ENOVIX

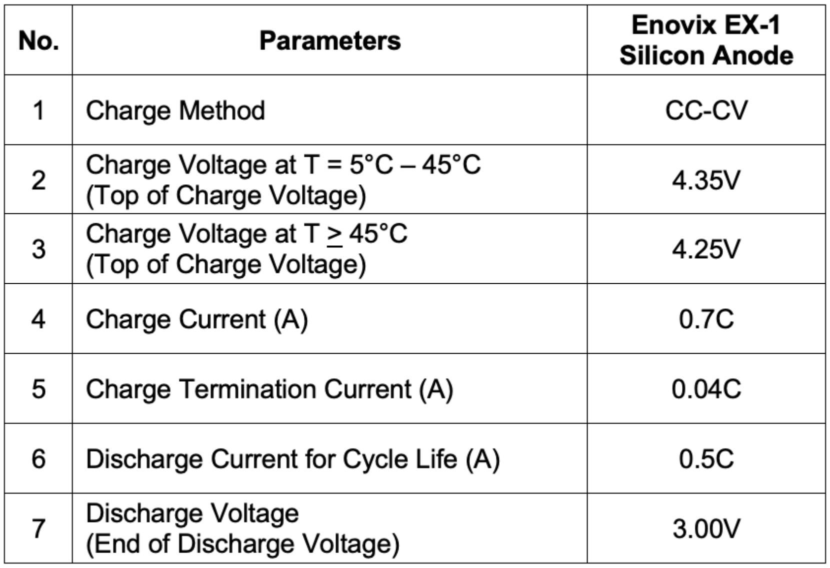
Testing Considerations for Enovix 100% Active Silicon Anode Cells vs Li-ion Graphite Anode Cells

July 2023

Contents

I. Summary

Enovix cells are uniquely architected using precise laser cut electrodes that are stacked with accurate alignment, allowing for volumetric and active material packing efficiencies, as well as accommodating the use of a 100% active silicon anode. Silicon is a plentiful and sustainable material that can store more than twice as many lithium ions as graphite by volume (1800 mAh/cc[1] versus 800 mAh/cc[2]), which is used in most conventional lithium-ion batteries today. Due to its novel mechanical structure and silicon anode, Enovix cells have exceptional energy density, capacity, thermal performance and abuse tolerance. Testing methods cannot simply be applied because of legacy standards and procedures. The use of silicon anodes is a technology shift like the Nickel-based chemistry (Nickel Cadmium/Nickel Metal Hydride) to new Lithium-ion (Li-ion) chemistry transition. Adjustments were required to adopt the new high energy density technology. The same is true today with silicon anode technology. By using representative testing conditions suited to the device applications and adhering to the optimized cell parameters, the energy benefits of the Enovix technology will be apparent. The testing parameters for the Enovix cell are shown in Table 1 below and compared to Lithium-Ion Graphite anode cells.



No.	Parameters	Enovix EX-1 Silicon Anode
1	Charge Method	CC-CV
2	Charge Voltage at T = 5°C – 45°C (Top of Charge Voltage)	4.35V
3	Charge Voltage at T ≥ 45°C (Top of Charge Voltage)	4.25V
4	Charge Current (A)	0.7C
5	Charge Termination Current (A)	0.04C
6	Discharge Current for Cycle Life (A)	0.5C
7	Discharge Voltage (End of Discharge Voltage)	3.00V

Table 1: Enovix EX-1 Silicon Anode Cell Electrical Parameters for Use in Testing

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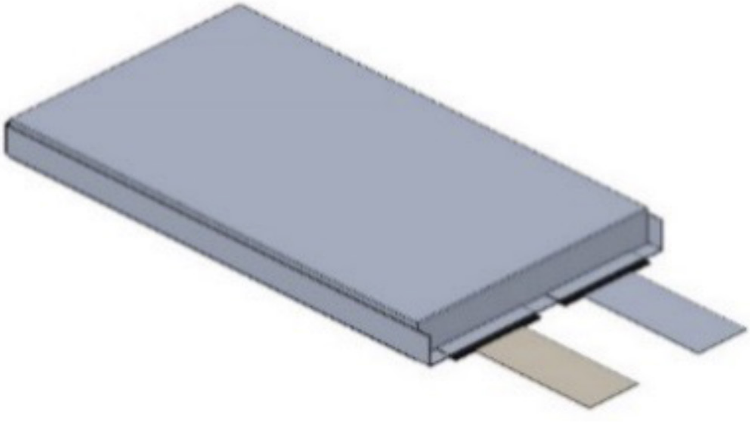
[1] *De-rated from theoretical capacity of 2194 mAh/cc for Li trapping losses.*

