personnel to exit room once this relay has been closed.**
25. Start Matlab r2007 and find battery DAQ folder
26. Run “setup” into command line
27. Open “batteryDAQv2.m” program and document test limits, defined in first four lines of program.
    a. Voltage upper limit _______________
    b. Voltage lower limit _______________
    c. Yellow TC (AI2) temperature max _______________
    d. Blue TC (AI3) temperature max _______________
28. Run “batteryDAQv2” in command line
    a. Set 30 second delay
    b. Set relay to 2 (discharge relay)
    c. Press any key to start
    d. Ensure cell voltage is at expected level
    e. Ensure TC outputs are all near ambient temperature

    f. After 20 seconds, Turnigy unit should turn on and discharge will start.
29. Actively monitor test
    a. To stop relays, click on Matlab figure and press “s” key
    b. To stop logging, click on Matlab figure and press “k” key
    c. Stop relays or set kill switch to “SHUTDOWN” if limits are violated.
30. When complete, save file
    a. Click “File” “Save workspace as” in Matlab window.
    b. Save file name as MSN*XX*C*NN*CF*YY*.mat where
        i. MSN stands for module serial number
        ii. XX is the module serial number (example 04)
        iii. C stands for cycle count
        iv. NN is the cell cycle count. Simply increment from last cycle count as logged in the test matrix.
        v. C is charge, D is for discharge
        vi. F stands for file index.
        vii. YY is a file index. If two files were needed to capture charge or discharge, increment YY.
        viii. Example file name: “MSN04C06CF02.mat” Serial number 04, cycle 6, charge, file index 2.

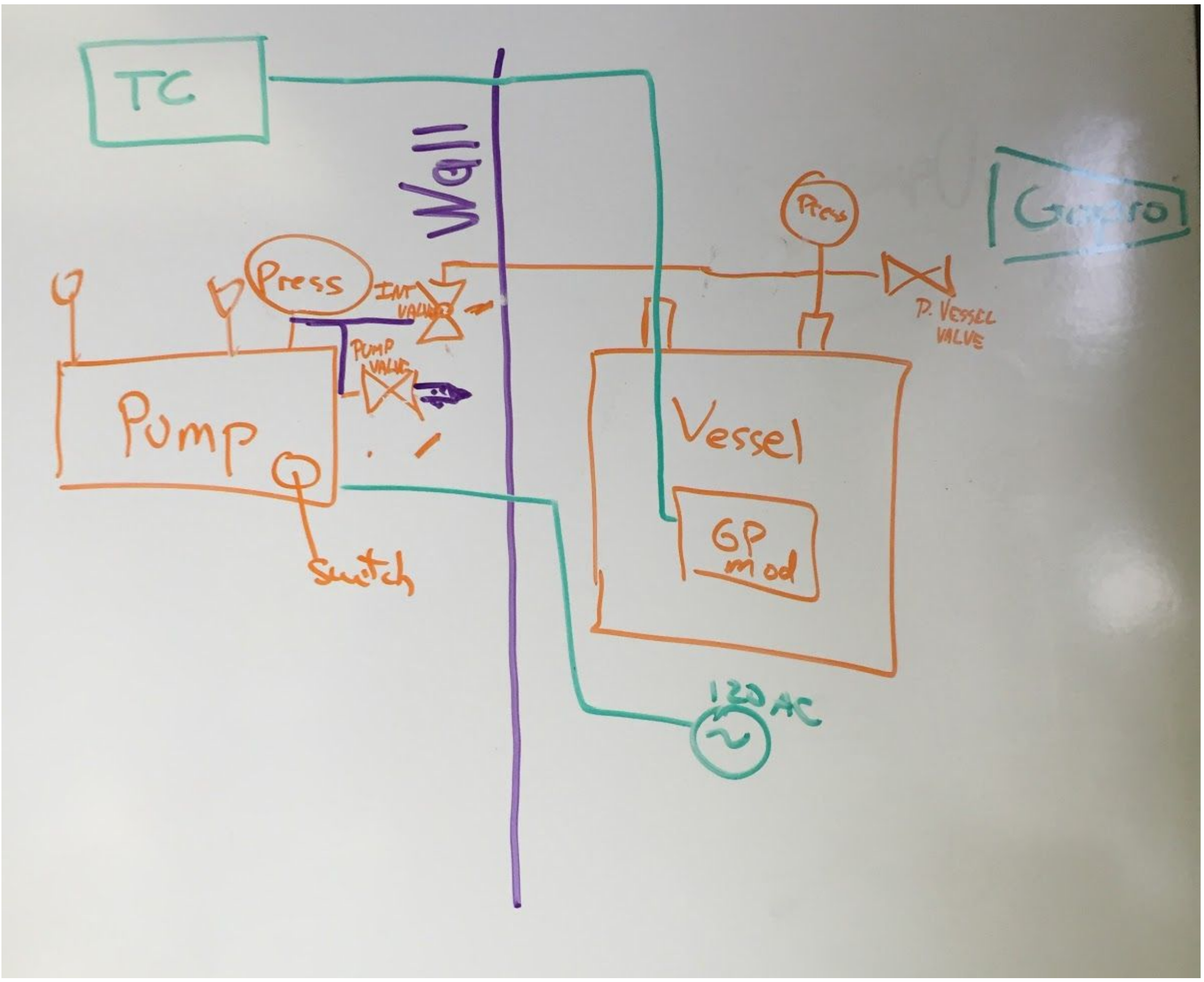
For ending test:

