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SMART BATTERY BOARD SPECIFICATION DOCUMENT REV2.0

Board Rev 2.0

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1. Introduction

This document describes the design and operation of the Smart Battery Electronics system. There are in fact two electronics cards that are integral to the system but in general, they will be referred to as one as they are interdependent and permanently connected in operation. There is a mother board which integrates the power switching elements, electronic protection, controller, connectors and there are Daughter boards. These Daughter boards are individual measurement cards driven on a common SPI interface that are used use to monitor and balance each cell.

1.1. Processor

The processor used is the same as that used on the Power Control Boards and Power Switch Board, namely a PIC16F877, chosen for its reasonable code space (8K), 10 bit ADC channels and in circuit programmability. Software changes can be made via the RS485 connection.

1.2. Location, Mounting and Electrical Issues

The Mother Board is designed to mount with its underside attached to the lid of the battery pack. There are certain advantages to this. Primarily, it eases the design of the heat-sinks and secondly it simplifies the wiring problem as the penetrator cables can be shorter. This leaves the low current monitoring and sensing wires to be connected to the battery but these are more easily bent and cable formed. There are two holes in the Mother board through which the external penetrator wires will pass. These wires are designated the negative and positive cable but in fact the negative cable also carries RS485 communication and an enable line. The wires terminate in a Positive Pack Output stud located on the Mother Board and a Ground stud. The Ground stud is shared with the Battery Ground. Three wires from the “Negative” wire terminate in the only Minifit connector on the board and these are the RS485 and Enable lines. Other connectors includes the temperature monitoring (10 pin Microfit) , water alarm (2 pin Microfit) and a Positive Input power stud.

2. Precautions

There are a mixture of voltages on the Mother Board and ALL PARTS ARE LIVE, even with the Board Enable disconnected. The only suitable location for connecting a Ground referenced meter is to the Ground stud. Measurements on the current sensing circuitry have to be performed with care as the "-Ve" for this portion of the circuitry is referenced to the Battery Positive and the highest voltage sits at +6V above the Pack Voltage.

The daughter boards include test points located on the edge of the board. Whilst these are included for ease of testing, shorts between these test pins or connection of the ground of a ground referenced meter will certainly cause damage to the boards, the least of which will be the fusing of the Daughter Card fuses.

High temperatures may exist near the Power components. Running the Board at high currents in air without adequate heat-sinking may damage these components (the power diodes are unprotected components).

The Battery Pack to Board Power lines are un-fused (fusing is on the circuit board) and as such represent a hazard so care should be taken to avoid shorts in the cable.

3. Principle of Operation

3.1. Power and Power Up

For protection and Fuel Gauging estimation, the board has to maintain power to the current measurement circuitry whenever the pack is powered on. The current sensing circuitry consumes a reasonable current (10mA). Therefore leaving the board powered is not an option. In addition, the board requires a means of activation in the vehicle. So to simply solve both of these problems, one of the penetrators includes an enable wire. This enable wire runs to a magnetically operated reed switch situated in the sphere (Thales set up) which is used to take the line to ground. All packs share the same enable line and when grounded, an internal opto relay turns on and delivers power to the board. It is true that the optical relay is not strictly required there are no grounding issues. But this method effectively isolates cross-coupled fluctuations on the long enable conductor. This might otherwise affect the instrumentation perfomance and also serves to prevent damage to what would otherwise be a FET or Bipolar input to the board from mis-handling. In short, it's a robustness issue.

4. Master/Slave Power Switching.

Each board is capable of delivering 30 amps continuously. If all battery packs switched on instantaneously when power was applied then a fault condition could theoretically provide 90 Amps from 3 packs. This would result in rapid failure of wiring and connectors without causing a fuse to blow. Clearly this is unacceptable so the solution is that one pack is able to be designated a Master pack. It is this pack and only this pack that provides power when the enable line is grounded. This solves the high current problem and also solves the problem posed by having to have the vehicle powered in order to turn a battery on. Once powered, the vehicle can then turn on the remaining batteries at will. The method of designating the Master Pack is through the setting of an option in the RS485 communication link. It is highly recommended that only 1 pack be designated as a Master.

5. Safety and Protection.

5.1. Voltage / Current / Thermal Protection

The controller receives requests from the main vehicle computer to Charge or Discharge. The firmware in the controller decides whether the battery pack condition is okay and if so, toggles a line high as required. If the battery is within voltage and temperature limits the protection circuitry will turn on the Charge/ Discharge FETs.

The logic of the protection circuitry inherently prevents the activation of Charge and Discharge FETs at the same time. In addition, there are hard wired limits that prevent the activation of the FETs if the battery pack is over/under voltage, over temperature or if the pack goes over current during charge or discharge. This circuitry is in place to prevent failure of the firmware/ controller from causing catastrophic failure of the pack. In normal behaviour, the controller should act first (in the case of temperature and voltage shut off) but in the case of current surges, it is more likely although not guaranteed that the protection mechanism will turn off the pack first.

In addition, great care in the selection of the Power Switching devices means that the devices themselves are protected against thermal overload, over current, over voltage transients, inductive load switching and high DV/DT. To enhance the reliability of the switches, the pack output includes a freewheeling diode to ground for inductive load protection.

Because there are a number of ways in which the pack might turn off, there might be confusion so to summarise:

Firstly, the control processor monitors and turns off the pack in the case of a sustained high current that is deemed large enough to be out of spec but within the tolerance of the other protection systems (say 30.5 Amps).

Secondly a hard-wired comparator monitors and turns off the pack (transient filtering is included) the instant the current builds up above the comparator threshold for longer that the filter time constant.

Thirdly, the Fets themselves can turn off but this is in the case where the individual current limits have been exceeded or the die temperature is too high

Fourth, to complete the suite, there is an automotive style – non-resetable Blade fuse that will permanently disconnect the Battery from the input.

In addition to protection of the power components, the board itself has a non-resetable fuse as does each and every daughter board.

5.2. Communications failure / Watchdog Activity

The board expects a valid communication from the MVC or charge computer within a certain time. If no communication is received then the board will shut down all power outputs but remain communicative.

5.3. Monitoring

5.3.1. Cell voltages

Cell voltages are monitored via the daughter cards. Each daughter card hosts a very low power (but slow) 16 bit ADC and an optically isolated SPI link. The input to the ADC is taken directly from each cell through a resistive divider. This means that each card is completely isolated from the Mother Board but being a string measurement is not isolated from its neighbor. At the top of each card is a test point that is connected to the high side of the cell. During communication, the boards use up to 10mA of current per board but in the off state this figure reduces to a theoretical maximum of 2uA (To be measured). The boards are powered from the cells themselves and are always on regardless of the state of the enable line.

5.3.2. Pack Voltage

Pack voltage is monitored through a resistive divider network on the Mother board. The voltage is measured to an accuracy of 10 bits (Approx. 40mV).

5.3.3. Temperature

There are 4 temperature sensors that are all based upon the LM35DZ placed in the battery pack. Four of the sensors are mounted in the battery pack proper and 1 is mounted on the Mother Board. Thus there is a means of distinguishing the oil temperature from the Pack temperature. All sensors are read with an accuracy of 10 bits.

5.3.4. Current

Current is measured on the high side using a floating isolated measurement system. The reason for using this and not a LEM style Hall effect sensor is that there is a power tradeoff at around 18 Amps. This means that at 18 Amps, it becomes more effective to use the LEM sensor. In the main, the boards are intended to be used at lower currents so it is preferable to use this alternative. In this scheme, the current across a small sense resistor is optically transferred to a low side op-amp which is measured with 10 bit resolution. Low side current sensing was considered but found to confuse the grounding arrangements considerably.

5.4. Balancing

The battery board has been designed with the capability of battery balancing built in.

The reason for balancing is forced by the fact that the cells are being charged in series. When a cell reaches 4.2V, the charger should go into a constant voltage mode (uncontrollable for all cells in series) rather than the constant current mode (controllable). To ensure that all cells are charged to the maximum; all cells should reach the 4.2V limit at exactly the same time. In practice, this is nigh on impossible but we can approach a solution by reducing the energy stored in the cells having the highest stored energy.

There are three methods:

1) Balance when flat or partially discharged.
2) Balance when charging.
3) Balance in operation.

Balancing when flat is attractive because the pack will be off and not generating heat in the electronics pocket and the accuracy of the voltage measure is good because the gradient of the discharge slope is high. It is likely that the vehicle will be returning to the surface with flat batteries and therefore no time is wasted if balancing is performed at this time.

Balancing when charging is attractive because it is possible that if a cell can be held below 4.2V by a balancing resistor, then all cells could theoretically reach 4.2V at the same time, the charge could drop into constant voltage mode and the charge process could approximate the Valence charge curve accurately. It is not clear at this moment if a small load will be sufficient or whether full charge current has to be diverted around the cell. Regardless of whether it is sufficient, it is impractical to divert the entire charge current around the cell (4.2 volts * 15 Amps=63W) so a fraction of the current must be used.

Balancing in operation seems reasonable until power is considered. One argument is that the capacity of the lowest cell defines the pack capacity; therefore, creaming off the top shouldn't affect the total capacity available. This is wrong because power is the product of current and voltage and if the pack loses volts, the pack current has to rise to preserve the same power output.

It seems therefore, that the answer is to balance when the pack is low and during charging. The balancing resistor chosen at present is 8.4 ohms; this resistor and the voltage drop across the Darlington drive gives a balance current of between 300 mA and 500mA.

Absolute worst possible scenario is that the highest brick combination is fully charged (125AH or 420 W/H assuming cell voltage of 4.1V) and the lowest is fully discharged (0). Time taken to balance is therefore of the order of 17 days.

5.4.1. Instrumentation Problem During Balancing

To eliminate wiring, the balancing discharge resistors share the same wire as the measurement system. Unfortunately this method introduces an error due to the voltage drop across the wires during balancing. Therefore, to make a measurement when balancing, any load resistors across cells must be turned off. This method seems complex, but it is sensible considering the additional wiring that would be required for the optimum (4 wire) solution.

5.5. Communication Protocol

Communications are half duplex RS485. Multiple boards can be daisy chained together but the boards are not networked in the true sense. No board can see any other board (at present). Each board has a unique but programmable 2-digit address, but each board responds to the address 0. The reasoning for this is that in the field, or anytime one is presented with a battery with an unknown address, it can be connected to a computer and it will always respond to the board address 0. To facilitate the identification of battery board in vehicle, a strategy has been adopted whereby each board will respond to a synchronization command after a delay calculated as the product of its address and 4mS. Simply put, the higher the address, the longer the board takes to respond to an address request. This means that there shouldn't be a bus contention.

