ROAMER

XTREME LOW TEMPERATURE LIFEPO4

TEST SUMMARY

The Roamer Xtreme lithium batteries use a revolutionary new type of LiFePO4 cells that offer superior performance across a wide temperature range from -40 to 60 degrees. This document outlines the results from a wide range of stringent lab tests carried out by an independent body on behalf of the cell manufacturer.

Cycle capacity of the cells was above 94% at all tested temperatures even down to minus 40

Xtreme cells are able to deliver a useful amount of energy in any environment

Voltage curve during charge and discharge at various temperatures is stable even at very high C rates

Cells deliver reliable and consistent power in all use cases

Capacity remaining after 1500 cycles of 100% DoD and discharge rates of 3C is still 79% of nominal capacity

Market leading cycle life even when stressed to limits of the cells

High temperature storage tests show over 98% capacity remaining after 4 hours at 85 degrees

Long cycle lifes even when exposed to very high temperatures

Cell tests were designed to verify performance at various temperatures, charge and discharge rates and storage conditions. Some highlights:

When discharging at minus 40 degrees, it was possible to extract 97% of the rated capacity which was way better than expected. After putting the cells through another 300 full cycles (0% to 100% and back again), the cells were allowed to warm up to room temperature and were then tested to measure the capacity recovery rate. The cells had only lost 4% of their original rated capacity which isn't far off the expected results at room temperature.

While at this low temperature, the cells were also loaded at a very high discharge rate of 3C and testing shows they were able to maintain a stable high current until the battery was almost empty. Standard LiFePO4 cells are only capable of sustaining 1C discharge rates even at normal temperatures so this represents a massive power increase especially at low temperatures.

The cells were also tested at very high temperatures, charging at discharging at 60 degrees C. The effect on discharge performance (the voltage curve) was negligible. High temperatures still affects overall life cycles (as it does with all LiFePO4 cells) but the effect was reduced.

This was also true when storing at high temperatures and at 100% state of charge, something which can severely damage LiFePO4 cells. The most extreme test involved fully charging to 100% then baking in an oven at 85 degrees for 4 hours, , yet capacity losses were just 5%. While it is still a bad idea to store in these conditions, it is reassuring to know that the Xtreme cells are very resilient and can survive exposure to very high temperatures.

Xtreme cells are also able to sustain very high discharge rates. Normally a LiFePO4 will max out at 1C (1 x capacity) but these will happily put out 3C continuously and up to 5C for short periods. To test the impact on cycle life, the cells were discharged at 3C for 1000 full cycles (0% to 100% and back again) and the remaining capacity was measured. The total available capacity had dropped to 88% of the starting value. Although testing was stopped at 1000 cycles, extending these results suggests cells should be good for over 2000 cycles even when maxed out at 3C discharge and 100% depth of discharge.

This is comparable to results for a standard LiFePO4 cell at a much lower discharge rate of 1.0C. In a complete battery pack, Roamer batteries will be limited by the BMS to a maximum of 2.0C meaning even at the limits of the battery, the cells will not be damaged due to overloading.

Full charge and discharge voltage tests were also carried out at each temperature, the results are shown in the first set of graphs. Note that allowable charging temperature ranges from -30 to 60 whereas discharging is ok from -40 to 60, hence there is not a charge graph for -40.

Xtreme LiFePO4 cells have a wider voltage range than normal LiFePO4 and can be safely discharged to 2.0V (normally 2.5V) and even down to 1.5V at very low temperatures. The BMS has also been tested at temperatures down to minus 40 to check performance. Results of this test are available separately.

