

### Operating the EnerChip™ in High Temperature Environments

#### Introduction

EnerChip™ solid state rechargeable batteries are distinct from conventional rechargeable batteries. The EnerChip can be used in environments typically ill-suited for batteries and other storage devices at risk of leaking toxic and volatile solvents, catching fire, exploding in high temperature environments, or that are simply too large to fit within space-constrained enclosures. The EnerChip CC combines the EnerChip with integrated power management, for use in applications requiring backup or bridging power, or as the main power source.

Some applications demand occasional operation at temperatures above the +70°C rated specification of the EnerChip. If such temperature excursions are not properly compensated for in the system design, the result can be degraded performance or outright failure of the energy storage device. This Application Note provides information on how to mitigate the detrimental effects of high temperature operation on the EnerChip in such environments. The following topics are addressed:

- Factors that influence the operating characteristics of EnerChips and the parameters that are affected
- Effects of high temperature, bias voltage, and state of charge on operation and service life of EnerChips
- Recommendations for mitigating detrimental high temperature effects on EnerChip performance
- Configuring the EnerChip CC to offset temperature-induced effects using the integrated functions
- Operating the EnerChip in medical sterilization and high temperature food processing environments

Figure 1 illustrates the benefits of proper EnerChip management in high temperature environments.

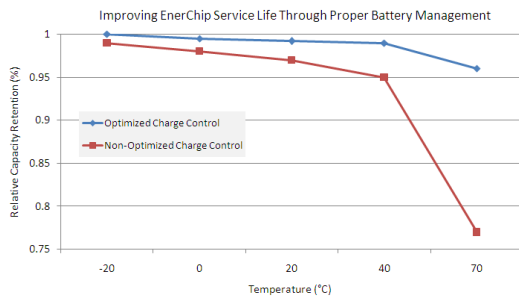


Figure 1: Relative Capacity Retention with and without Proper EnerChip Management

Factors affecting parameters such as cell resistance, self-discharge, and capacity fade include:

- Time
- Temperature
- State of charge (SoC)
- Bias condition (i.e., continuous charging vs. floating terminal voltage)
- Depth of discharge

With a fundamental understanding of how these factors interact to affect battery life and performance, it is possible to deploy readily available circuit techniques to mitigate such effects. By controlling or compensating for these factors with proper battery management, the service life of a battery that might otherwise not meet the requirements of a given application can be greatly extended – even under operating conditions beyond the specified rating of the battery. The data and analysis in this Application Note are presented in several forms, describing the influence of these factors on the EnerChip and means to achieve desired performance and service life objectives under the particular application operating conditions.

## AN-1052: Operating the EnerChip™ in High Temp. Environments

As a starting point, it's important to understand how the state of charge of the EnerChip can be adjusted by regulating the charge voltage and allowing the charging or discharging current to settle to a steady state value. Figure 2 represents the relative state of charge as a function of this charge voltage.

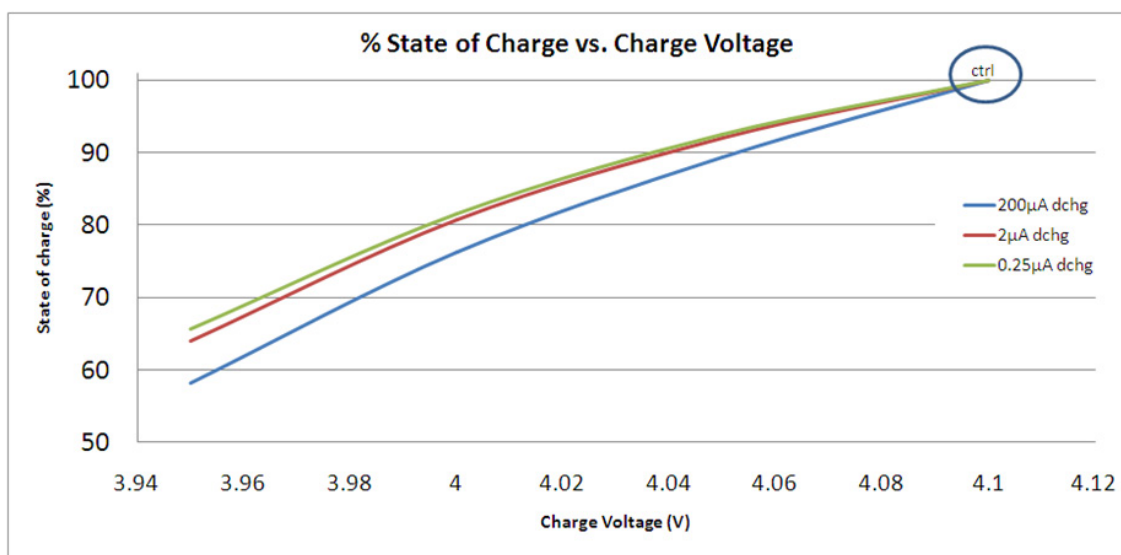
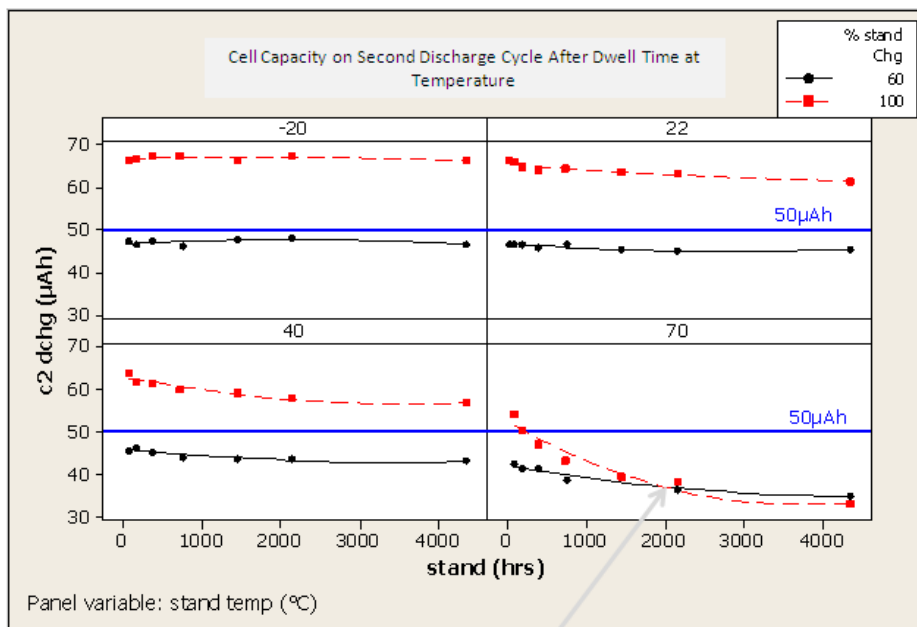