5.6. Power

There are 4 Power FETs on the board and 2 Power diodes. During charge or discharge, two FETs and 1 diode are on and conducting current. The switching mechanism allows current to steer around the "Off" pair of FETs

5.7. Fault Handling

If any fault is detected, charge and discharge switches are switched off and latched off permanently. The boards can be reset only after the fault has been removed AND a specific sequence is transmitted to the board; this sequence is detailed in the communication firmware spec. In the fault condition, the board locks the value and the parameter that caused the fault for diagnosis.

5.8. Charging and the Charge Process

The inclusion of the Power Switching components and protection diodes in the Battery Packs has several advantages, not least of which is the ability to charge batteries in-situ . The reason this can work is because the Charge FETs allow control over the individual batteries. One way in which this scheme may work is that the shore power cable is attached to the vehicle in the normal way and a charge computer is allowed to talk to the battery packs directly through the Ethernet/ serial interface inherent on the MVC. The Battery charge computer then enables the charge FET on the appropriate pack and charging takes place. The small pertubation in charge current during the constant current mode caused by the vehicle itself should not affect the process unduly.

5.9. Charge Process

It is impossible to control individual cell voltages in a series configuration but it is possible to charge one of those cells in the correct manner by using a procedure similar to that applied to a single cell.

(My) understanding of the process of charging a single cell is as follows: The cell is charged at a maximum constant current of C/4 until the point when the cell voltage rises to 4.2 volts. At this point, the power supply must switch from current limiting mode to voltage limiting mode and hold the cell voltage at 4.2 volts. As the cell EMF increases, the current flowing through the cell must reduce until equilibrium is restored between source and cell. However there is a limit on this action because the cell chemistry changes, eventually causing failure of the cell through dendritic growth. That aside, the fact remains that it is the cell that controls the current and not the supply. When the current falls to C/20, the charge must be stopped.

In the case of 2 cells charging in series, the same method can be employed, but individual cells must be monitored and computer control of the supply is required. Initially, the cells are charged at C/4 until one of the cells reaches 4.2 volts. Then, regardless of the voltage of the other cell, the power supply must clamp the voltage across both of the cells. This will stop the higher voltage cell from rising above 4.2V. This cell will now control the current as before and the charge should be terminated at C/20. There is an additional problem that I am unsure of and that is that the second cell may be close to the first cell in voltage. It too tries to rise in voltage but is prevented from doing so, so it too may control the current. This may lead to the situation where the current falls off faster than would be expected. Allowing the supply voltage to increase slightly so that the second cell can catch up may allow the second cell to reach 4.2 volts but it might not and the result may be that the first cell simply increases to 4.3 volts instead. The optimum solution is not apparent, but the balancing circuitry might be used during charging to ensure that all cells arrive at 4.2 volts at almost the same time.

The more complex solution is to pulse the power supply on and off and measure the open circuit cell voltages during the off time. The power supply voltage is then adjusted to equal the sum of the cell voltages. Again, quite how this would function in practice is unclear at this time.

Using the balancing circuitry to “slow down” the rate of charge of particular cells should allow all cells to reach 4.2 volts at the same time and negate many of the problems posed herein, but again this requires some testing to validate.

5.10. Calibration

The boards have been designed to minimize the requirement for calibration but some calibration is required. To this end, the firmware includes calibration routines for the daughter boards and the current monitoring. The temperature sensors do not require calibration.

5.11. Current Sharing and Operational Optimization

It is well known that MOSFET transistors share current when used in parallel. But this is only true if the MOSFETS are at the same temperature. It is assumed that the heatsinks on the Battery Packs will be at roughly the same temperature but this cannot be guaranteed. In this case, the Power Switches will tend to have the same temperature, therefore the same $R_{DS}On$, and will therefore tend to share current equally. The inclusion of the diode onto the battery monitoring board confuses this scheme a little. Whereas the MOSFETs act to reduce current as they heat, the diodes display the opposite transfer function. Of concern, is the runway thermal effect that the diodes pose but the MOSFETs with their inherent protection and electrical characteristic should prevent this unwanted failure mode in all but the most extreme cases of misuse as they are connected in series with the diodes. The heatsinks are large enough to keep the diode junction temperature below failure in most conditions. The failure mode for the diode is likely to be non-conduction. The allowable operating conditions are specified in XXX

5.12. Power Dissipation and Efficiency

The efficiency of the Power delivery system is key to vehicle performance and a design goal is to maximize this efficiency. As expected, operational and other matters force trade offs which degrade this performance metric. Some trade offs in this design are volumetric efficiency, weight and availability of suitable, high voltage, high current switching components and the desire to interconnect packs in parallel. All losses in the Power delivery system are seen as thermal dissipation. Figure 1shows the Power Dissipation versus current.

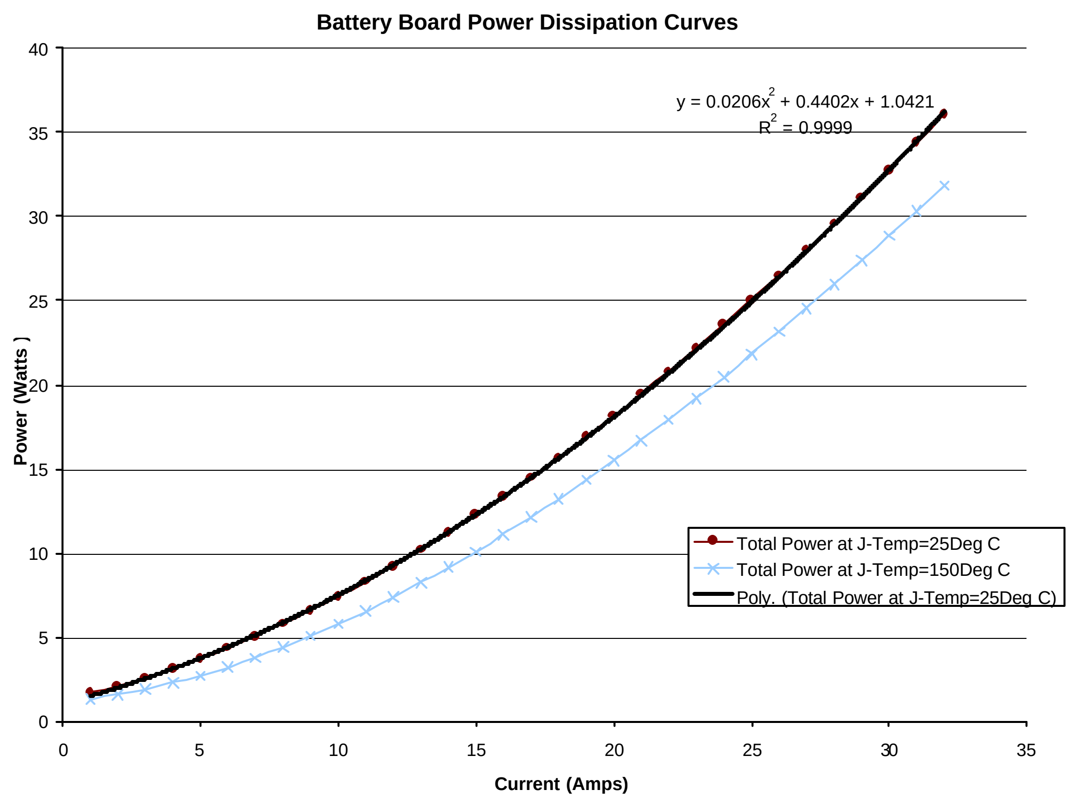


Figure 1:Graph of Power Dissipation Versus Current For Smart Battery Board.
Assumptions and Conditions as outlined in XX

1. Thermal Characteristics

At high current output and high ambient conditions, heat dissipation from the Power components becomes a significant problem. This problem has been modeled and the results are presented in Figure 2. The Assumption and operating conditions for the model are shown in Table 1.

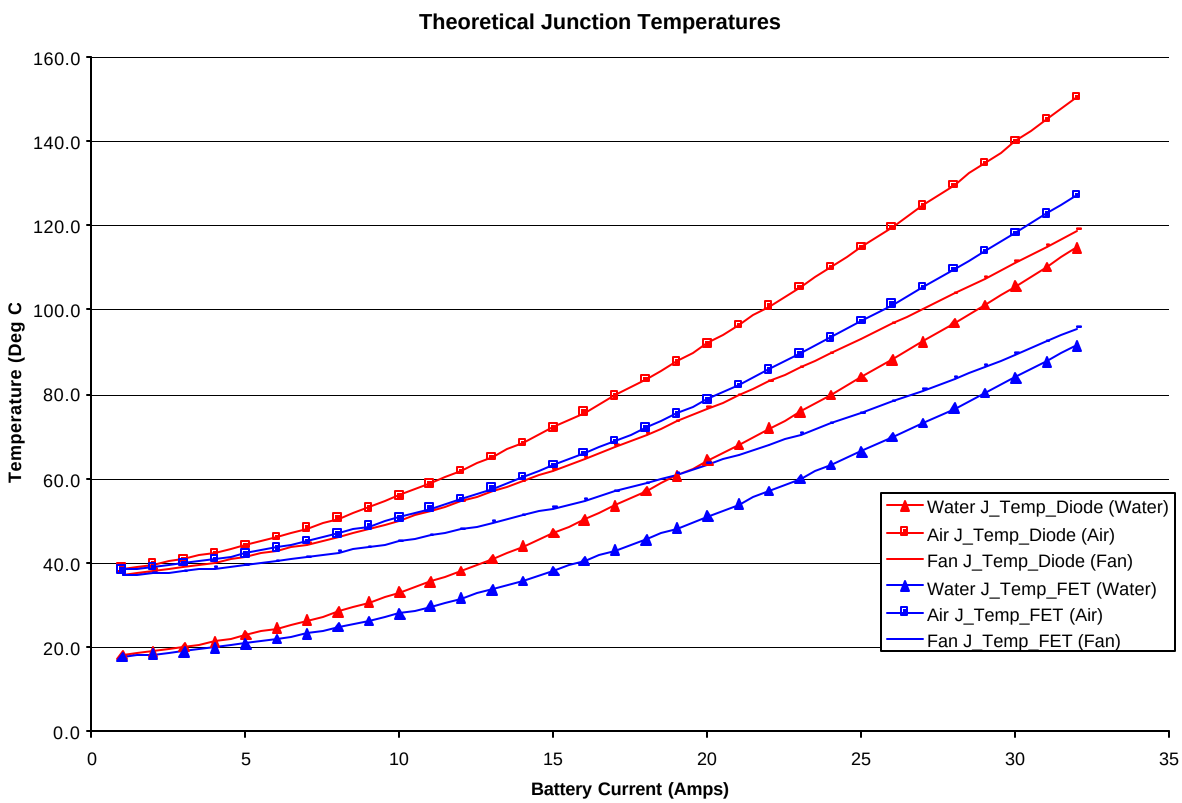


Figure 2: Graph of Junction Temperature for Power Components Versus Battery Current. Assumptions and Conditions as outlined in Table X

Diode Data	Thermal resistance(C/W)	
J_case	1.4	From data sheet
Case_Stub	0.5	From data sheet
Profet	Thermal resistance(C/W)	
J_case	0.75	From data sheet
Case_Stub	0.5	From data sheet
Stub	Thermal resistance(C/W)	
Stub_Sink	1	Calculated
Heatsink	Thermal Resistance(C/W)	
Sink_Water	1	Estimate
Sink_Air	1.5	Estimate
Sink_Air_Fan	0.5	Estimate
Water Temp	15	Estimate
Air Temp	35	Estimate

Table 1: Table of Assumptions and Conditions for the theoretical calculation of temperature for the Power Switching components.