[2] *Nominal capacity between host capacity of 841 mAh/cc and lithiated capacity of 719 mAh/cc.*

II. Introduction

Since Sony Corporation developed and commercialized the first Li-ion battery in 1991, the energy density annual growth rate has generally been about 4-5% year over year. In the decade after 2010, this growth rate started to decline as the limits of the traditional Li-ion chemistry, mainly lithium cobalt oxide cathode coupled with the graphite anode, started to reach its capacity limits. In addition, traditional cell design strategies simply maximized the energy density of cells by offsetting inert, non-energy contributing materials for more dense packing of the active materials. Metals, separators, foils/conductors and free space within the cell became smaller, but this strategy also approached a physical limit. The key to continuing the energy density growth rate was changing the fundamental active materials within the cell. Silicon has been of interest for decades due to its high specific capacity. However, the challenge to implementing a silicon anode in a Li-ion cell has been the ability for the cell system to prevent the silicon particle from disintegrating from its 300% particle expansion and contraction during cycling. Enovix solved this problem with a novel constraint system. The Enovix cell and technology allows a standard Li-ion cathode coupled with a silicon anode to cycle over 500 times and offer energy density over 900 Wh/l (cell 3.87 x 55 x 77.5mm).



A fully packaged Enovix high energy density silicon anode cell has the same exterior features as standard Li-ion graphite anode pouch cells. The cell has an exterior laminate foil material (aluminum / polymer film) that is heat sealed along its perimeter. Tabs protrude from the end of the cell with an aluminum positive tab and a nickel negative tab similar to standard pouch cells. Enovix's cells are tested using the same equipment as standard Li-ion cell technology; however, the testing parameters differ. Table 2 lists the cell parameters for both the Enovix 100% Active silicon anode cell and Li-ion cell with a graphite anode. To fully realize the energy available from the Enovix 100% active silicon anode cell, the cell parameters must be used to evaluate the cell.

III. Difference in Testing Methodology

Recall that prior to 2000, nickel cadmium and nickel metal hydride were the predominant rechargeable cell chemistries requiring only simple constant current charging for a fixed time or to a maximum cell temperature. No voltage control was needed; however the charge and test equipment required the ability to monitor temperature. These cell chemistries required charge termination methods that monitored the cells change in temperature over time (dT/dt) and the cell's negative voltage change (-dV). Each of these termination methods required specific conditions to maximize the cell charge. Incorrectly terminating charge can lead to lower capacity or poor cycle life. As the industry shifted to Li-ion chemistry with graphite anodes, protocols and equipment changed to properly test the new higher energy density cell technology. New protocols and parameters were required such as voltage and current control. This was a paradigm shift not only in testing but also in terms of implementation into host devices. The Enovix technology represents a paradigm shift from standard Li-ion chemistry with a graphite anode to high energy density Li-ion cell technology utilizing a 100% active silicon anode. Utilizing the same testing methodologies and parameters traditionally used for standard Li-ion cells will not fully expose the benefits of Enovix cells with the silicon anode. The sections that follow describe specific details about each parameter and testing considerations.

IV. Cell Parameters

The parameters to properly test Enovix cells are highlighted below and compared to standard Li-ion graphite anode cells. Where appropriate, a range is shown for standard Li-ion cells to cover the slight differences in cell chemistry. The parameters listed for the Enovix cell have been optimized to meet the high capacity, high energy density, and cycle life characteristics for the cell. Deviation from these parameters may lead to different performance results.

No.	Parameters	Enovix EX-1 Silicon Anode	Lithium Ion Graphite Anode
1	Charge Method	CC-CV	CC-CV
2	Charge Voltage at T = 5°C – 45°C (Top of Charge Voltage)	4.35V	4.40 - 4.45V
3	Charge Voltage at T $\geq$ 45°C (Top of Charge Voltage)	4.25V	Not allowed or < 4.20V
4	Charge Current (A)	0.7C	0.3C – 1C
5	Charge Termination Current (A)	0.04C	0.05C – 0.02C
6	Discharge Current for Cycle Life (A)	0.5C	0.5 – 1C
7	Discharge Voltage (End of Discharge Voltage)	3.00V	3.00V