31. Set kill switch to “SHUTDOWN” to end test, press “k” to stop DAQ if running.
32. Log into test matrix, report on #mfg-testing channel
33. Loosen cell terminal nuts. **Warning! Do not short terminals**
34. Remove cell from holder
35. Place isolation cap on positive terminal
36. Return cell to storage.

Module Vacuum Exposure Test

Purpose: To expose the 6P battery module to vacuum (one module is comprised of six cells and seven PCM sheets inside a structure). This will simulate the case of pressure loss while inside the tube.

Method: Insert module into vacuum chamber. Remotely activate vacuum pump and chamber valve to bring down pressure in a controlled fashion, all while monitoring module temperature. Maintain module at max vacuum for one hour, and repressurize.



The test setup is shown above. The test is designed to be monitored and controlled remotely to keep personnel away from any danger. There will be a GoPro monitoring and recording the vacuum valve, pressure gage, and rubber feedthrough. A thermocouple will be attached to the module body and fed through a rubber feedthrough. The vacuum is expected to force the rubber feedthrough into the pipe and create a seal. The vacuum pump will be activated remotely, and the vacuum valve will be opened using a stepper motor. This will drop the pressure of the vessel.

The pressure will be controlled using the vacuum valve and stepper motor. The pressure will be dropped in three steps: first to 50% atmosphere (-50kPa), then to 25% atmosphere (-75kPa), then to full vacuum (-100kPa). Each step will be 15 minutes while temperature is monitored. The full vacuum step will be 1 hour.

When test is complete, the vacuum valve will be closed slowly to refill with air. Once backfill is complete, the vacuum pump will be turned off. If temperature reading is nominal, it will then be safe for personnel to enter and inspect module.

<u>Success Criteria:</u> No venting of cell observed. No significant heating observed. No structural damage to module.

<u>Risks:</u>

Cell Short: It has been shown that these cells will expand significantly when exposed to vacuum. It is not known whether the module structure is sufficient to prevent this expansion, and it is not known whether this expansion can cause internal shorting of the active materials. Only one cell has been exposed to vacuum to date, it did not vent.

A short would cause very rapid heating. Cell above 100°C can initiate thermal event. Thermal event can be violent venting of hot gases or explosion, can lead to severe injury and damage to facility.