Figure 2: State of Charge can be Adjusted by Varying the Charge Voltage

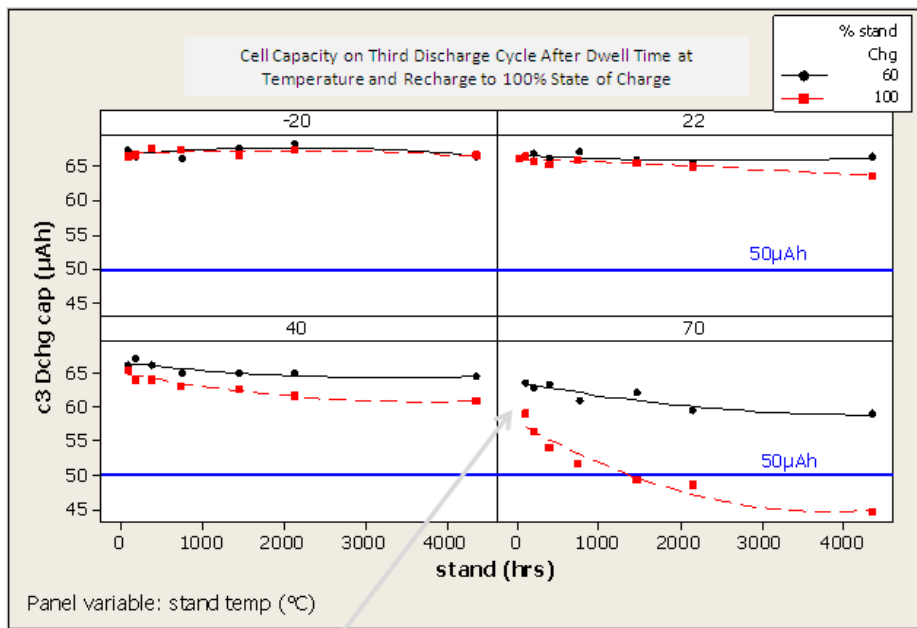
The EnerChip CC has a charge voltage temperature coefficient with a slope of  $-2.2\text{mV}/^\circ\text{C}$  so as to lower the charge voltage as the temperature increases. The charging source can also be enabled or disabled by way of an external control line. The advantage of activating/deactivating the charge pump will become apparent in the next section. As shown in Figure 3, a lower state of charge improves capacity retention at higher temperatures.

In applications where high temperature excursions are likely, the cumulative life-cycle capacity can be improved by keeping the EnerChip at a lower state of charge, thereby retaining that capacity over a greater number of charge-discharge cycles. The experimental results of Figure 3 were derived by charging the cells to 4.1V (100% SoC) at room temperature and discharging each cell to establish the baseline discharge capacity. The cells were then charged to either 60% or 100% SoC and subjected to the temperature shown in the charts. After the prescribed time at temperature, the cells were discharged (top quad chart), then fully charged and discharged again (bottom quad chart). Note the higher discharge capacity in the cycle 3 discharge vs. cycle 2 for the 100% SoC cells, as the third discharge cycle includes the recoverable portion of the capacity that was lost during the previous (cycle 2) charge-discharge cycle.