Table 2: Enovix EX-1 Silicon Anode and Lithium Ion Graphite Anode Electrical Parameters

V. Explanation of C-rate, CC, and CV

It is important to understand the concept of C-rate before a discussion on battery test parameters. The Handbook of Batteries1 defines C-rate as a normalized parameter to describe current applied to a cell. The definition is:

C-rate = I = M x Cn

Where
I = Current (mA)
M = fractional rate
Cn = Cell Capacity (mAh); typically rated or minimum cell capacity
n = discharge time (hours) of the cell capacity rating eg. 5 hours

So, C-rate will be stated as some fractional or who multiple of the cells rated capacity. For example, for a cell having a rated capacity of 1000 mAh and M= 0.5, the C-rate is:

Cn = 1000 mAh
M = 0.5

C-rate = 0.5 x Cn = 0.5C rate

In terms of absolute current, the 0.5C rate is 0.5 x 1000 = 500 mA.

Similarly for 1C rate, M = 1, the C-rate is

Cn = 1000 mAh
M = 1

C-rate = 1 x Cn = 1C rate

In terms of absolute current, the 1C rate is 1 x 1000 = 1000 mA.

In practical terms, the 0.5C means that it will take 2 hours to fully discharge the cell, while 1C rate will fully discharge the cell in only 1 hour.

CC – CV (constant current – constant voltage) Profile

Both Enovix and Standard Li-ion cells charge with a Constant Current – Constant Voltage (CC-CV) profile. However, every Li-ion cell model is designed to different specifications which means that the cell electrical parameters in Table 2 above will differ slightly. This is no different for Enovix cells which will have different electrical parameters for future generations.

The CC-CV profile consists of a CC step immediately followed by a CV step.

Step 1: CC Charge

The cell is charged by applying the Charge Current to the cell until the cell Charge Voltage is reached. Note that the charge voltage differs for different chemistries and conditions. The Enovix cell has 2 different charge voltages depending on the charging temperature range.

For the Enovix cell, the CC charge rate is 0.7C which means for a 322 mAh (minimum) cell (Cn), the charge current is:

0.7C = 0.7 x Cn = 0.7 x 322 mA = 225.4 mA (0.225A)

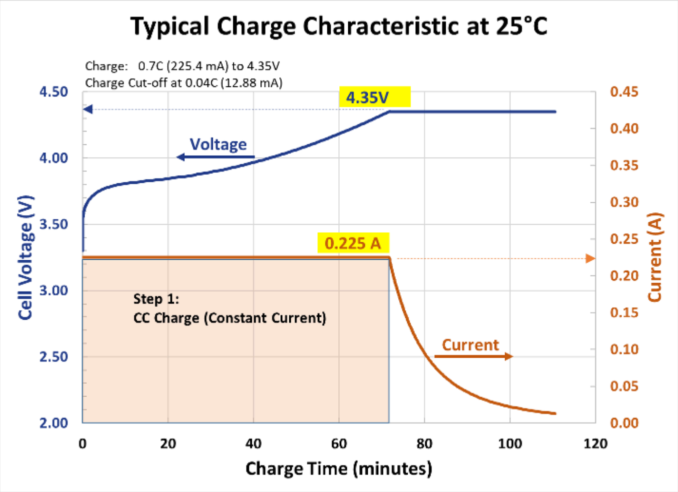


Figure 1: Typical Charge Voltage Profile – Step 1: CC Charge

Figure 1 shows the charge current held constant at 0.225A for Step 1 and the charge voltage progressively increasing to 4.35V.

Step 2: CV Charge

Immediately upon reaching the charge voltage, the charge current begins to decrease to maintain a constant charge voltage. The current continues to decline as the cell increases charge. Figure 2 below shows the CV step with the voltage fixed at 4.35V and charge current decreasing to 0.01288A (12.88 mA). At 0.01288A, charge is terminated. No more current is applied. This is the Charge Termination Current and is defined for the Enovix cell as 0.04C.