Mitigation:

- No personnel in room when test activated.
- In case of fire, personnel are not to enter until flames and fumes have subsided. Enter with heat protective gloves, face shield, and ABC fire extinguisher. No attempts will be made to suppress fire.
- Temperature will be monitored. If any sudden increases in temperature detected, the chamber would be backfilled and vacuum pump would be turned off.
- If a thermal event occurs while in vacuum, no fire is expected due to lack of oxygen, but rapid heating and pressurization will occur. The conical cork feedthrough will pop off relieving pressure.
- If the conical cork does not pop off, as a last resort, the vacuum valve can be used to relieve pressure.

Procedure:

Date ____________________

Print procedure and check off all steps. Note any changes required and add them to follow up procedures. To abort test, follow the abort procedure at bottom. In case of emergency, follow the emergency procedure at bottom.

1. Check off needed items
    a. Vacuum vessel
    b. Vacuum pump
    c. Vacuum gage (2)
    d. Valves
    e. Piping
    f. Extension cords
    g. GoPro
    h. Module and cells
    i. Amprobe TC reader
    j. Laptop with Amprobe software
2. Log cell S/N for all six cells here and voltage if available
    a. S/N _______________ V _____________
    b. S/N _______________ V _____________
    c. S/N _______________ V _____________
    d. S/N _______________ V _____________
    e. S/N _______________ V _____________
    f. S/N _______________ V _____________
3. Inspect module assembly
    a. Ensure there are six cells and seven PCM sheets in module.
    b. Ensure the cell terminals have been completely isolated from each other.
    c. Ensure the end plates are installed and all 12 nuts on the tension rods have been finger tightened.
4. Feed thermocouple through rubber feedthrough and insert through lid of chamber
5. Securely tape TC to the body of cell 3. Place a second TC to measure outside temperature.
6. Insert module assembly into chamber.
7. Close lid. Do not tighten the clamps. Use only the weight of the lid to close vessel.
8. Start AMPROBE program on the computer and start logging cell 3 and ambient.
    a. Check that both TC readings read ambient temp
    b. Press the graph window
    c. Press “Record” then “OK”
    d. Check that a new reading is placed into the table once per second
9. Check GoPro is connected to power, and that there is sufficient disc space for three hours.

10. Start up GoPro display on phone. Ensure that rubber feedthrough and vacuum gage is visible.
11. Check that pressure vessel valve is closed (screwed in).
12. Check that vacuum hose is connected to pressure vessel.
13. Leave room and close doors. **Do not enter room while test is running.**
14. Record starting temperature ____________________ °C
15. Open intermediate valve.
16. Ensure pump valve is open.
17. Turn on vacuum pump.
18. Ensure pressure reading begins dropping immediately. If pressure reading does not start dropping, turn off vacuum pump and investigate.
19. Close intermediary valve and turn off pump when reaching approximately -50kPa. Monitor temperature and hold at this pressure for 15 minutes. If temperature reaches 5°C above starting temperature, go to abort test procedure.
20. Turn on pump and open intermediary valve.
21. Close intermediary valve and turn off pump when reaching approximately -75kPa. Monitor temperature and hold at this pressure for 15 minutes. If temperature reaches 5°C above starting temperature, go to abort test procedure.
22. Turn on pump and open intermediary valve.
23. When reaching minimum pressure, close the intermediary valve and shut down the pump
24. Wait one hour. If temperature reaches 5°C above starting temperature, go to abort test procedure.
25. Open Intermediary valve
26. Wait for gage reading to reach ambient.
27. Wait 10 minutes before entering room once ambient pressure is reached and monitor temperature to not be 10degC a bove starting temperature.

Abort Procedure

1. Open intermediary valve
2. Turn off vacuum pump.
3. Wait for gage reading to reach ambient. Monitor cell temperature.
4. Wait 10 minutes before entering room once ambient pressure is reached.

Emergency Procedure

If temperature begins rapidly increasing, there could be a cell venting inside vacuum chamber.