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EXPLANATION OF TERMS & STANDARD TESTING METHODS

CYCLE CAPACITY	How many Ah can be extracted from the cell over a full cycle.
CAPACITY RETENTION	A measure of how much charge is left in the cell after a storage test.
CAPACITY REMAINING	Batteries degrade over time. Capacity remaining is a measure of the total useful capacity per cycle.
CYCLE LIFE	The number of charge and discharge cycles until capacity remaining falls to 70% of the nominal capacity.
C RATE	A measure of charge/discharge rate. 1C would mean discharging a 100Ah battery at 100A (100% to 0% in 1 hour).
SOC	State of charge of the battery cell ie 50% SoC means its half full.
DOD	Depth of Discharge. 80% DoD means discharging the cell to 20% remaining.
DEGREES	All temperatures are degrees Celsius. To avoid confusion, temperatures is written as XX degrees rather than using C
STANDARD CHARGE METHOD	At 25 degrees, charge the single cell with a constant current to 3.65V then switch to a constant voltage until the flow is less than 0.05C.
STANDARD DISCHARGE METHOD	At 25 degrees, discharge to a single cell voltage of 2.00V with a constant current of 1C
LOW TEMPERATURE DISCHARGE METHOD	After battery is charged using standard charge method, use silver spot welding to weld the battery, double wire the test equipment to the engraved plate and put into a low temperature environment for 16-24 hours. The test point is sealed and discharged to the minimum discharge voltage of the single cell with a constant current of 1C.
LOW TEMPERATURE CHARGING	After battery is discharged using the standard discharge method, use silver spot welding to weld the battery, double wire the test equipment to the engraved plate and put into a low temperature environment for 16-24 hours. The test point is sealed and charged to the single cell voltage of 3.65V with a constant current of 0.2C, and then switched to a constant voltage of 3.65V. Stop charging when the charge current is less than 0.05C.

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TEST RESULTS SUMMARY

DESCRIPTION	TEST CONDITIONS	RESULT
Single cycle capacity at -40 degrees	Discharge 1C at -40 degrees to 1.5V. Rest. Charge 0.9C at 25 degrees to 3.65V. Repeat 0.2C, 0.5C.	Pass
Single cycle capacity at -30 degrees	Discharge 1C at -30 degrees to 1.5V. Rest. Charge 0.9C at 25 degrees to 3.65V. Repeat 0.2C, 0.5C.	Pass
Single cycle capacity at -20 degrees	Discharge 1C at -20 degrees to 2.0V. Rest. Charge 0.9C at 25 degrees to 3.65V. Repeat 0.2C, 0.5C, 3C.	Pass
Single cycle capacity at 0 degrees	Discharge 1C at 0 degrees. Rest. Discharge 0.9C at 25 degrees to 2.0V. Repeat 0.2C, 0.5C, 3C.	Pass
Single cycle capacity at 25 degrees	Disharge 1C at 25 degrees to 2.0V. Rest. Discharge 0.9C at 25 degrees to 3.65V. Repeat 0.2C, 0.5C, 3C.	Pass
Single cycle capacity at 60 degrees	Charge 1C at 60 degrees. Rest. Discharge 0.9C at 25 degrees to 2.0V. Repeat 0.2C, 0.5C, 3C.	Pass
Cycle life at 1C charge, 1C discharge, 100% DoD, 25 degrees	Charge 1C, discharge 1C at 25 degrees with 100% DoD for 500/1000/1500 cycles.	Pass
Cycle life at 1C charge, 3C discharge, 100% DoD, 25 degrees	Charge 1C, discharge 3C at 25 degrees with 100% DoD for 500/1000/1500 cycles.	Pass
Cycle life at 1C charge, 3C discharge, 100% DoD, 45 degrees	Charge 1C, discharge 3C at 45 degrees with 100% DoD for 100/240 cycles.	Pass
Storage capacity retention at 85 degrees	Charge to 100% store at 85 degrees for 4 hours, 1C discharge to 0%.	Pass
Storage capacity retention at 60 degrees	Charge to 100% store at 60 degrees for 7 days, 1C discharge to 0%.	Pass
Storage capacity retention at 25 degrees	Charge to 100% store at 25 degrees for 30 days, 1C discharge to 0%.	Pass

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XTREME LOW TEMPERATURE LIFEPO4

KEY CERTIFIED INFORMATION FOR ROAMER XTREME LT26650 3.2AH CELLS

DESCRIPTION	VALUE
Nominal capacity	3200mAh (when discharged at a rate of 0.2C to a termination voltage of 2.00V, at temperature of 25 degrees)
Minimum capacity	3150mAh
Nominal voltage	3.2V
Energy density	124 Wh/kg
Minimum discharge voltage	2.00V (ambient temperature > -20 degrees) 1.50V (ambient temperature < -20 degrees)
Maximum charge voltage	3.65V
Standard charge current	0.5C
Standard discharge current	1.0C
Maximum charge current	3.0C (ambient temperature > 0 degrees) 0.5C (ambient temperature <0 degrees) 0.2 degrees (ambient temperature < -20 degrees)
Maximum discharge current	5.0C
Temperature range	Charging -30 to 60 degrees Discharging -40 to 60 degrees
Weight	85g
Cell size	Height 65.7mm Diameter 26.3mm
Cell storage and transportation environment	< 1 month: -20 to 45 degrees, <75% SoC <3 months: -20 to 35 degrees, <75% SoC <12 months: -20 to 25 degrees, <75% SoC
Discharge performance at 25 degrees	0.5C discharge 0.2C charge: capacity 98% 1.0C discharge 0.2C charge: capacity 97% 3.0C discharge 0.2C charge: capacity 96%
Charge retention	After charging and 28 days storage at 25 degrees, capacity retention 90% After a discharge and charge cycle, capacity remaining 95%