0.04C = 0.04 x Cn = 0.04 x 322 mA = 12.88 mA (0.01288 A)

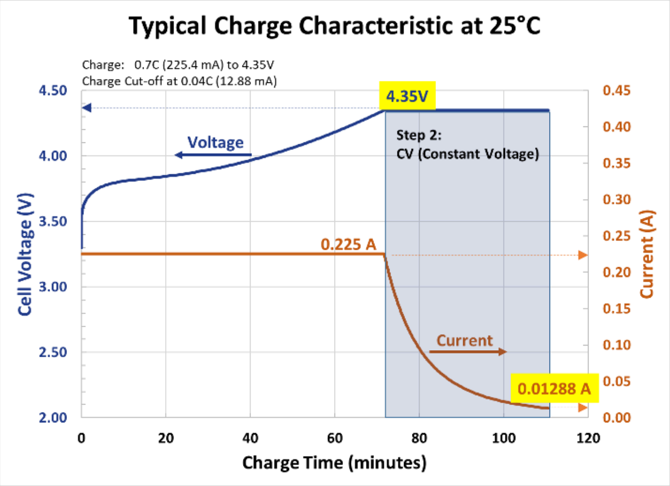


Figure 2: Typical Charge Voltage Profile – Step 2: CV Charge and Charge Termination Current

VI. Explanation of Cell Electrical Parameters

Charge Method Parameters versus Charge Temperature

Notice that in Table 3, the charge voltage differs for different temperatures for both the Enovix cell and Li-ion graphite anode cells. It is known in the industry that Li-ion cell charging at elevated temperatures requires different charge conditions. This also applies to the Enovix cell.

No.	Parameters	Enovix EX-1 Silicon Anode	Lithium Ion Graphite Anode
1	Charge Method	CC-CV	CC-CV
2	Charge Voltage at T = 5°C – 45°C (Top of Charge Voltage)	4.35V	4.40 – 4.45V
3	Charge Voltage at T ≥ 45°C (Top of Charge Voltage)	4.25V	Not allowed or < 4.20V

Table 3: Charge Voltage at Different Temperatures (Excerpt from Table 2)

The industry follows a profile originally defined by JEITA (Japan Electronics & Information Technology Association) which graphically describes the conditions that cells can be charged with respect to temperature. These parameters are defined by each cell manufacturer. The Enovix cell JEITA profile is shown in Figure 3 below.

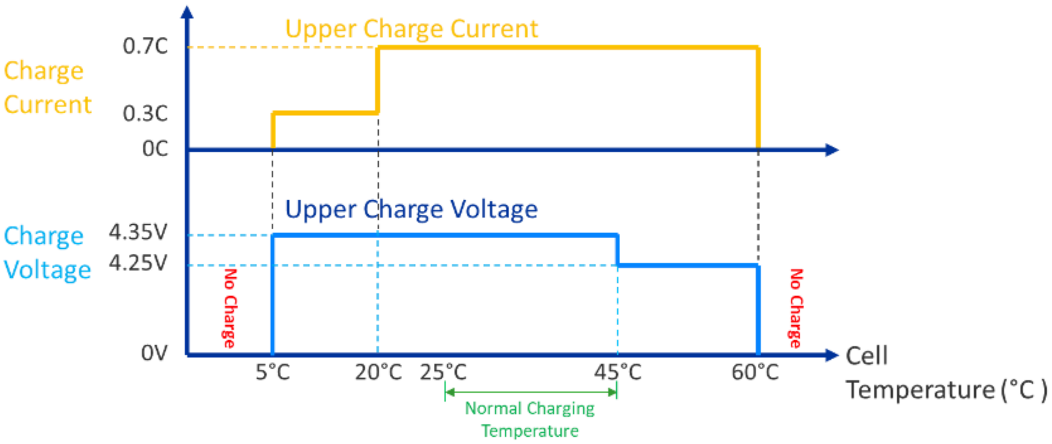


Figure 3: JEITA Profile for Enovix Cells

The CC-CV cell charging example in Section 3 is the the normal charge condition for an Enovix cell when the cell temperature is between 5°C and 45°C. The cell is optimized to meet the cycle life requirement along with other specifications between these temperatures. As the temperature increases above 25°C, the cathode and the anode electrode chemistry changes such that the overall cell charge acceptance increases. This means that more lithium ions are transferred between the anode and cathode electrodes, which effectively increases the cell capacity by about 10% at 45°C when charged to 4.35V. However, the higher temperature also increases the cathode voltage for a given cell voltage and this increases the degradation reactions during cycling. Therefore, to compensate and ensure that the cell achieves the cycle life specification, the upper charge voltage is lowered to reduce the impact of the degradation reactions at 45°C. It is important to note that the Enovix cell maintains about the same initial capacity at 4.25V (45°C) as at 4.35V (25°C), while traditional Li-ion when charged to a lower voltage at 45° effectively reduces its capacity.