1. Move away from building
2. If smoke is visible coming out of bunker, call TE security at 650 361 3610
3. Call Tom (650 390 7174) to contact Jim Toth
4. Prevent anyone from getting within 20m of building for 30 min

18S String System Integration

Purpose: To validate all the cell's capacity, internal resistance, voltage, and temperature rise in a simulated pack system under reduced loads. To validate the power supply, resistor loads, and BMS in preparation for Full Pack System Test.

Method: Connect 18 cells in series by lining them up side by side and using a simple conductive clamp (aluminum or copper) to connect cells. This clamping is not permanent but also is not capable of conducting high currents. Connect the BMS prototype hardware to the 18S string. Charge the string to 4.2V. Discharge the string at 2.5A for 1 hour. Measure voltages. Measure temperature rise of the cells.

Success Criteria: TBD

Full Pack System Test

<u>Purpose:</u> Complete system test prior to rPod integration. A full 6P18S pack shall be built, charged, and discharged using a 2Ω load. This will provide assurance that all 108 cells have proper capacity and internal resistance.

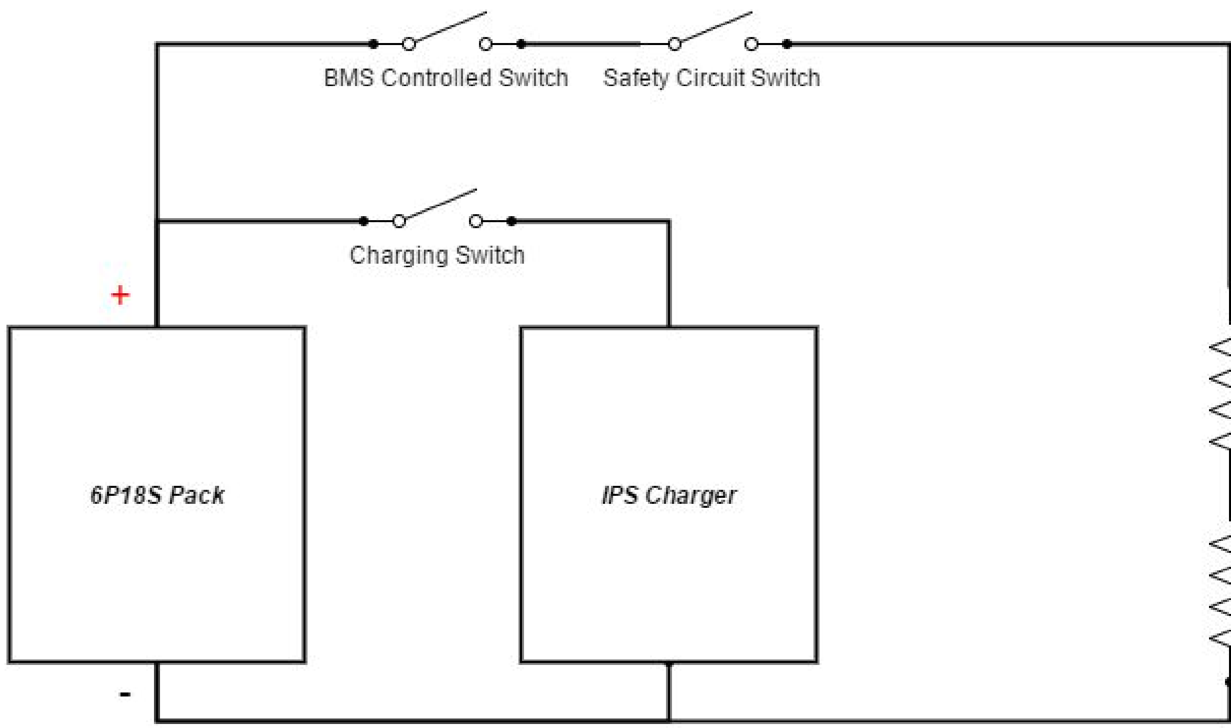
<u>Pack Build Safety Requirements:</u>

- Pack build requires two people present at all times.
- People working on the battery packs should have appropriate PPE, concerns would be a spark or flash causing eye damage.
- Required PPE for pack build:
  - Face mask
  - Electrically insulating gloves
  - Long sleeves jackets
  - Complete pants and close toed shoes
  - No exposed skin
- Assemble one module at a time from negative terminals to positive terminals. Cover modules as they are complete.
  - Install module 1 and attach negative bus bar
  - Install module 2 and attach negative 2/positive 1 bus bar
  - Since module 1 is complete, cover module 1 with isolating foam
  - Continue installation
- If something does go fatally wrong with the battery pack (i.e. you drop a socket extension bar across the bus bars), the room will turn to smoke very quickly.
  - Evacuate and move away from building immediately
  - Call TE security at 650 361 3610
  - Call Tom (650 390 7174) to contact Jim Toth
  - Call Aaron (305 898 2869)
  - Prevent anyone from getting within 20m of building for 30 min

<u>Test Safety Requirements</u>

- Pack test to occur inside battery room with no personnel inside room.
- Continuously monitor the battery pack temp sensors (~270 of these) and also monitor the BMS boards temperature.
- Continuously monitor the battery pack voltage (via the BMS) and the current (Via an external current sensor).
- One person should be watching all the data and be solely responsible for any power on and power off of the packs based on the data.