TESTING

2. Pressure Tests

Some components have been previously pressure tested, those that haven't and affect eh accuracy of the instrumentation system are detailed in this section.

3. Daughter Board-Analog to Digital Converter Pressure Tests

3.1. Purpose

The Smart Battery Monitor Boards measure the voltage of each individual cell in the battery using a circuit referred to as the "floating ADC." Basically, each cell has its own TC3400 ADC (powered by the cell itself) for measuring its voltage. Since the cell voltages are not referenced to ground, the results are communicated digitally across an opto-isolator to the micro-controller. To simulate the stresses that the circuit would be subjected to during operation, it was tested in the pressure vessel.

3.2. Circuit

The circuit is that of the Daughter Board (See Schematic XX). Essentially a resistive divider network reduces the input voltage to the span of the ADC input voltage.

The circuit consists of the following parts:

MAX666	Voltage regulator
TC3400	Analog to Digital converter (ADC)
4n37	Opto-isolator (x2)
3906	PNP small signal transistor
Discretes	Resistors and tantalum capacitors

3.3. Procedure

The circuit was immersed in oil and pressurized to 7000 psi 10 times. Dive times ranged from 10 to 20 minutes while hold times at 7000 psi ranged from 0 to 60 minutes. Results recorded include ADC reading, pressure, Vcc (+2.5V supply from the MAX666), and Vin (input of the TC3400). Due to difficulties in operating the pressure vessel, not all pressurization cycles were recorded.

3.4. Results

All components in the circuit functioned normally throughout the test. Neither Vcc nor Vin showed any changes within the accuracy of the multimeter used to measure them. The ADC output reading changed exhibited a linear change with pressure, but the magnitude of the change was always less than .2% of the ADC's total scale (0 to 32767).

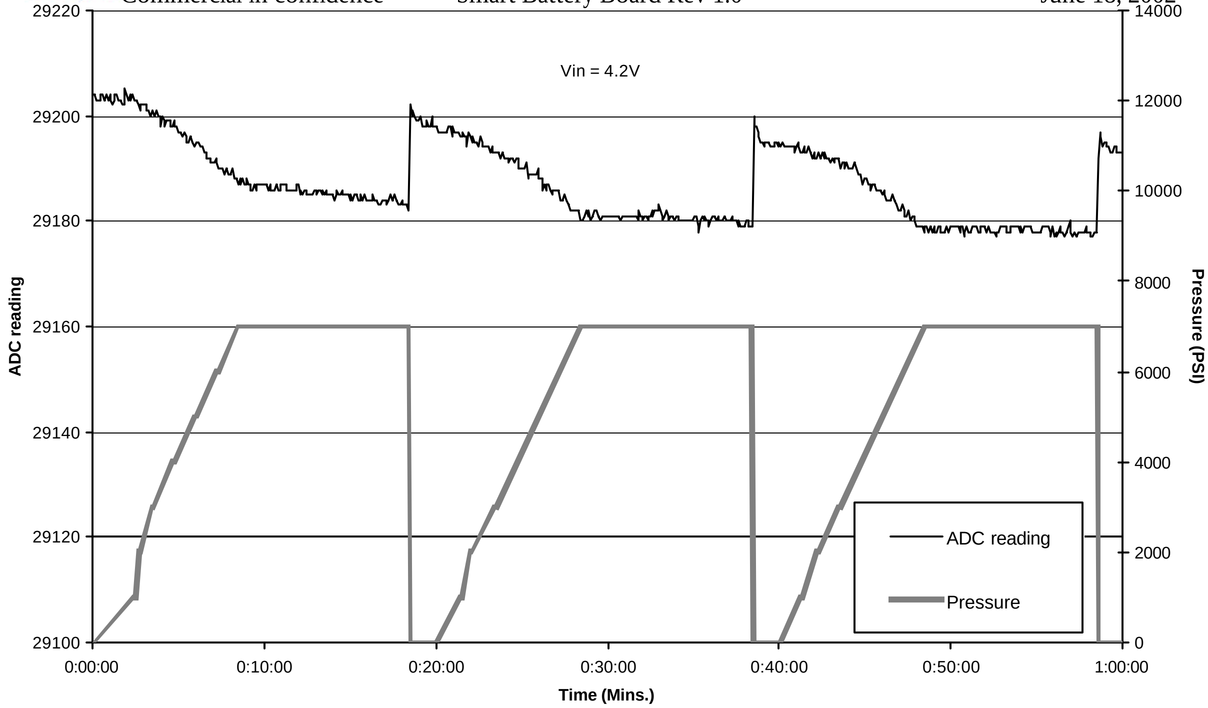
Figure 3A shows the ADC reading and pressure during three dives in an early test. It is interesting to note the strong linearity between the two.

Figure 3 B shows the ADC readings and pressure after the resistors in the voltage divider that creates Vin were changed to metal film type (it was necessary to change the resistors to minimize the effect of making multimeter measurements at that point). Note that with the new resistors, the ADC reading dropped with the pressure rather than rising.

3.5. Conclusions

The floating ADC circuit appears to be tolerant of pressure and deviates by less than .2% of its scale. Based on the difference between the results before and after the resistors were changed from carbon to metal film, it appears that most significant pressure sensitivity is due to its effect on the resistance values. In the production Daughter boards, surface mount metal film resistors are used for sensitive values. Thin film resistors are preffered but due to procurement difficulty it is only practical to use these if the boards are manufactured externally.

"Floating" ADC Pressure Tests



"Floating" ADC Pressure Test using 5% Carbon

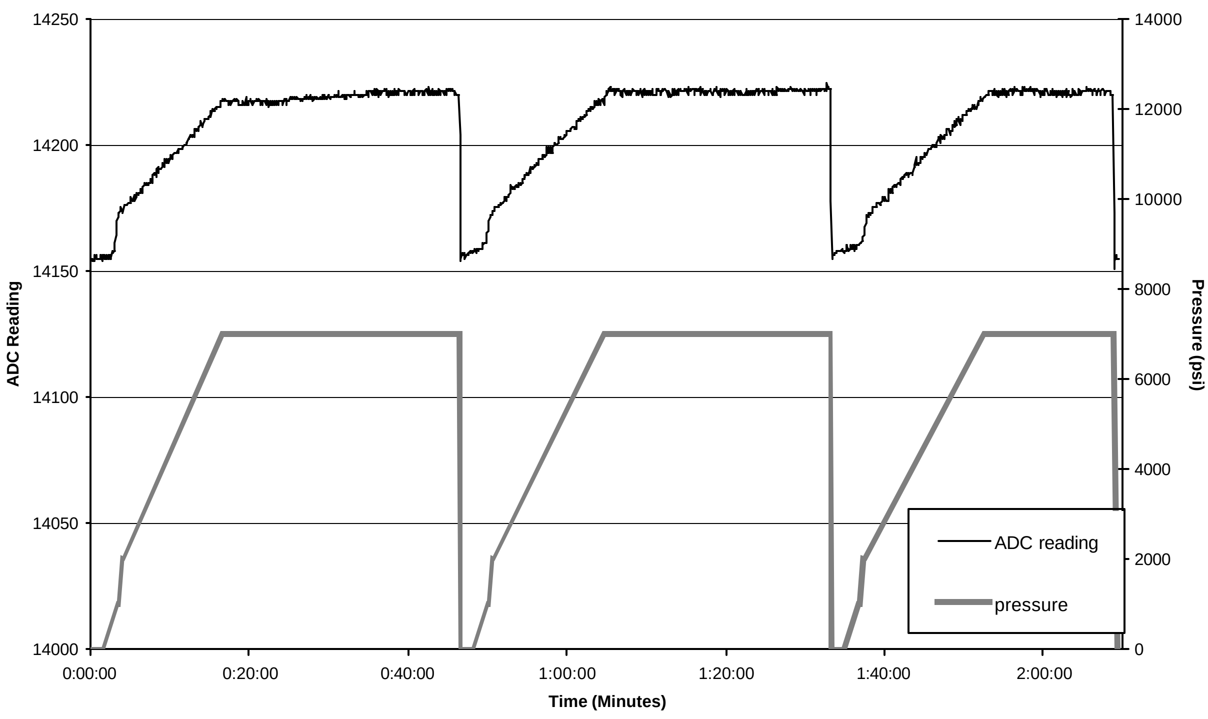


Figure 3:Graphs of ADC readings Versus Applied Pressure for the Smart Battery Monitoring Boards in the case of Carbon and Metal film resistors.

4. Mother Board Current Monitor Tests

4.1. Purpose

A difficulty with the design and implementation of current measurement circuitry is that the only suitable isolated current measuring systems available use a considerable amount of current. To solve this problem a floating current monitor based around the use of a linear optocoupler has been designed and tested at pressure. The linearity of the device is seen in the graph of output voltage versus current over 2 pressure ranges can be seen in Figure 4 .