# AN-1052: Operating the EnerChip™ in High Temp. Environments



Note the crossover point of 60% SoC and 100% SoC at 70°C.



Note the greatly improved capacity retention after 6 months at 70°C at 60% SoC vs. 100% SoC. Discharge capacity was measured after recharge to 100% SoC.

Figure 3: High Temperature Effects can be Offset by Adjusting the State of Charge

# AN-1052: Operating the EnerChip™ in High Temp. Environments

Figures 4 and 5 illustrate the effects of time at temperature on the capacity loss. Capacity loss from the cell can be both recoverable and non-recoverable. Recoverable capacity loss is that portion that can be replaced on the subsequent charge cycle and becomes available on the following discharge cycle. The non-recoverable portion of capacity loss is just that: Once it is lost, it can not be recovered on subsequent charge-discharge cycles.

As depicted in Figure 4, cell capacity loss is strongly dependent on temperature and state of charge. By maintaining a lower state of charge on the cell, the deleterious effects of temperature can be offset considerably. This is true for both recoverable and non-recoverable capacity loss.

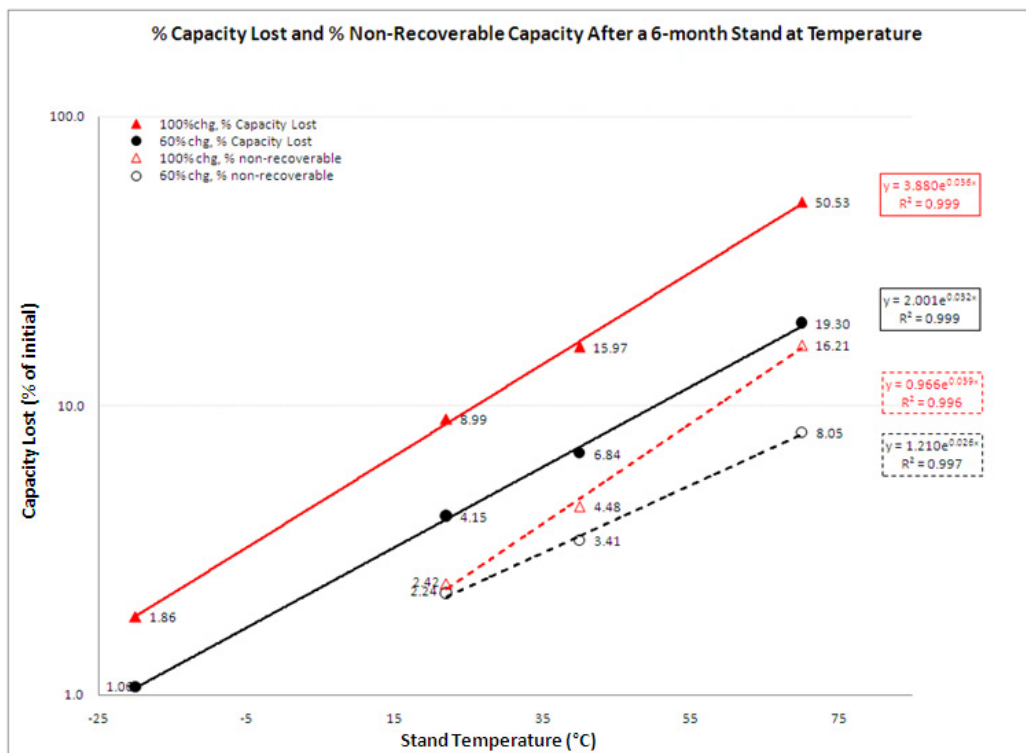


Figure 4: EnerChip Capacity Loss as a Function of Temperature and State of Charge

Figure 5 presents the data in another form, with stand time being the dependent variable and all data points representing stand time at 70 °C. The loss rate over time at temperature is a logarithmic function. Again, note the significant reduction in capacity loss (both recoverable and non-recoverable) by maintaining a lower state of charge, especially over extended time at temperature. The data here was collected at several intervals, including 6 months of continuous exposure to 70 °C.

In a typical application, leaving the cell in this ‘floating’ condition is achieved by disabling the EnerChip CC charge pump after charging the EnerChip to a full or partial state of charge, leaving the EnerChip terminal voltage to float, as opposed to maintaining a constant bias on the cell as would be the condition when leaving the charge pump enabled at all times. The effects on cell performance as a function of constantly biasing the EnerChip - versus allowing the terminal voltage to float - are described next.