- One person should be dedicated to fire control, this person should have the correct extinguisher, PPE and training.

<u>Method:</u>



- The fully built pack shall be connected to both the IPS charger and the resistive load and controlled completely remotely (outside battery room).
- For charging:
    - One relay will be gating the IPS charger and the pack. This will have to be closed manually and externally when ready to connect charger.
    - When closed, charger can be set up to provide 25A or less as needed.
    - Voltages, temperatures, and current must be monitored by BMS software and by personnel.
    - Voltage for all 18 modules must remain between 4.2V and 3.0V
    - Temperatures for all sensors must remain between 0°C and 40°C
    - Cabling must be rated to handle 25A. Minimum 6AWG or greater diameter.
- For discharging:
    - One relay will be same as expected to use in pack.
    - Another relay will be the safety relay designed for module and cell testing. Voltage inputs should be connected to a single module. Temperature input should be connected to a middle module body. This will have to be activated first, by an operator.
    - When closed, the 2Ω load will draw a current from the battery based on the battery voltage. Maximum 37.8A (6.3A per cell), minimum 27A (4.5A per cell). Discharge should take approximately 1 hour.
    - Voltages, temperatures, and current must be monitored by BMS software and by personnel.
    - Voltage for all 18 modules must remain between 4.2V and 3.0V

- Temperatures for all sensors must remain between 0°C and 40°C
- Cabling must be rated to handle 37.8A. Minimum 6AWG or greater diameter.

Procedure:

1. Charging:
    a. Initiate balancing mode until all voltages are +/- 10mV
    b. Close charger relay
    c. Initiate charge at 25A. Monitor carefully that no limits are violated during charge.
    d. When the first module reaches 4.2V, drop charge to 12A.
    e. When the first module reaches 4.2V, drop charge to 6A.
    f. When the first module reaches 4.2V, drop charge to 3A.
    g. When the first module reaches 4.2V, stop charge.
    h. Initiate balancing mode until all voltages are +/- 10mV
    i. Initiate charge at 3A.
    j. When the first module reaches 4.2V, end charge
2. Discharging:
    a. Ensure BMS discharge relay is open.
    b. Actuate safety circuit by pressing button for 5 seconds. When relay audibly clicks, exit room.
    c. Actuate BMS discharge relay, this will begin discharge.
    d. Monitor carefully that no limits are violated during charge.
    e. When the first module reaches 3.0V or when the safety circuit actuates, stop discharge.

Success Criteria: TBD