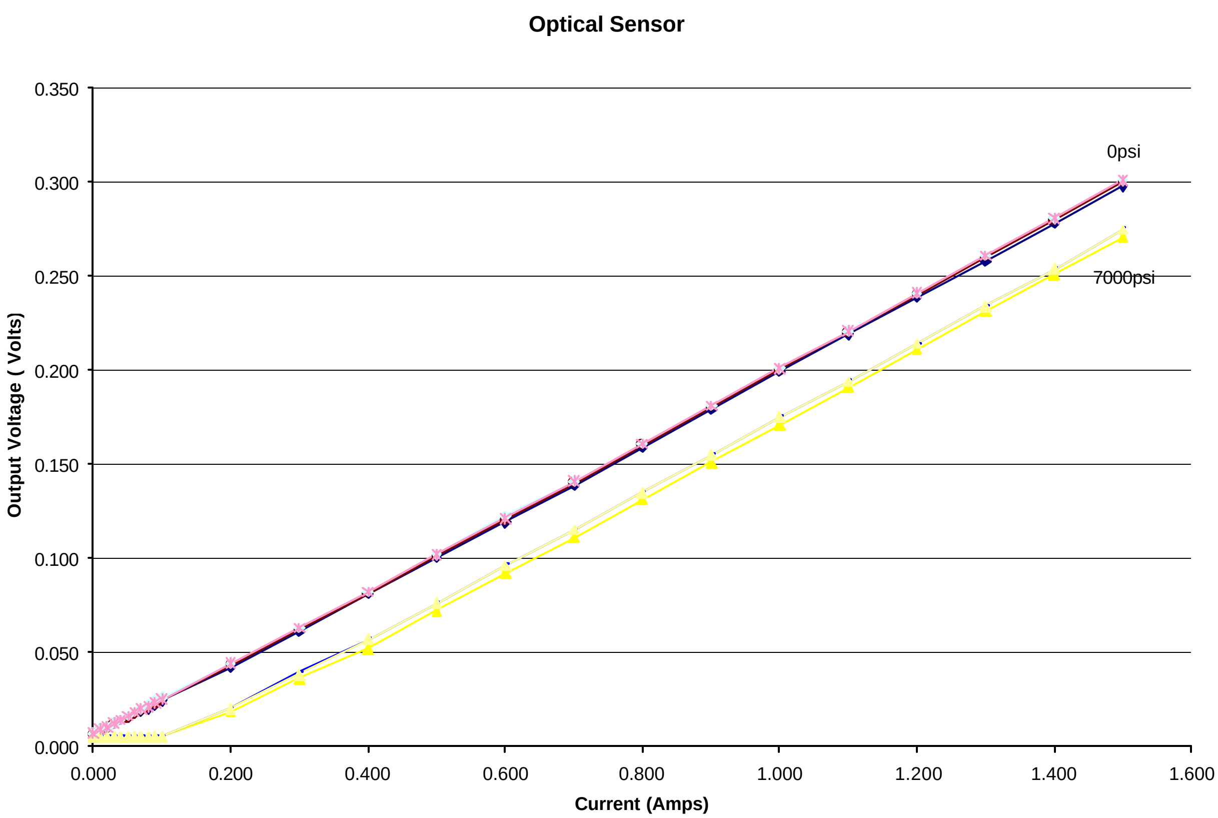


Figure 4: Voltage output from Optical Current sensor over a range of current at two different pressures.

4.2. Procedure

The current was adjusted externally to the pressure housing and the measured output was recorded for a range of currents.

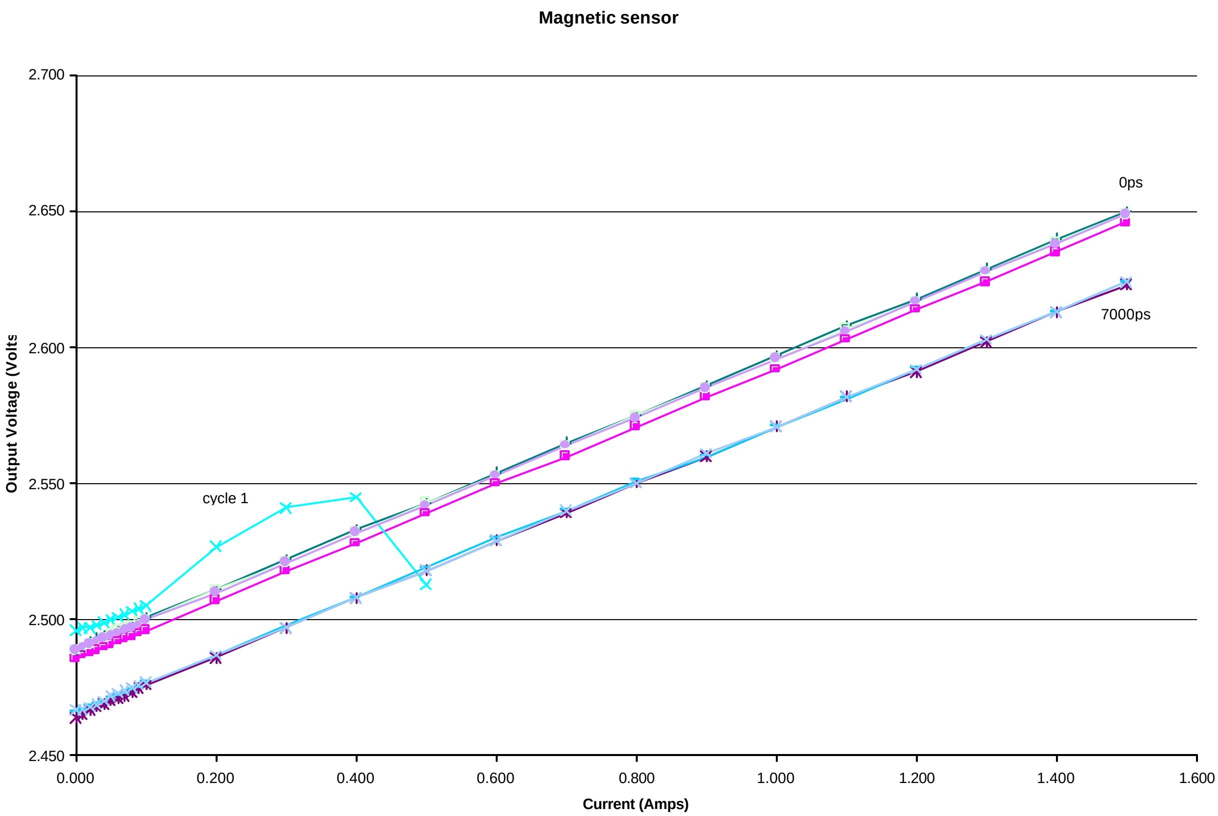


Figure 5: Magnetic sensor voltage output over a range of current at two different pressures.

4.3. Conclusions

The floating ADC circuit appears to be tolerant of pressure and deviates by less than .2% of its scale. Based on the difference between the results before and after the resistors were changed, it appears that the significant pressure sensitivity is due to resistance changes.

5. Power Component tests

5.1. Purpose

Power components were taken down to a pressure of 7000PSI following the same test regimen as the Magnetic / Optical sensors.

5.2. Procedure

6. Resistor Components Pressure Test

6.1. Purpose

Pressure tests were performed to measure the pressure sensitivity of several varieties of resistor include 1% Metal Film (axial), 5% Carbon Film (axial), 1% SMT Thick Film, and 5% SMT Thick Film.

6.2. Procedure

Two values (1K and 100K) of each resistor (except %5 SMT which was represented only by a single 100K) were placed in oil in the pressure vessel and pressurized to 7000psi three times. Using a multi-meter, the resistance of each resistor was measured at the top and bottom of each pressurization cycle.

6.3. Results

The resistance values for the 100K resistors as a function of pressure are shown in Figure 6. All of the varieties of resistors showed an obvious but small response to pressure. The Metal Film resistors performed the best, demonstrating a change of less than 0.1% with pressure.

The Carbon Film resistors showed a much larger sensitivity, though still less than 1% of their value. The SMT Thick Film resistors showed the greatest sensitivity, but this was still less than 1% of their value.

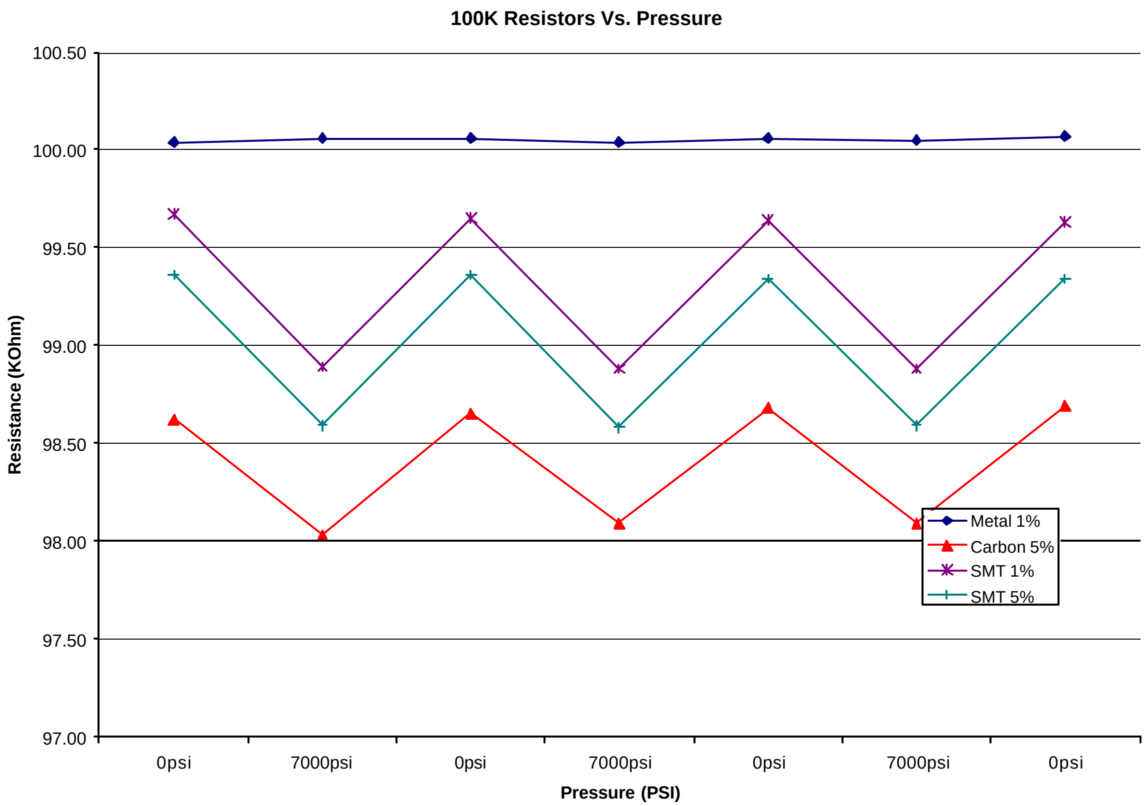


Figure 6: Graphs of the effect of pressure on differing types of resistive components.