# AN-1052: Operating the EnerChip™ in High Temp. Environments

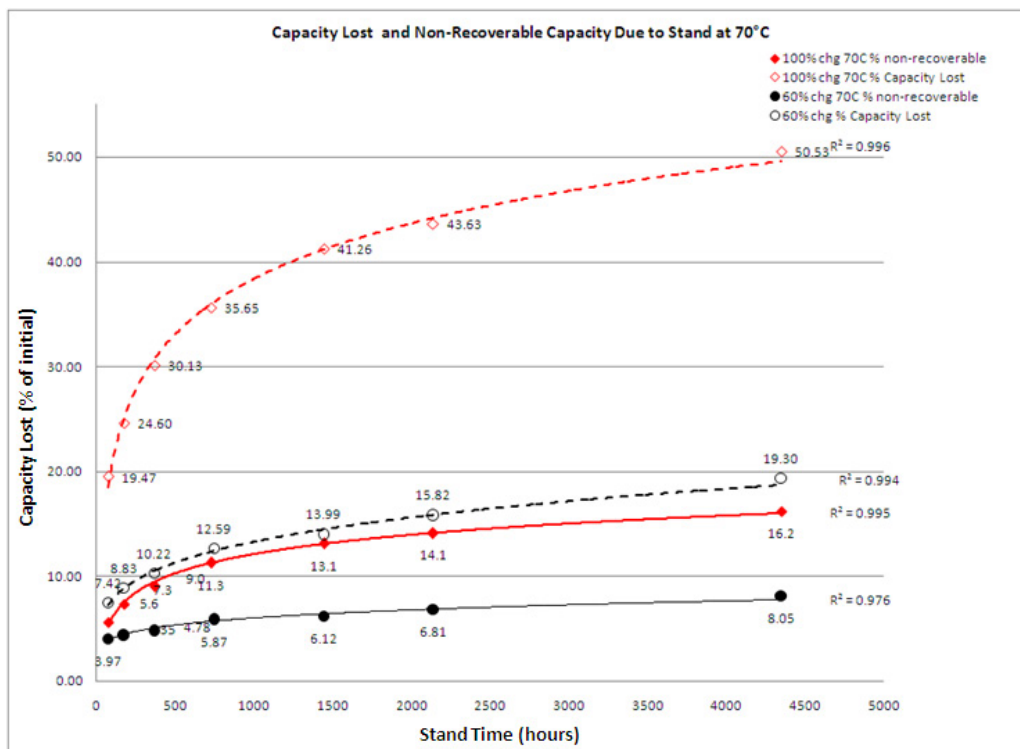


Figure 5: EnerChip Capacity Loss as a Function of Time and State of Charge at 70°C

Figure 6 represents the effects of bias conditions and state of charge on the EnerChip cell resistance. While there is an advantage to holding cells in a partially - rather than fully - charged state, the impact of trickle charging or continuously biasing cells at temperature is no more detrimental to the cell resistance than storing cells in an unbiased (i.e., floating terminal voltage) state in the normal operating temperature range. A 3.98V bias condition (~70% SoC) as shown in Figure 6 is the voltage the EnerChip is charged to in the EnerChip CC products, all having integrated battery management functions with a built-in charge voltage temperature coefficient.

Figure 7 represents the same operating conditions as Figure 6, but in Figure 7 the effects on cell capacity loss due to bias condition, state of charge, and temperature are shown. In addition, Figure 7 includes an extrapolation of the data from 70°C to 85°C to give an indication of how the cell is likely to perform when operated above its specified operating temperature.

Unlike the effects on cell resistance, trickle charging or biasing cells at temperature is more detrimental to the capacity loss of the cells than storing cells in an unbiased state. There is a significant advantage to holding cells in a partially - rather than fully - charged state at higher temperatures. This condition is implemented easily by disabling the EnerChip CC charge pump after the EnerChip is charged. The charge pump is disabled by driving the input pin ENABLE low. Doing so also lowers the operating current of the EnerChip CC device, thus reducing total system power consumption.