Discharge Rate

The Enovix technology is optimized for high energy density and capacity which means that to extract the full energy from the cell, it must be evaluated under specific conditions. Traditional methods for Li-ion cell cycle life evaluation do not show the true benefits of the Enovix 100% active silicon anode technology. Cycle life testing at rates higher than 0.5C discharge will reduce the effective cycle life of the cell. At these higher rates, the cell is not fully discharged when it reaches the 3.0V cutoff. Thus using 1C discharge rate cycle life evaluation, while reducing the testing time, is not a practical measure to estimate performance in real-world product applications. Recall that 1C means that the entire cell capacity is fully discharged in 1 hour. Practical applications discharge at much lower currents than 1C to ensure the device can operate for many hours or days. For example, if the device operates for 10 hours this represents a 0.1C rate. The Enovix cell is optimized for cycle life at 0.5C to ensure that it can handle reasonable pulse current demands from the host device and also for a reasonable cycle life test time (see Table 4). Traditional Li-ion cells can cycle at higher rates, but cannot offer the same energy benefit as the Enovix technology even if the cycling rate is reduced.

No.	Parameters	Enovix EX-1 Silicon Anode	Lithium Ion Graphite Anode
6	Discharge Current for Cycle Life (A)	0.5C	0.5 - 1C

Table 4: Discharge Rate Comparison for Enovix Silicon Anode Cells and Lithium Ion Graphite Anode (Excerpt from Table 2)

Certainly, the Enovix cell can be optimized to achieve higher rates, but the energy density would be reduced.

Maximum Discharge Rate

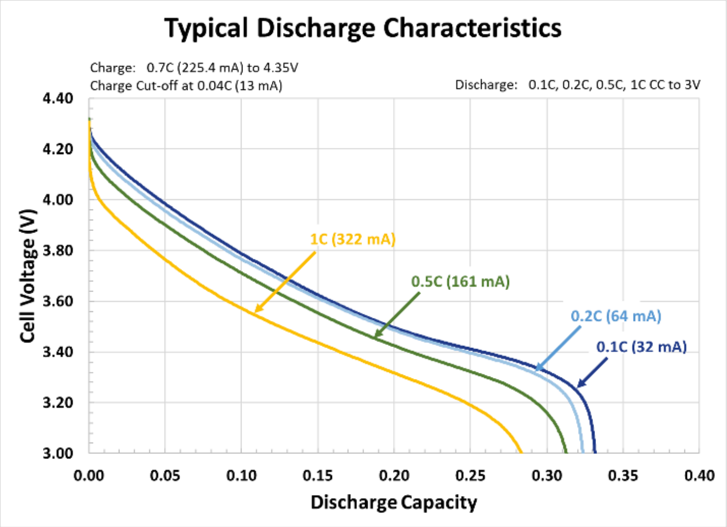
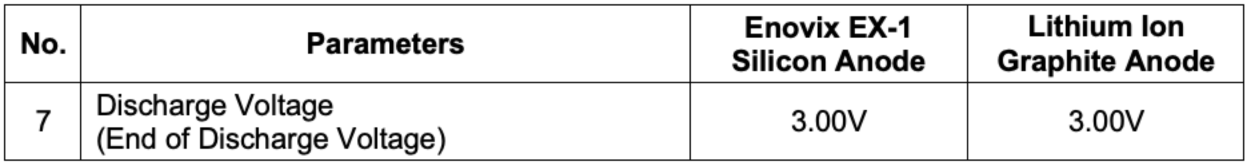


Figure 4: Typical Enovix Cell Discharge Profile at Different C-rates

The Enovix cell cycle life testing protocol is 0.7C charge followed by 0.5C discharge, which gives over 500 cycles before reaching 80% of the cells initial 0.5C capacity. The cell is capable of delivering energy at higher and lower discharge rates and is typically shown as a voltage discharge curve like Figure 4. Notice that the capacity is highest at the lowest discharge rate, 0.1C and lower at higher discharge rates. This is expected and is similar for standard Li-ion cells. It is also typically expected that cycle life at higher rates will be less than cycle life at 0.5C. Cycling performance at other rates outside of the cell specification will require further evaluation.

Discharge Voltage (End of Discharge Voltage)

The Discharge Voltage or End of Discharge Voltage defines the lower voltage threshold where discharging terminates. The amount of capacity discharged at the Discharge Voltage is defined as the Cell Capacity, which is specified under a constant current rate. Both the Enovix 100% active silicon anode and Li-ion graphite anode cells discharge to 3V (Table 5).