7. Temperature Tests

To be done

8. Load Tests

8.1. (Preliminary)

Prior to building the circuit boards, the power component circuitry was tested to verify that the paralleling of the 4 Power FETs in the back to back Charge / Discharge circuitry performed as expected. Preliminary testing using two power supplies and an electronic load proved that the circuitry worked as intended up to a voltage of 40 Volts and a current of 30 Amps in ambient conditions of 21°C. Heat-sinking was minimal (4°C/Watt). Because of this, the devices could not sustain the high output current and shut off, thus proving their functionality.

8.2. (Thorough)

To be done

SPECIFICATIONS

This Chapter is broken into two sections; one where the specifications are verbosely described and the other just giving the Specifications in a table. Each section describing an event or specification is broken down into the subsections that cause the event or spec. For instance there are many ways in which power shut down can occur and each of these is listed below the general heading of Power Shut-down.

9. Specifications

9.1. Watchdog Timeout

If no valid communication has been received within 60 seconds then the Charge and Discharge Power FETs will be turned off permanently.

9.2. Power Shut-down

9.2.1. Watchdog Timeout (see Watchdog Timeout)

9.2.2. Temperature Exceptions

9.2.2.1. Over Temperature FETs

If a FET device junction temperature exceeds 125 °C the Power FET affected automatically turns off and tells the processor that it has shut off. This is a device independent function.

9.2.2.2. Over Temperature Oil

The PIC measures the oil temperature, if the oil temperature exceeds a preset of 50°C, the Power FETs and balancing resistors shut off.

9.2.2.3. Over Temperature Batteries

If any battery temperature exceeds 45°C XXXX, the PIC will turn off, all power FETs and balancing resistors.

If any battery temperature exceeds 50.47°C XXXX, the protection circuitry will turn off the power FETs.

9.2.2.4. High Ambient Conditions

The ambient temperature (i.e. the temperature outside the battery pack) is not measured. In conditions of high ambient temperature, the pack output current must be derated. The derating is linear with current (TBD)

9.2.3. Over Current

9.2.3.1. PROFET Device shutdown

If the internal Over Current limit of 70 Amps (transient) is exceeded then the PROFETs will shut down. In addition they will not switch on into a short.

9.2.3.2. Over Temperature

If the internal temperature limit of 125°C is exceeded the PROFETs will turn off. Depending on device availability and experience in use, the auto-start on cooling version of this device may be used in place of the permanently off devices. This mechanism can be invoked by over current or high ambient conditions.

9.2.3.3. Main Fuse

Non resettable fuse set at 40 Amps. Replacement requires the removal of the cover and the de-soldering of the fuse from the board. This fuse should never blow. If it does it suggests that a failure of the electronic monitoring system has occurred. The battery pack should be serviced by trained personnel only.

9.2.4. Over Voltage

9.2.4.1. Controller

The PIC measures the pack and cell voltages, if any voltages exceed 4.2volts then the charge FETs are turned off.

9.2.4.2. Over voltage protection circuit

If any voltages exceed 4.2 XXXX volts then the charge FETs are turned off.

9.2.5. Under Voltage

9.2.5.1. Controller

If the pack voltage falls below 26.4 XXXX volts, or if any cell voltage falls below 3.1 XXXX volts then the discharge Fets are turned off

9.2.5.2. Under voltage protection circuit

If the pack voltage falls below 25.6 XXXX volts, or if any cell voltage falls below XX volts then the discharge Fets are turned off

9.2.6. Balancing/ Daughter Board Protection

9.2.6.1. Controller

The controller switches the balance resistors on and off. If the individual cell voltages fall below 3.1XXXX V then the controller will turn the balance resistors off.

9.2.6.2. Balance/Daughter Board Fusing

Each daughter board is fused. If the current for any daughter board exceeds 2 XXXX amps then the individual board fuse will blow.

9.2.6.3. Balance/Daughter Board Failure

A failed board will not return a correct voltage measurement and thus the controller should be able to detect the failure. If a daughter board has failed then the controller should turn off the Charge/Discharge FETs. If a board does fail then the entire pack should be discarded until the electronics has been replaced.

9.3. Absolute Maximum specs

Maximum Input Voltage	40VXXXX
Minimum Input Voltage	24VXXXX
Output Current	30A
Temperature	80^{o}C

The board components have been selected to work between 0 and 80^{o}C, however over the linearity and accuracy of the measurement systems are affected by temperature and the board should not be used outside of 0 to 50^{o}C.

Storage Temperature	-10<80^{oO}C
Humidity	0

9.4. Measured Board Current

Board Disabled (Enable High or Floating)	
Board Current	XXXXmA
Cell Current	XXXXmA
Total Pack Current	XXXXmA
Quiescent (Enable Grounded)	XXXXmA
Transmitting (RS485)	XXXXmA
Cell voltage measurement	XXXXmA
Current Measurement	XXXXmA
Temperature Measurement	XXXXmA
Charge FETs On	XXXXmA
Discharge FETs On	XXXXmA
Balance On	XXXXmA
Board Current Off	XXXXmA

9.5. Accuracy

9.5.1. Pack Voltage	10 bit conversion / 35mV 36 volts FSR
9.5.2. Cell Voltage	16 bit conversion / 68uV 4.5 volts FSR
9.5.3. Current Measurement	10 bit conversion / 30mA 30 Amps FSR
9.5.4. Fuel Gauging	10%

Basic measurement accuracy should be better than 5% for current and better than 5% for pack voltage. However it is difficult to estimate the error introduced by measurement of loaded rather than unloaded cells and the compounded integration errors over time, but it is likely that the estimate will be better than 15% initially.

9.6. Cell Specifications

Absolute Minimum Voltage	3.0 Volts
Absolute Maximum Voltage	4.2 Volts
Temperature	-10<60°C
Operational Minimum	3.1 Volts
Operational Maximum	4.2 Volts
Average Voltage	3.8 AH
Expected Capacity per cell	4.3 AH

9.7. Mission Specifications (Suggested)

Maximum Pack Current (Hard Wired)	30A
Minimum Cell voltage	3.2V
Minimum Pack Voltage	25.6V

9.8. Environmental

9.8.1.1. Temperature

There are 4 temperature monitoring sensors distributed through the battery pack. These temperatures are monitored by the controller and the protection circuitry. See Temperature exception in the Power Down section.

9.8.1.2. Pressure Range *<7000PSI*

Components individually tested to operate at 7000PSI. Complete system testing TBD.

9.8.1.3. Oil temperature (1)

There is one temperature sensor located in the oil pocket

9.8.1.4. Water alarms (1) *<7k?*

There is one water alarm located in the electronics pocket. If water is detected (Impedance less than 6 to 7k?), the board will issue a water detected alarm via the serial port (when communication is requested) and latch on. The Charge / Discharge FETs will be turned off.

9.9. Reliable operating curve. (I versus ambient T)

9.9.1.1. Maximum current versus ambient temperature

9.9.1.2.

9.9.1.3. Table 2: General Specifications.

10. Board outline and connector location

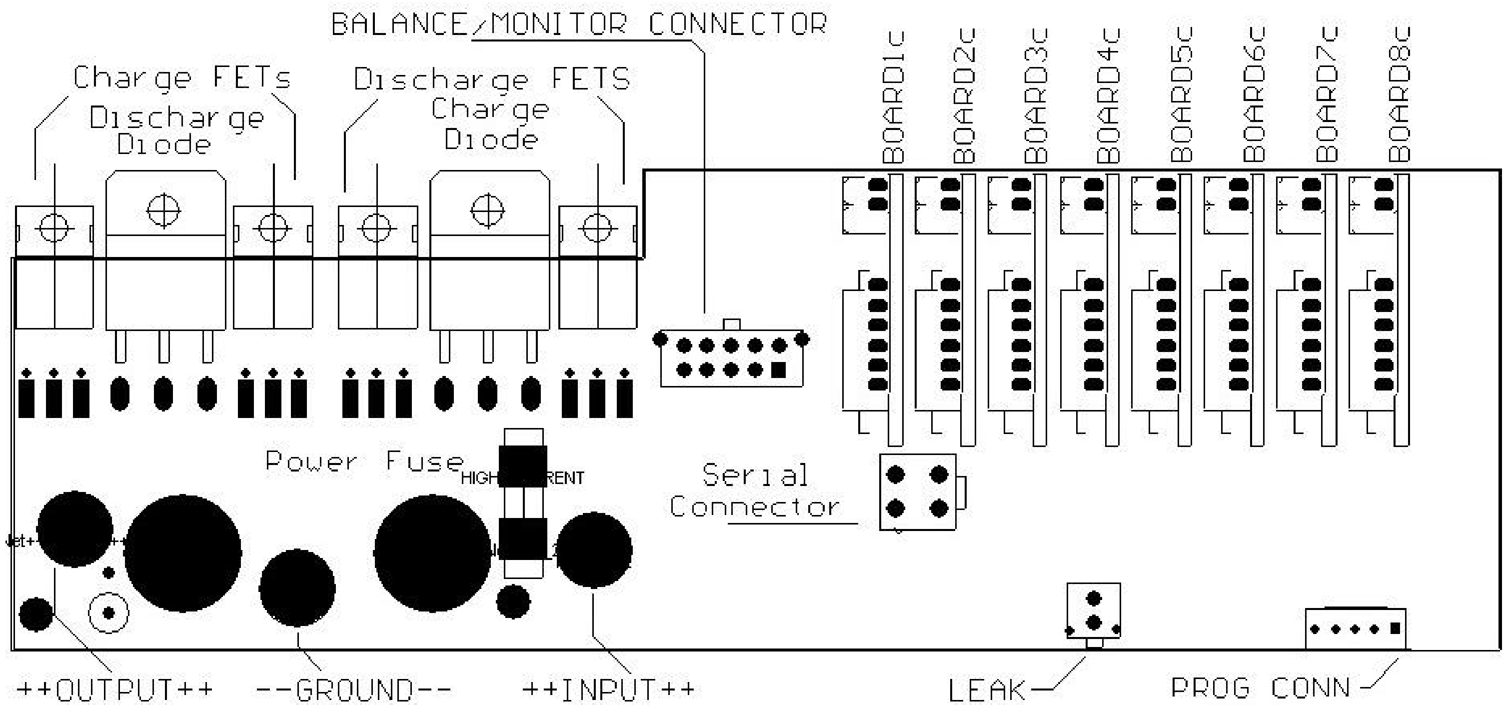


Figure 7: Plan view of board showing connector positions.