# AN-1052: Operating the EnerChip™ in High Temp. Environments

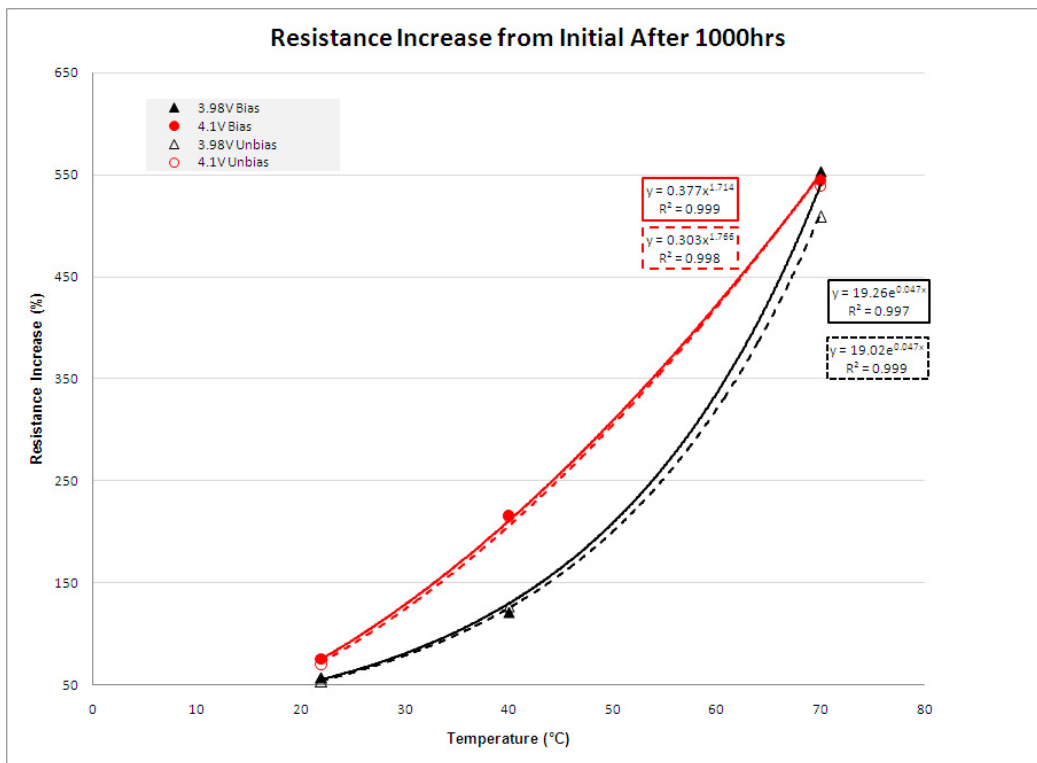


Figure 6: EnerChip Cell Resistance Change as a Function of Temperature, State of Charge, and Bias Condition

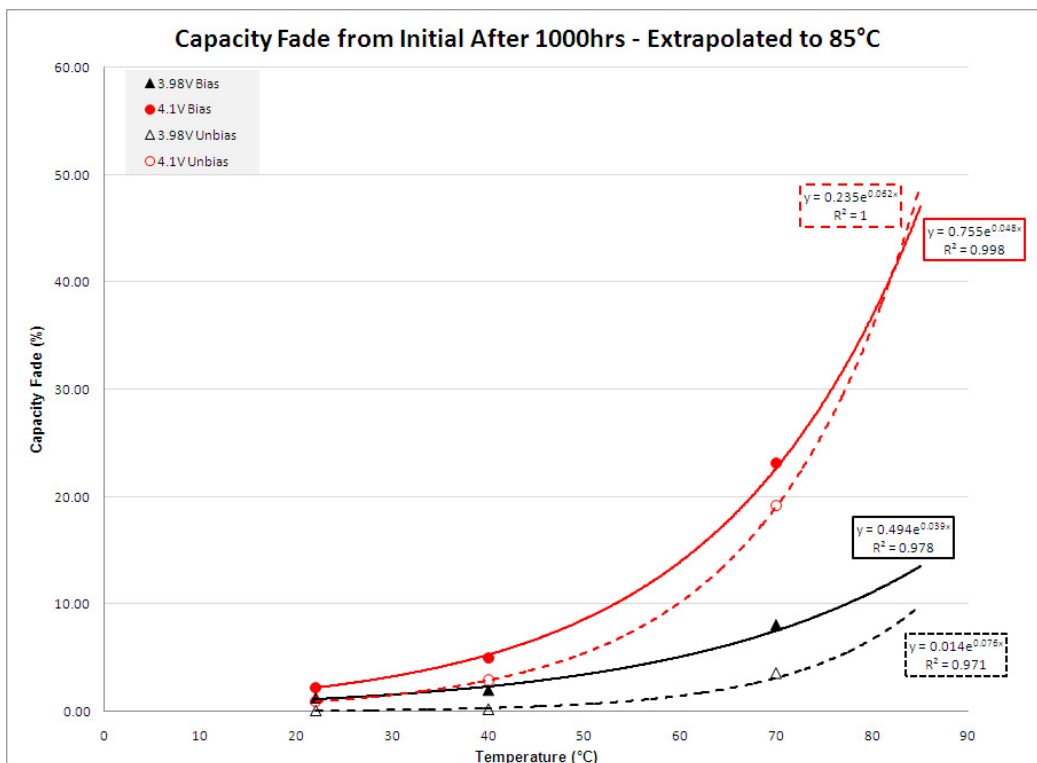


Figure 7: EnerChip Capacity Loss as a Function of Temperature, State of Charge, and Bias Condition

# AN-1052: Operating the EnerChip™ in High Temp. Environments

## Applications in Medical Device and Food Sterilization

Process temperatures such as those reached in autoclaves used in medical device and food sterilization are generally not suitable for devices containing batteries. Temperatures reaching 137 °C are common in sterilization equipment and can be catastrophic to conventional batteries containing volatile solvents and other additives. Yet, there are many devices that must be processed through sterilization equipment and processes that can benefit from having batteries. Such devices include surgical tools with embedded RFID tags; implantable sensors; and temperature sensors in the equipment for enabling more precise temperature control of the equipment and contents being sterilized. Moreover, often times it is essential that such sensors and RFID tags be hermetically isolated from the environment to prevent moisture ingress to the device, or to prevent outgassing from the device to the environment - such as the autoclave or, in the case of implantable sensors, the human body. Hermetic encapsulation often requires the use of a rechargeable - rather than a primary - battery for re-use and, to further complicate matters, a convenient non-contact means of recharging this energy storage device.