No.	Parameters	Enovix EX-1 Silicon Anode	Lithium Ion Graphite Anode
7	Discharge Voltage (End of Discharge Voltage)	3.00V	3.00V

Table 5: Discharge Voltage for Enovix Silicon Anode and Lithium Ion Graphite Anode Cells (Excerpt from Table 2)

The present Enovix EX-1 silicon anode technology has a discharge voltage of 3.00V; however, as Enovix introduces next generation Enovix silicon cells further optimized for higher energy density beyond 900 Wh/l, the Discharge voltage may be reduced below 3.0V, to as low as 2.50V.

During cell evaluation, there are two main reasons that a cell does not achieve its rated capacity during testing:

1) Higher cell discharge rate causes the cell voltage to drop faster and
2) The cell is not fully discharged when terminated at the Discharge Voltage.

Lower capacity due to rate can be explained by reviewing Figure 4 in the previous section. The progressively lower discharge capacity with increasing discharge rate (current) is due to cell voltage drop induced by the current and the cell's internal resistance (Ohm's Law). The voltage drop causes the cell to reach the 3V discharge voltage threshold sooner, terminating cell discharge before all of the cell capacity is extracted. It is important to evaluate the Enovix cell under rates that represent the practical device discharge loads for a fair comparison of the cell's ability to provide capacity and to properly evaluate its benefits.

Excessive Rates for Testing

To illustrate this, an example is helpful. The Enovix 100% active silicon anode cell has higher energy density than a Li-ion graphite cell. Assume that two cells of the same dimensions; the Enovix silicon anode cell has 5000 mAh capacity and the incumbent cell has 4000 mAh capacity.

For standard Li-ion graphite cell testing, a typical protocol may be 0.5C which means that the discharge current is

0.5C = 0.5 x 5000 = 2500 mA

If the device only discharges at 250 mA current. The 2500 mA current is 10 times larger than the actual device current.

The same calculation for a Li-ion graphite cell at 4000 mAh capacity and 0.5C rate, the discharge current is

0.5C = 0.5 x 4000 = 2000 mA

For the Li-ion graphite cell, the 2000 mA discharge current is only 8 times larger than the actual device current.

The test protocol based on the same C-rate unduly stresses the Enovix cell and does not represent actual device operating conditions. The same analogy applies if the cell capacities are 600 mAh and 500 mAh for the Enovix silicon anode and Li-ion Graphite cells; respectively.

If the device discharges at 50 mA current, the C-rate fraction factor, M for each cell is:

Enovix Silicon Anode Cell:	M = 0.08 (50 mA / 600 mAh) or 0.08C Rate
Li-ion Graphite Cell:	M = 0.10 (50 mA / 500 mAh) or 0.1C Rate

This means that the equivalent discharge current for the Enovix silicon anode cell is 80% of the Li-ion graphite cell and represents a lighter load on the Enovix cell leading to less voltage drop and more available capacity. It is understood that Customer test protocols are standardized to ensure that the same relative test "stress" is applied to cells regardless of capacity. However, Enovix recommends that a reasonable test "stress" or C-rate be used to highlight the true performance benefits of the Enovix 100% active silicon anode cell. The Enovix cell is designed for high energy density at reasonable discharge rates.

Voltage Drop from Excessive Rates

Figure 5 below shows how the cell voltage drops for an Enovix 100% active silicon anode cell discharged at 0.1C and 1C discharge rates. If the host device actually requires a 1C rate, then the Enovix cell will terminate discharge at the end of discharge point, C1. The capacity at C1 is about 282 mAh capacity. However, if the actual host device discharges at only 0.1C rate, then the capacity is 330 mAh at point C2. Using a much higher discharge rate than representative to evaluate the Enovix silicon anode cell will incorrectly measure the cell's useful capacity relative to actual use conditions. If the device actually discharges at 0.1C (ie. over a 10 hour period), there is ~17% unrealized capacity available between points C1 and C2.