BATTERYBOARD FIRMWARE COMMUNICATION PROTOCOL

11. Input Specification

#[aa][b][c] <arg>[\r or \n]

aa - address (hex)
b – command
c - circuit (hex)

[] - required
<> - optional

The start of a new message is signaled by the '#' character. This character is reserved and may not appear elsewhere.

This character is immediately followed by four bytes. The first two bytes make up a hex number that specifies which battery board is being addressed. The third byte is interpreted as the command and the fourth as a circuit number (in hex).

Some commands require additional data. In these cases, the argument should be separated from the command by a single space (' ').

All commands must be terminated with a '\r' or '\n'

12. Output Specification

$[aa][b][c] [value][\r\n]

In response to a message, the BatteryBoard sends a '$' character followed by an echo of the address, command, and circuit, and then, a space and the return value. Return values vary with command and are often a 1 or 0 (TRUE or FALSE) or a more complicated string.

Finally, the response is terminated with a "\r\n."

13. Addresses

Each board has a two-digit hex address stored in EEPROM which allows the MVC to talk to multiple boards sharing the same RS485 bus. Boards only respond to messages addressed to them or to address 0x00. Note that since all boards respond to address 0x00 at the same time, messages should only be sent to this address when only one battery is connected.

Since boards are "born" with the address 0xFF, it is recommended (but not required) that this address not be used.

14. Calibrations

Sensor values are computed by using a single sample point to scale the sensor readings to the real values. This assumes that (1) the sensors are linear and (2) the sensors have 0 offsets. These conditions appear to be satisfied, though further confirmation is recommended.

Calibrations are performed using a multimeter or other measurement device. The quantity in question is directly measured, and then the BatteryBoard is informed of the actual value. The BatteryBoard adjusts its conversion function so that the observed value matches the actual value.

Calibration values are stored in EEPROM, so they persist through board resets and power-downs.

15. Command and Query Summary

This section provides a list of all the commands and queries that the board responds to. Where possible, commands have been chosen to represent a word; For instance, the command D for Discharge. Where logical or possible, this has been highlighted in bold print.

15.1. Commands

Commands are used to force the board to perform an action

Command	Return	Description
? - address query		
?0	hex	print address
?8 <hex>	0 / 1	set address
B - **B**attery commands		
bf	0 / 1	battery o**F**f (also clears errors)
bd	0 / 1	Discharge battery
bc	0 / 1	**C**harge battery
bb	0 / 1	**B**alance Battery
Q – **Q**ueries		
q0	string	battery summary (see below)
q1	string	cell voltages (see below)
q2	string	temperatures (see below)
V – battery **V**oltage		
v0	float	print battery voltage
v8 <float>	0 / 1	calibrate battery voltage
I – battery current (**I** is for Amps!)		
i0	float	print battery current
i8 <float>	0 / 1	calibrate battery current

K – temperatures (**K**elvin!)

k0-k3	float	print cell temperatures
k4	float	print oil temperature

note: temperatures are not currently calibrated

C – **C**ell voltages

c0-c7	float	print cell voltage
c8-cf <float>	0 / 1	calibrate cell voltage

E – battery **E**nergy

e0	float	print battery energy
e8 <float>	0 / 1	set battery energy

M – **M**aster mode

m0	1	set as secondary pack
m1	1	set as primary pack
m2-mf	0 / 1	is this a master?

S - **S**treaming mode

s0	1	stream off
s1 <int>	1	stream on (at given period, if specified)

T - **T**ime

t0	string	print time
t8 ##:##:##	0 / 1	set time

Z – vers(**Z**)ion info

z0	string	print version
z1	hex	print serial number
z9 <hex>	0 / 1	set serial number (Can only be done once!)

P - **P**rocessor commands

p0 bootload	0 / -	start bootloader (if present)
p1 reset	0 / -	reset PIC

p2 sleep	0/-	sleep PIC
p3 halt	0/-	crash board

15.2. Queries

Queries are used to obtain information about the battery board.

q0 - battery summary

Sample: `$ffq0 c- 30.76 14.99 38.14 3.77 3.82 0   806.91 06:31:43`

Total: 58 bytes

Bytes	Meaning
4+1	$ and command echo
2+1	battery and error state (see below)
5+1	battery voltage (##.## V)
5+1	battery current (##.## A)
5+1	max temperature (##.## C)
4+1	min cell voltage (#.## V)
4+1	max cell voltage (#.## V)
1+1	water alarm (0/1)
8+1	estimated capacity (####.## WH)
8	current time (##:##:##)
2	\r\n

q1 - cell voltages

Sample: `$ffq1 3.77 3.80 3.81 3.80 3.78 3.79 3.82 3.80`

Total: 48 bytes

Bytes	Meaning

5+1	$ and command echo
8x(4+1)	cell voltages (#.## V)
2	\r\n

q2 - temperatures

Sample: `$ffq2 37.02 35.14 38.14 33.32 27.54`

Total: 38 bytes

Bytes	Meaning
5+1	$ and command echo
4x(5+1)	temperatures 0 to 3 (##.## C)
5+1	oil temperature (##.## C)
2	\r\n

16. Battery States

The BatteryBoard monitors the state of several vital battery characteristics and performs an emergency shutdown if specific preset thresholds are violated. This means that the actual state of operation of the battery can change without notice.

The firmware determines the state (with a mechanism independent of the mechanisms which change the state) and records any event leading to a battery shutdown. These are expressed as the “battery state” which represents the current condition of the battery, and the “error state” which shows the reason for a shutdown (if one has occurred). These are reported in the battery summary query.

The possible battery states are:

16.1. Battery State:

f - off

d - discharging

c - charging

16.2. Error State:

-all clear

V	battery over-voltage (charging only)
V	battery under-voltage (discharging only)
I	battery over-current
T	cell over-temperature
O	oil over-temperature
C	max cell over-voltage (charging only)
C	min cell under-voltage (discharging only)
H	hardware fault – usually voltage / temperature
h	transient hardware fault – usually current

FAULT FINDING

17. Pack won't supply power

If already communicating then check that the protection has been cancelled.

-Read Communication Spec., Hardware "faults" stick and require resetting.

Check that pack is a Master

-Only Master Packs switch on power at start up.

Check that enable line is grounded

-Board will not power up unless this line is grounded.

Check that connectors are connected.

-Board should now communicate.

Is Pack too hot?

-Let pack cool.

Is pack under voltage?

-Charge pack

Is pack discharging into a short circuit?

-Check load impedance is greater than 30 ohms.

Has fuse blown?

-Check output with multimeter. Even a pack that is off will present a voltage of around 25 volts if measured with a standard multimeter due to the reverse bias leakage current of the output diodes.

18. SCHEMATICS

SMART BATTERY REV 1.0

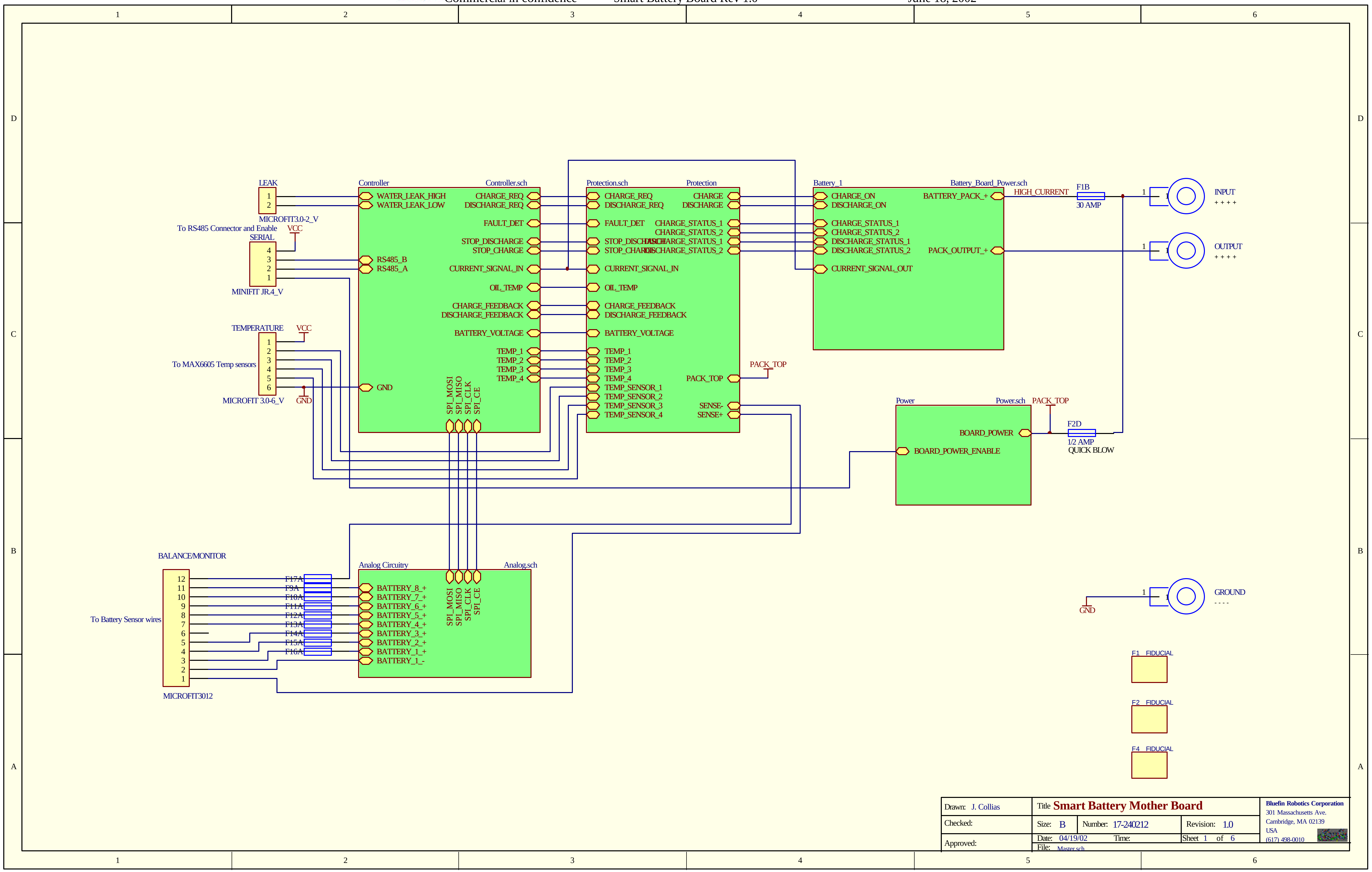


Figure 8:Schematic of Smart Battery Rev 1.0 – High Level.