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SAFETY TESTING RESULTS

DESCRIPTION	VALUE
Vibration	Vibrate in 3 dimensions for 30 minutes: No damage, leak, fire, explosion
Temperature shock	65 degrees to -20 degrees, repeat x10: No damage, leak, fire, explosion
Short circuit	Short using copper wires pos to neg: No fire or explosion
Overcharge	Charge to 10V: No fire or explosion
Overdischarge	Discharge to 0V: No leak, smoke, fire or explosion
Hotbox	Heat to 130 degrees: No fire or explosion
Drop test	Drop from 1m height, repeat x10: No leak, smoke, fire or explosion

SINGLE CYCLE CAPACITY TESTS

Steps followed:

1. The battery is tested at 25 degrees with a charge of 1C.
2. Cut-off current 0.05C
3. Discharge: 2V at 0.9C
4. Repeat step 1 with different temperatures (-40 degrees/-30 degrees/-20 degrees/0 degrees/60 degrees)

	-40 DEGREES 1.5V	-30 DEGREES 1.5V	-20 DEGREES 2.0V	0 DEGREES 2.0V	25 DEGREES 2.0V	60 DEGREES 2.0V
Discharged mAh	3112.3	3135.6	3019.0	3152.5	3187.1	3211.5
Cycle capacity	97.7%	98.4%	94.7%	98.9%	100%	100.8%

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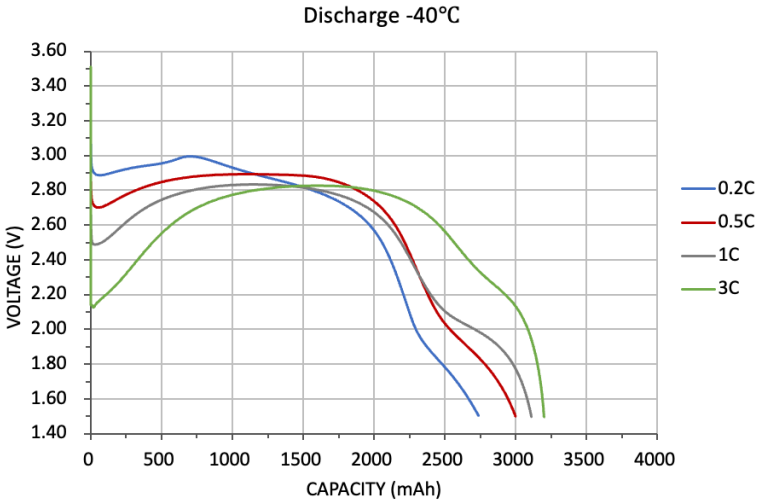
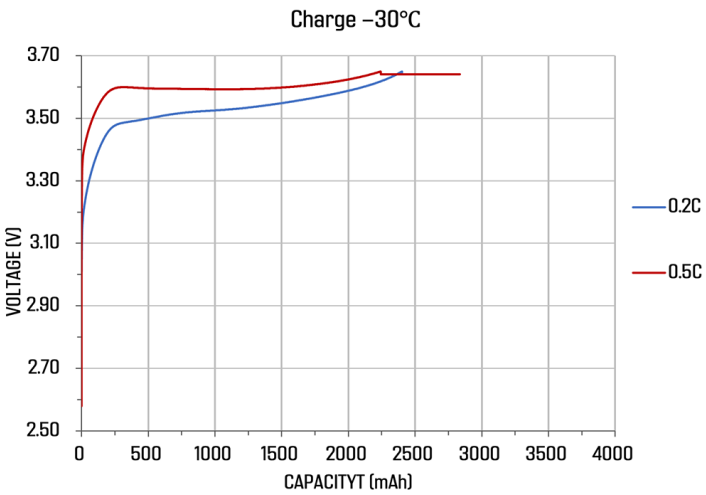
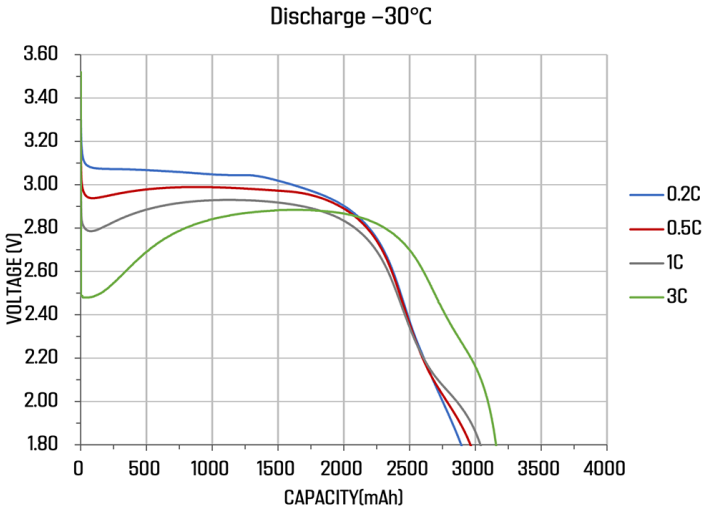
XTREME LOW TEMPERATURE LIFEPO4