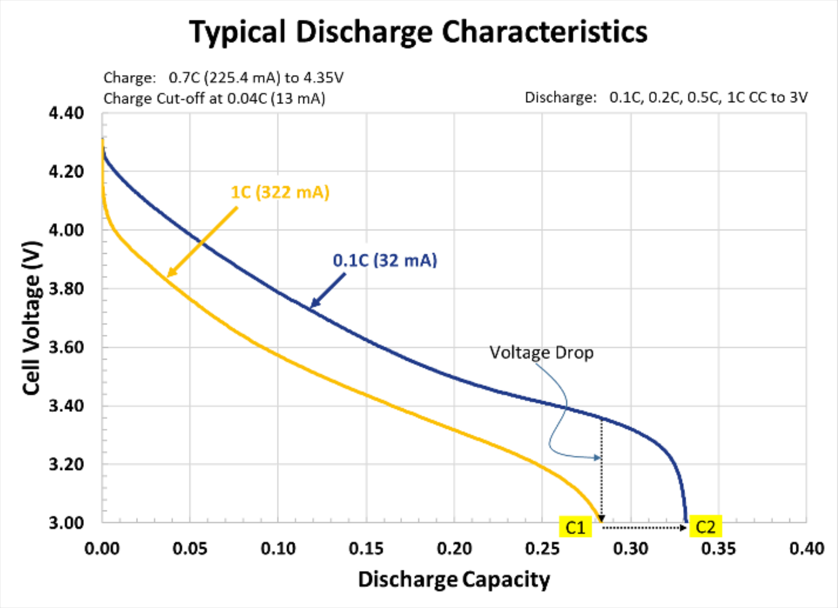


Figure 5: Cell Voltage Drop from 0.1C to 1C Rates

Fully Discharging to the Discharge Voltage

Enovix's 100% active silicon anode cell has high energy density but the cell must be fully discharged to realize the maximum benefit from the cell technology. This fact is best illustrated with an example of an Enovix 100% Active silicon anode cell and a Li-ion graphite anode cell of the same size (5.35 x 23.9 x 25.7 mm). The Enovix cell will achieve 20% more runtime when discharged at the same current due to its higher energy density. This is apparent in the run time chart in Figure 6 (left). Also notice that the voltage profile for the Li-ion graphite anode cell is higher than for the Enovix 100% active silicon anode cell. In particular, at the intersection of the two voltage profiles (~3.4V), the graphite anode cell is almost finished discharging; while the Enovix 100% active silicon anode cell still has 24% available capacity when it finishes discharging at 3V. In this particular case, the crossover voltage of ~3.4V is the point where the Enovix 100% active silicon anode cell begins to demonstrate the benefits of its higher energy density.

Figure 6 on the right shows the cell State of Charge (SOC) over the entire discharge range for each cell. Notice that the Graphite anode cell has a higher cell voltage profile than the Enovix 100% active silicon anode cell, but the Enovix voltage profile extends longer than the graphite anode cell. This means that there is more total energy for the Enovix cell, but at a lower voltage. The key fact after studying the chart is that to realize the capacity benefit of the Enovix 100% active silicon anode cell, the cell must discharge lower than about 3.4V. A comparison summary of the remaining capacity at several discharge voltage thresholds is tabulated in Table 6. It is clear from Figure 6 and Table 6 that to test and to utilize the full energy from the Enovix 100% active silicon anode cell, the device's internal end of discharge voltage must be set as close as possible to 3V; otherwise, residual useful capacity will remain in the cell.