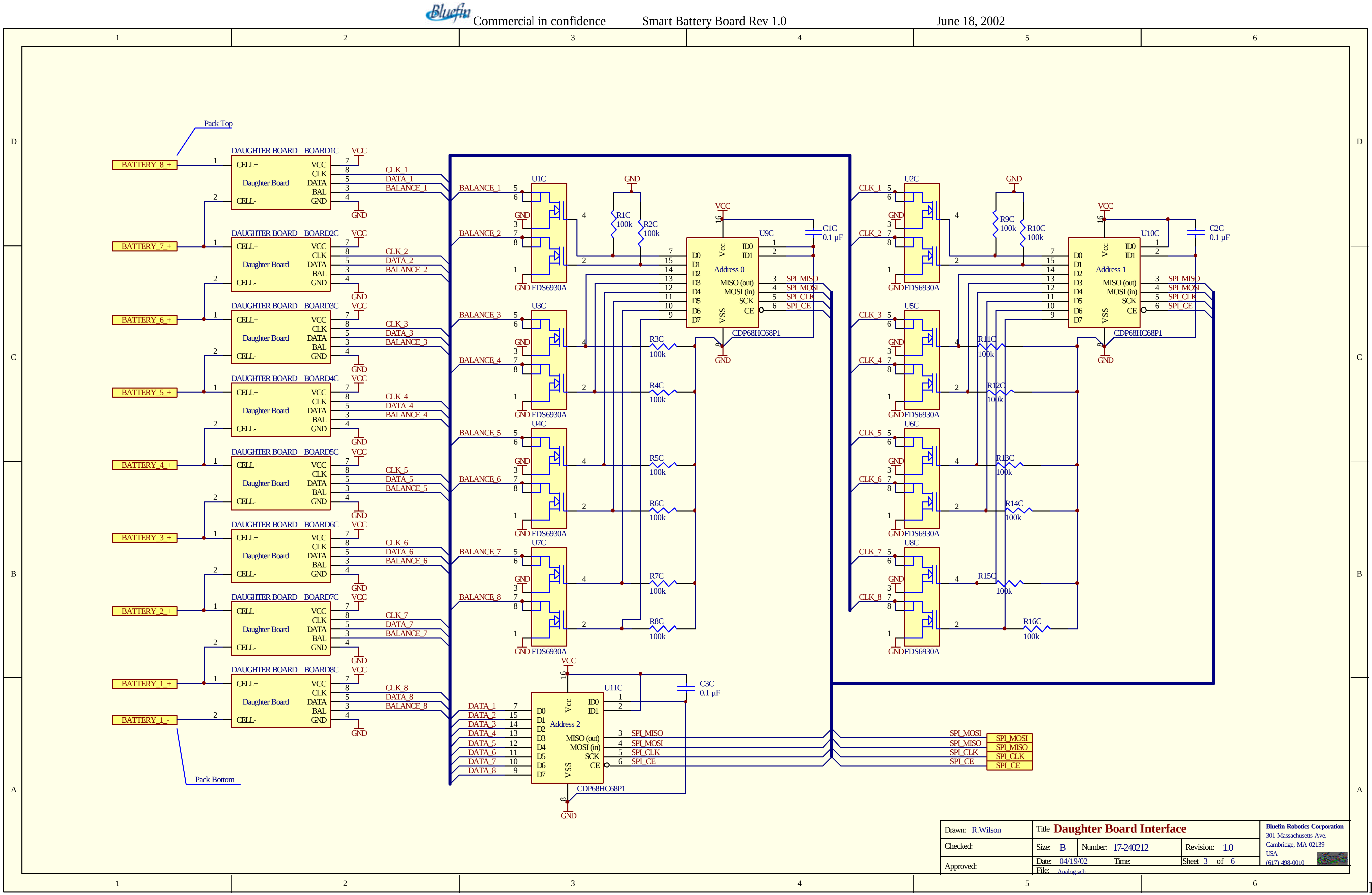


Figure 9: Schematic of Smart Battery Rev 1.0 - Daughter Board Interface.

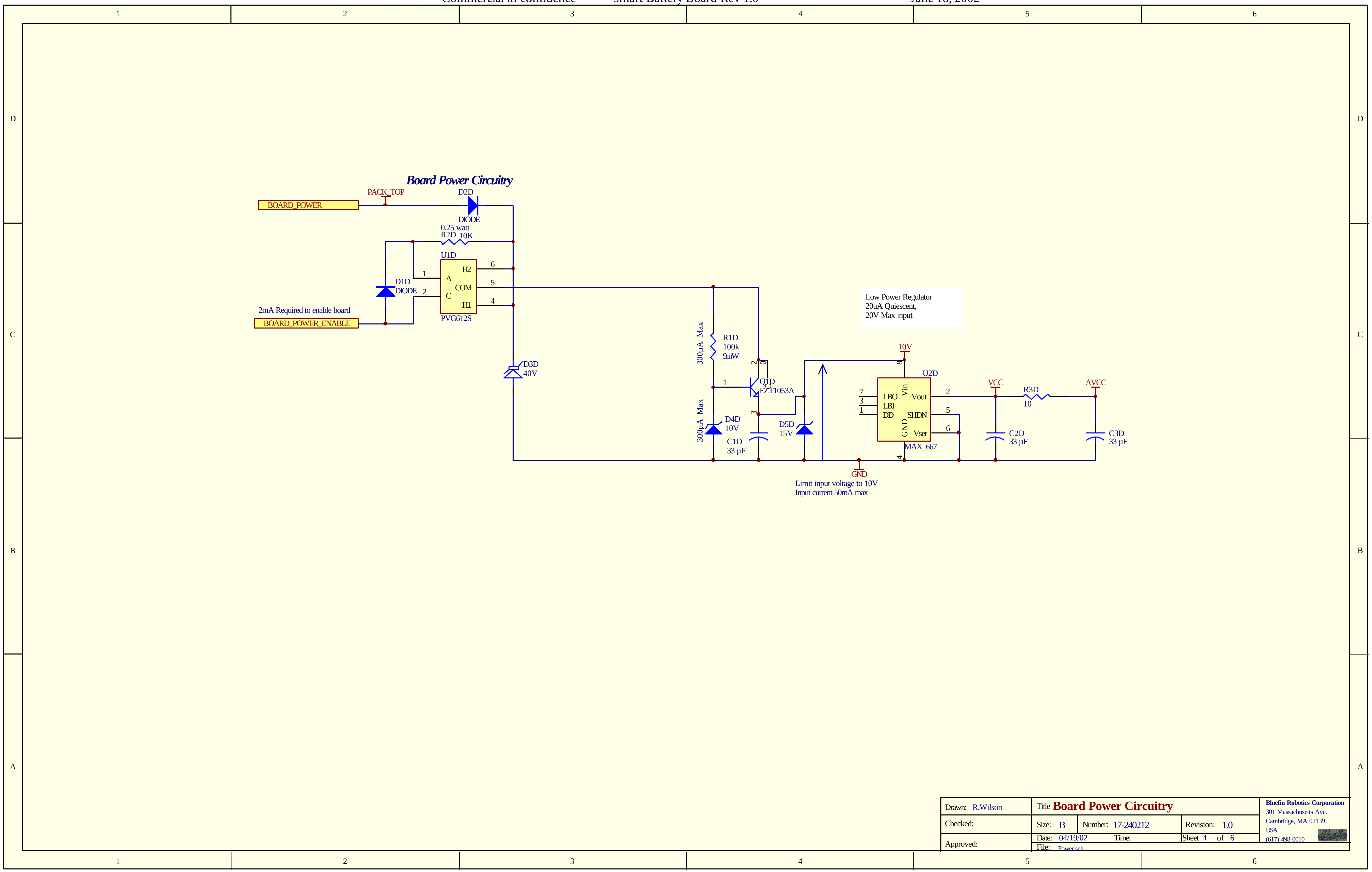


Figure 10: Schematic of Smart Battery Rev 1.0 - Battery Power Supply.