CHARGE AND DISCHARGE VOLTAGE CURVES AT VARYING TEMPERATURES AND C RATES

Charts for single cycle voltage curves are shown below. Note that allowable charging temperature ranges from -30 to 60 degrees whereas discharging is ok from -40 to 60 degrees.







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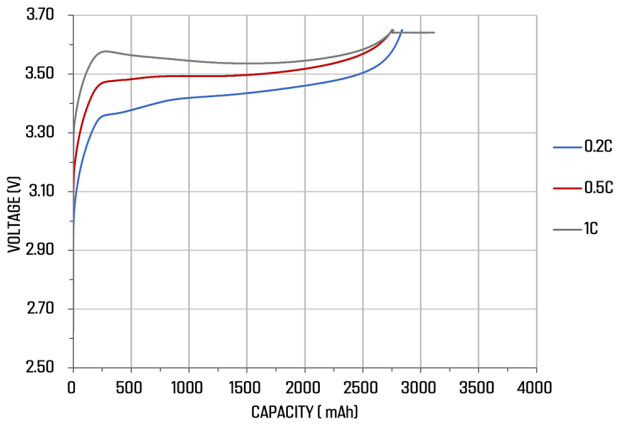
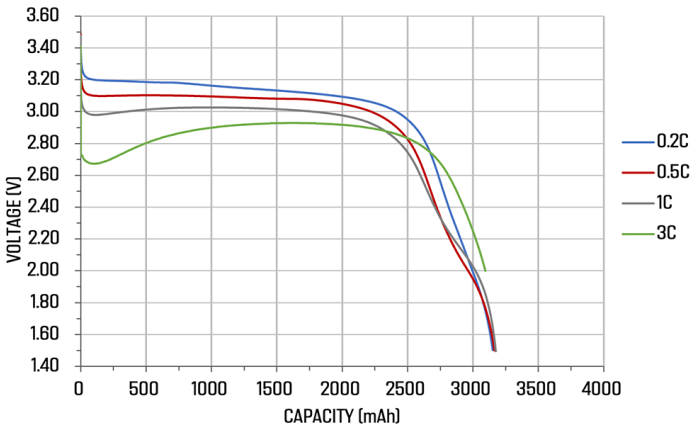
XTREME LOW TEMPERATURE LIFEPO4