An additional complication generally arises - one of needing a small power source that occupies little volume and no external components such as holder or socket in order to maintain a rugged connection that will not break, separate, or corrode in these harsh environments. Except for the solid state EnerChip, such storage devices do not exist. EnerChips can be used in bare die form with solder bumps or wirebonds, or in low profile surface mount packages with and without integrated battery management, and can be recharged easily using inductive near field charging for example. And as importantly, the EnerChip can tolerate excursions to the high temperatures found in autoclaves and similar equipment used in medical device sterilization and food processing. Figure 8 depicts the effect on EnerChip capacity as a result of having been subjected to 137 °C for up to 30 minutes in a charged state. The fade, while measurable, is not severe. In this study, cells were charged to 3.9V - or about 50% state of charge - prior to subjecting the cells to high temperature.

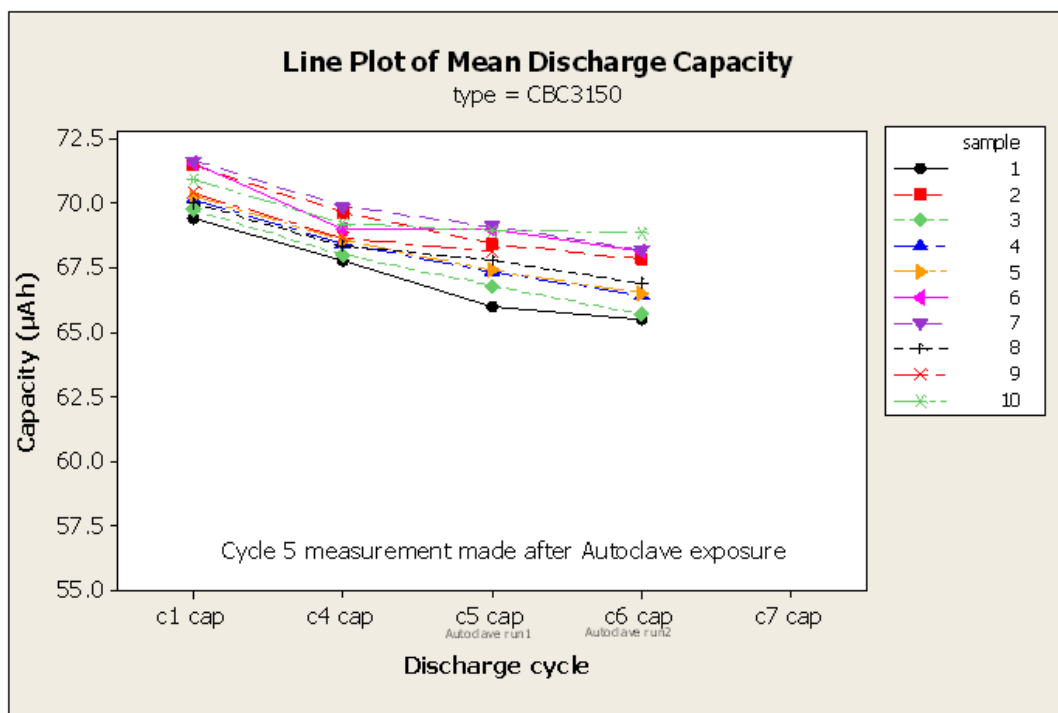


Figure 8: EnerChip Capacity Loss as a Function of Temperature, State of Charge, and Bias Condition

# AN-1052: Operating the EnerChip™ in High Temp. Environments

## EnerChip CC Circuit Description and Operation

The EnerChip CC is a surface mount device that contains a rechargeable battery with integrated battery management that performs the charge control, discharge control, threshold voltage detection, and supply supervisory functions all in one low-profile package. It operates over the range of 2.5V to 5.5V and the switchover threshold voltage is adjustable. A block diagram of the EnerChip CC is shown in Figure 11.

Under normal operation, the RTC, MCU, sensor, or other device, derives its power from the main system supply, which might be a large coin cell, prismatic cell, cylindrical batteries, or indirectly from wall power through a voltage regulator. Because the EnerChip has very low self-discharge, it needs to be charged infrequently. To maintain a charge of 90% or greater on the EnerChip when it has not been used as a backup power source for prolonged periods, the EnerChip needs no more than one hour of charging time per month. Such a low charging duty cycle presents a negligible parasitic load to the main power source, as the EnerChip charges quickly and its charging current decays to just tens of nanoamperes when fully charged. The EnerChip CC controls the EnerChip charging function internally. When main power is interrupted - as during line power outages or when the main battery is removed for recharging or replacement, the backup power source provides enough energy to maintain operation of the RTC, MCU, sensor, etc.