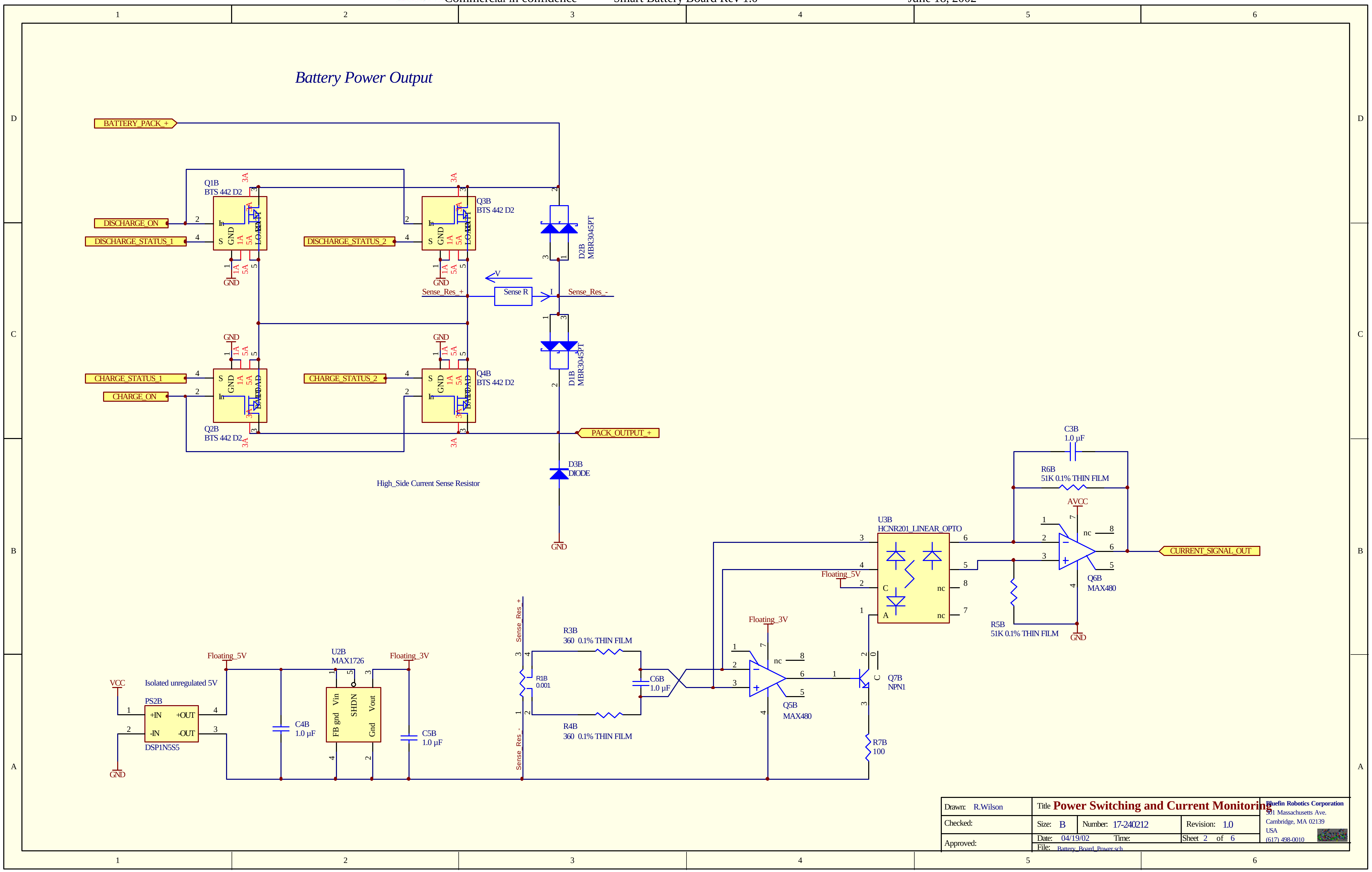


Figure 11: Schematic of Smart Battery Rev 1.0 - Power Output Components and Current Monitoring.

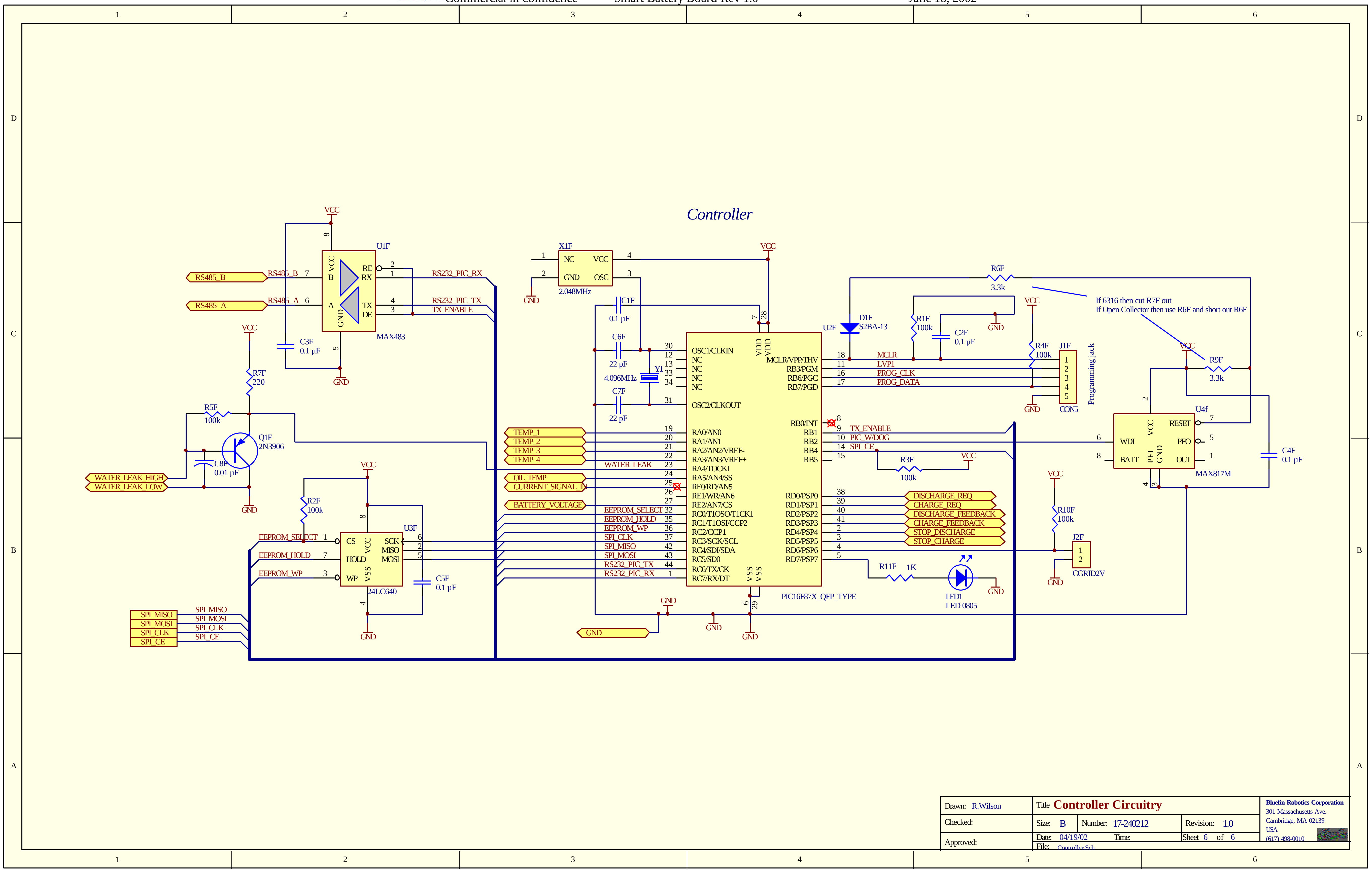
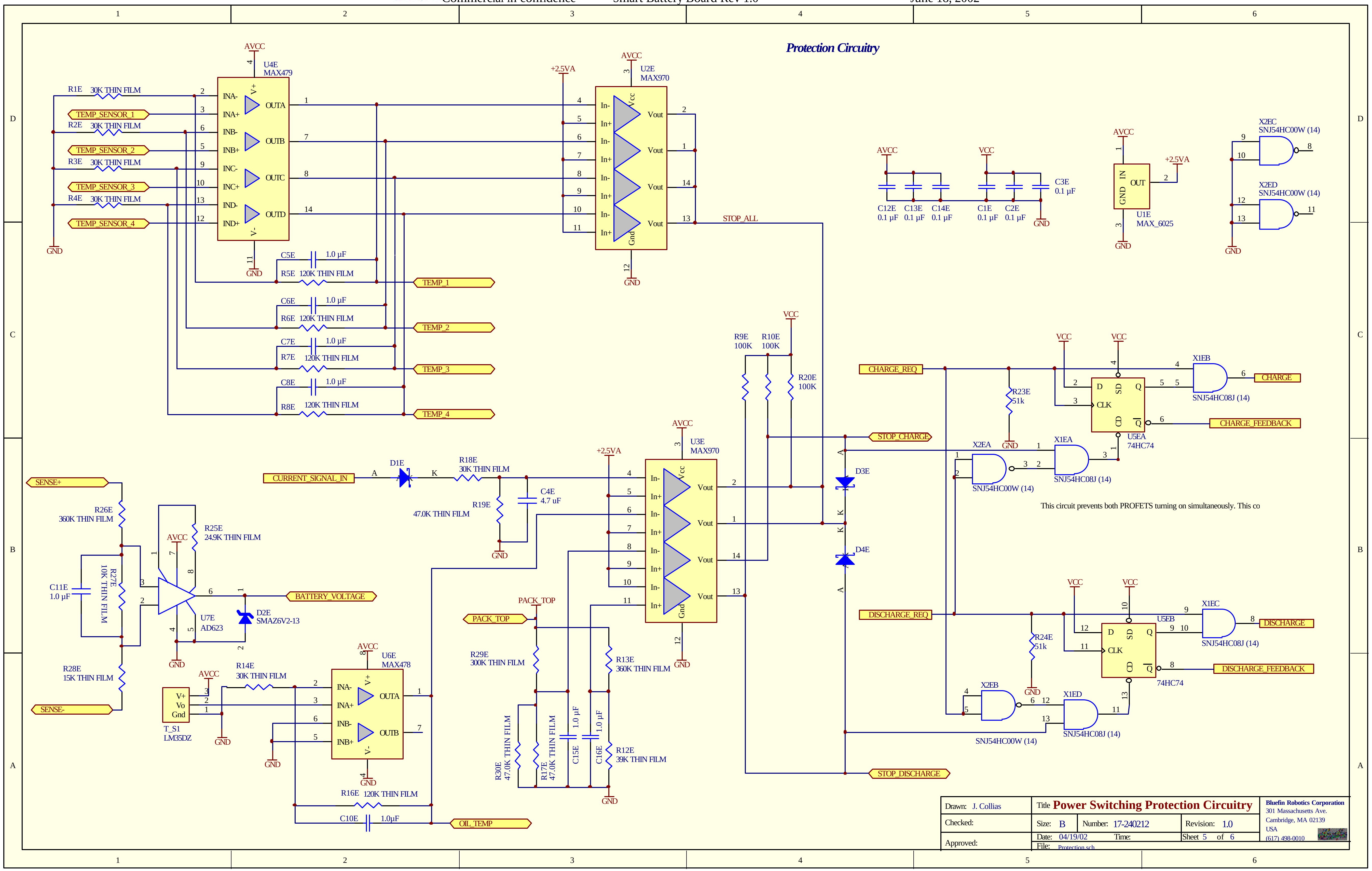


Figure 12:Schematic of Smart Battery Rev 1.0- Controller.



Smart Battery Rev 1.0 - Protection Circuitry.