CHARGE & DISCHARGE VOLTAGE CURVES AT VARYING TEMPERATURES & C RATES

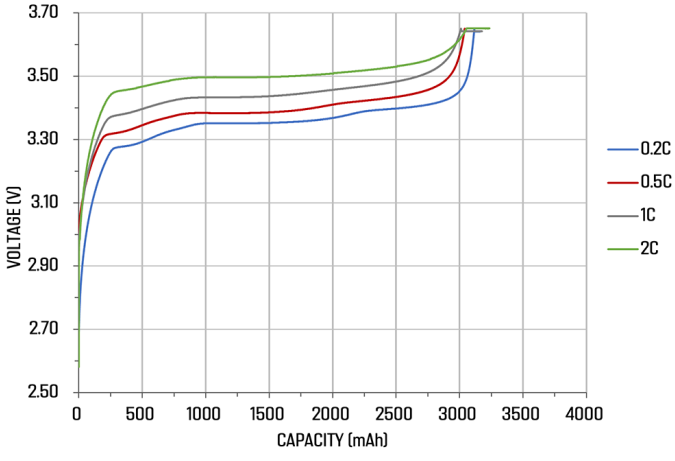
Charge –20°C



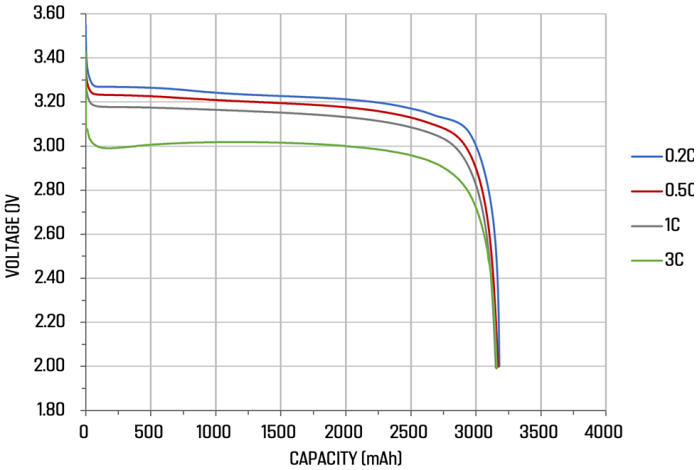
Discharge –20°C



Charge 0°C



Discharge 0°C



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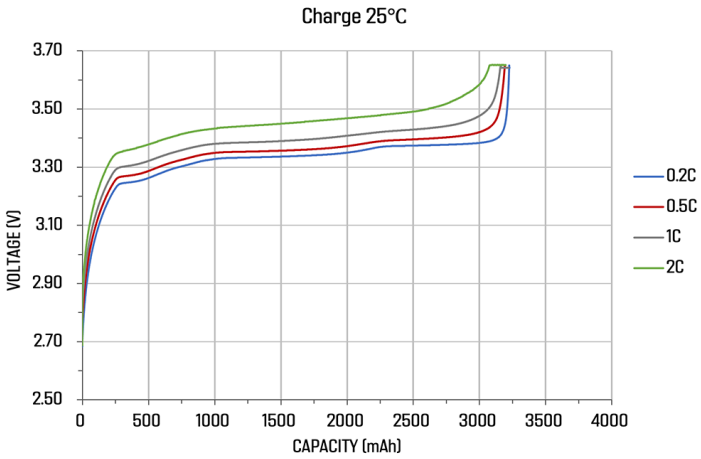
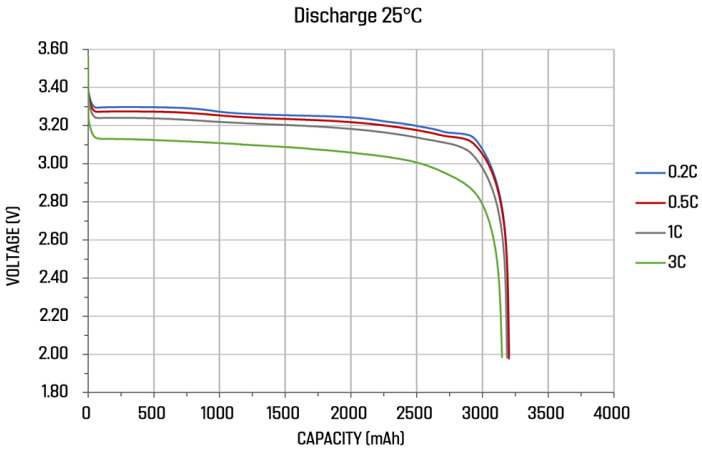
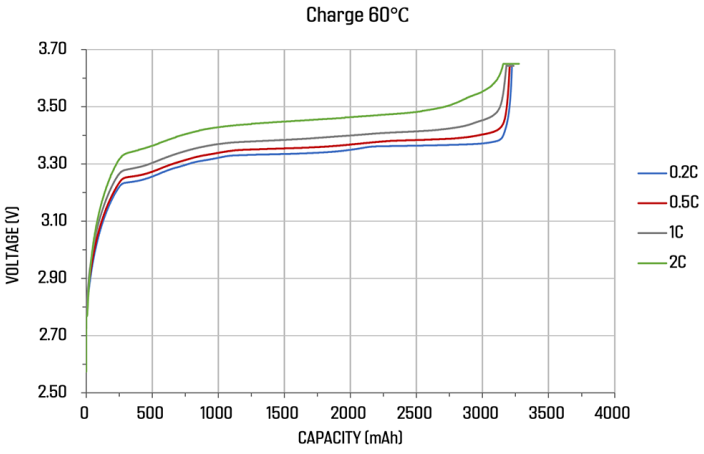
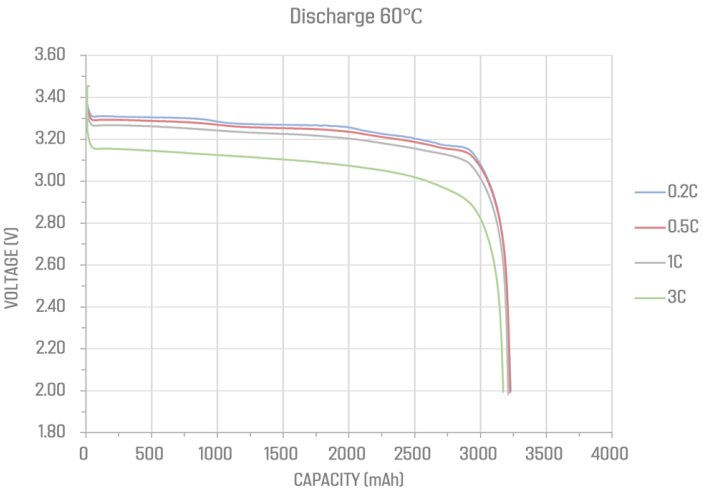
CHARGE & DISCHARGE VOLTAGE CURVES AT VARYING TEMPERATURES & C RATES