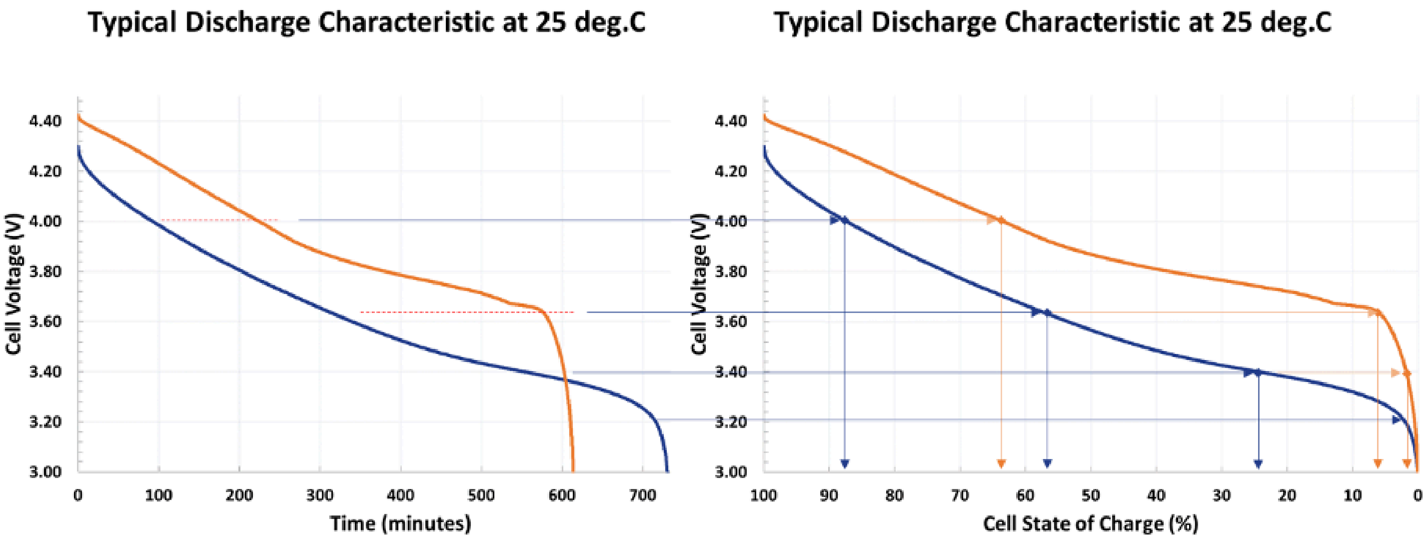


Figure 6:Comparison of Enovix 100% Active Silicon Anode Cell to Lithum Ion Graphite Anode Cell

Cell Discharge Voltage	SOC Silicon Anode Cell	SOC Graphite Anode Cell	Delta SOC	Comment
4.00V	87.3%	63.5%	23.8%	
3.63V	56.5%	5.7%	50.8%	Graphite Cell Voltage "Knee"
3.40V	24.3%	1.8%	22.5%	Graphite & Silicon Cell Capacity Crossover
3.20V	2%	0.5%	1.5%	Silicon Cell Voltage "Knee"

Table 6: Comparison of Cell Voltage Threshold and Cell State of Charge

VII. Conclusion

The Enovix 100% active silicon anode cell technology has unique electrical characteristics that need to be properly assessed to highlight the benefits of high energy density. The cell is designed with high energy density at typical end-product discharge rates. The test parameters must be followed to ensure that the cell is properly charged and fully discharged at the appropriate test temperature. Evaluating the Enovix cell technology under much higher rates than required by the host device will not show the true available capacity & advantage of the cell. The cell will terminate discharge due to the high rate and associated voltage drop resulting in an apparently lower useful cell capacity. The Enovix silicon anode technology will continue to improve to increase energy density which may change test parameters further. Traditional Li-ion test protocols may not apply to fairly assess the capacity in the Enovix silicon anode cells.

VIII. References

1) Linden, David, Reddy B., Thomas (2002), Handbook of Batteries (3rd), McGraw-Hill

Forward Looking Statements

This document contains forward-looking statements within the meaning of Section 27A of the Securities Act of 1933, as amended, and Section 21E of the Securities Exchange Act of 1934, as amended, about us and our industry that involve substantial risks and uncertainties. Forward-looking statements generally relate to future events or our future financial or operating performance. In some cases, you can identify forward-looking statements because they contain words such as “believe”, “will”, “may”, “estimate”, “continue”, “anticipate”, “intend”, “should”, “plan”, “expect”, “predict”, “could”, “potentially”, “target”, “project”, or the negative of these terms or similar expressions. Forward-looking statements in this document include, but are not limited to, the design, performance and increased energy density of our lithium-ion batteries. Actual results could differ materially from these forward-looking statements as a result of certain risks and uncertainties. For additional information on these risks and uncertainties and other potential factors that could affect our business and financial results or cause actual results to differ from the results predicted, please refer to our filings with the Securities and Exchange Commission (the “SEC”), including in the “Risk Factors” and “Management’s Discussion and Analysis of Financial Condition and Results of Operations” sections of our most recently filed annual periodic reports on Form 10-K and quarterly report on Form 10-Q and other documents that we have filed, or that we will file, with the SEC. Any forward-looking statements made by us in this document speak only as of the date on which they are made and subsequent events may cause these expectations to change. We disclaim any obligations to update or alter these forward-looking statements in the future, whether as a result of new information, future events or otherwise, except as required by law.

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Enovix Corporation, 3501 W Warren Ave, Fremont, CA 94538 USA Tel 510.695.2350 enovix.com JULY 2023