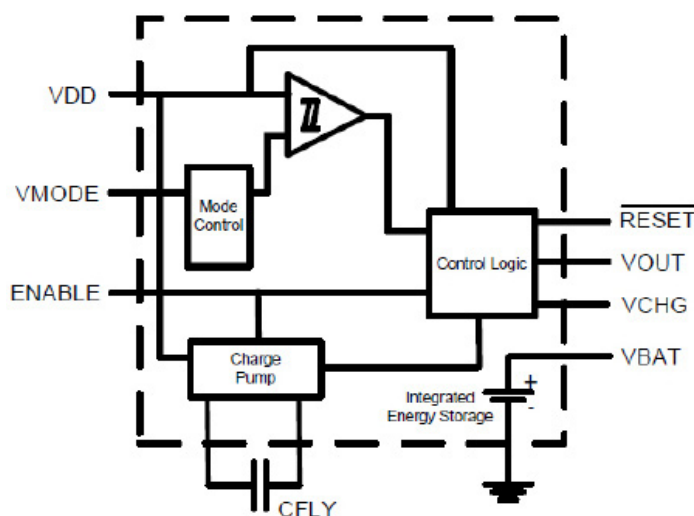


Figure 11. Block diagram of the EnerChip CC Thin Film Battery with Integrated Battery Management

EnerChip CC includes the following functional elements:

- Internal charge control circuit that converts a wide range of input voltages to a tightly regulated battery charging voltage;
- Battery cutoff circuit that disconnects the load from the embedded EnerChip when the discharge voltage reaches a preset limit;
- Output pin (RESET/) for driving an interrupt line on an MCU, indicating the system is in backup mode;
- A voltage detection circuit allowing a user-selectable threshold switchover voltage;
- A control line that enables and disables the internal charge pump to reduce power consumption when the internal EnerChip does not need to be charged, and to mitigate temperature effects in applications requiring such measures.

All of these features have been combined to create a backup power solution that eliminates the need for a dedicated supply supervisory circuit, battery holder or socket, separate battery management circuitry, and a conventional power source such as a coin cell or supercapacitor. The result is a compact, single-chip solution to backup and embedded power.



# AN-1052: Operating the EnerChip™ in High Temp. Environments

## EnerChip Charging Duty Cycle

As described, the EnerChip can be charged continuously, or charged and left to float. These modes are controlled using the digital I/O line ENABLE. A typical charging duty cycle when operating in high temperature environments is shown in Figure 12.

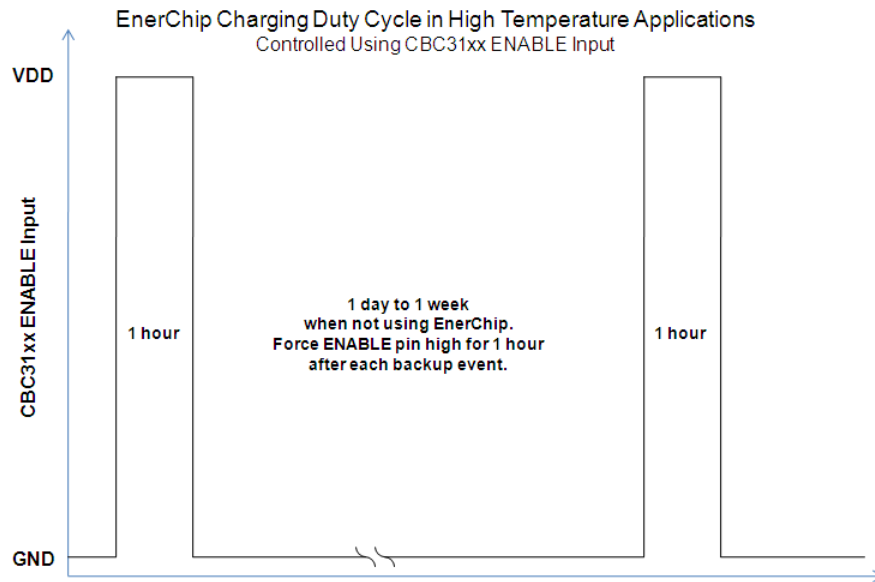


Figure 12. EnerChip Charging Duty Cycle in High Temperature Operating Environments

Several methods can be used to control the ENABLE line, and therefore the activation of the charge pump that charges the EnerChip. The simplest approach is to use an I/O line of the system MCU or CPU to activate the charge pump only when the EnerChip requires charging due to use or to account for the minimal capacity fade resulting from self-discharge. Or, the MCU/CPU could continuously force the ENABLE pin high and disable it only when the system reaches an elevated temperature that warrants removing the bias on the EnerChip as discussed in the previous sections of this Application Note.

Another approach is to use a thermal switch that will automatically drive the CBC31xx ENABLE pin low when a defined temperature is reached. Such an implementation is shown in Figure 13. The advantage of this approach is that the activation temperature is relatively tightly controlled and the trip point is user-selectable. A disadvantage is the parasitic current needed to operate the temperature switch, which has to be factored into overall power consumption in battery-operated systems. Moreover, the operational voltage range of many of the thermal switches available, in combination with the voltage level required on the CBC31xx ENABLE pin, limit this design to 3.3V systems.

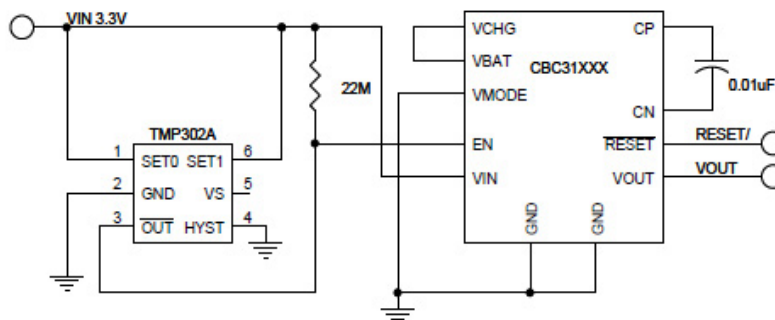


Figure 13. EnerChip Bias Control Using a Temperature Switch

## AN-1052: Operating the EnerChip™ in High Temp. Environments

Yet another approach is to use an array of diodes connected to the input of a power-on reset (POR) circuit having an active low output, as shown in Figure 14. With the natural temperature coefficient of the diodes (about  $-2\text{mV}/^\circ\text{C}$ ), the POR circuit will trip and force the CBC31xx ENABLE pin low at elevated temperature. The resistor sets the diode current the voltage differential from the main supply to VIN of the POR circuit. The advantage of this design is that, with the proper selection of diodes and POR circuit, the parasitic current can be just 200-400nA. POR circuits are readily available in a variety of trip voltages and diode arrays can be acquired in a single, low cost, compact package. A minor disadvantage of this design is the need for more than one component to control the ENABLE pin.

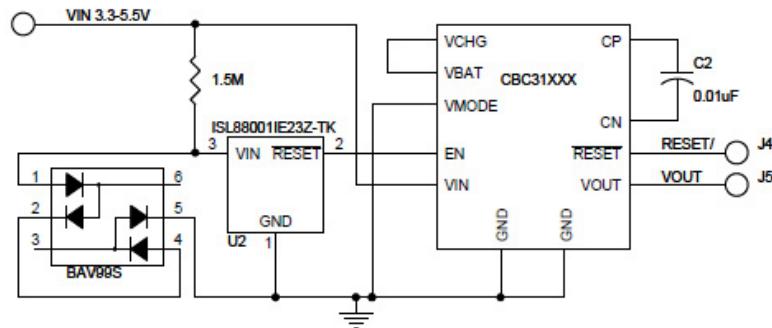


Figure 14. EnerChip Bias Control Using Series Diodes and a Power-on Reset Circuit

### Summary and Conclusions

Several factors influence the survivability and long-term performance of solid state EnerChips. Proper system design techniques can mitigate these effects to allow operation at temperatures in excess of the rated operating temperature of these cells. The EnerChip CC has built-in charge voltage temperature compensation and bias voltage control capabilities to achieve such improvements using standard product. Additional low cost and easy-to-implement techniques can also be used to further improve performance in extreme environments. It is also possible for Cymbet to adjust the charge voltage of the EnerChip CC product to optimize the device for a particular application environment.

Several general rules can be used during system design to ensure long-term survivability and operation of the EnerChip solid state battery when operated in extreme environments:

- Cell resistance increases (decreases) by  $\sim 2x$  for every  $10^\circ\text{C}$  decrease (increase) in operating temperature.
- Capacity fade is influenced by temperature and state of charge.
- State of charge is defined by charge voltage .
- Charge voltage is more influential than bias condition on capacity fade at elevated temperature.
- Lower state of charge results in longer life at high temperature.
- Lower charge voltage at high temperature reduces cell resistance rate of increase.
- Lower charge voltage at high temperature results in lower capacity fade.
- Operating the EnerChip with its negative electrode lean of lithium (i.e., not fully charged), generally provides better long term performance at elevated temperature, with a commensurate reduction in nominal discharge capacity being the trade-off. In this condition, more of the lithium contained in the cell is bound in the crystalline matrix of the positive electrode,  $\text{LiCoO}_2$ .

Because EnerChips are offered in bare die, are recharged easily through various direct and contactless (e.g., near-field RF) methods, and can survive high operating temperatures, they allow product designers the opportunity to miniaturize their products, encapsulate the power source with the other system components, and deliver power in space-constrained and extreme environments. Only EnerChips afford such unique capabilities.

To optimize the performance of EnerChips in your system design, contact Applications Engineering at Cymbet Corporation: <http://www.cymbet.com/products/support.php>