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XTREME LOW TEMPERATURE LIFEPO4

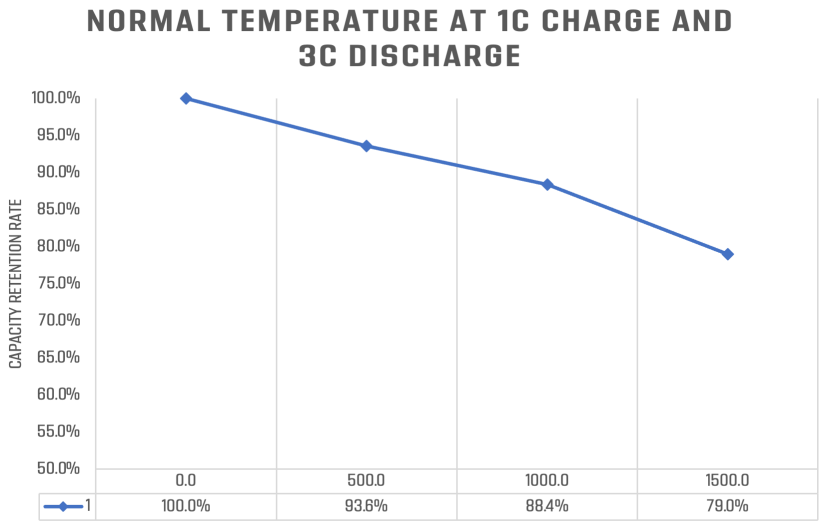
CHARGE AT 1C – DISCHARGE AT 3C AT NORMAL TEMPERATURE

Steps followed:

1. Charge: 3.65V at 1C
2. Cut-off current: 0.05C
3. Set aside time: 900 seconds
4. Discharge: 2V at 3C
5. Set aside time: 900 seconds
6. Repeat steps 1-5 for 1000 cycles

Judgement criteria: 1000 times capacity retention rate > 80%

	INTERNAL RESISTANCE BEFORE CYCLE (MΩ)	1ST CYCLE (MAH)	500 CYCLES (MAH)	500 TIMES CAPACITY RETENTION RATE	1000 CYCLES (MAH)	1000 TIMES CAPACITY RETENTION RATE	1500 CYCLES (MAH)	1500 TIMES CAPACITY RETENTION RATE
1	13.5	3435.37	3217.1	93.6%	3038.2	88.4%	2714.3	79%



Even at 3C discharge rates and 100% DoD, capacity remaining after 1500 cycles is 79%. If extended to 70% remaining, expected cycles should exceed 2000 which is in line with standard LiFePO4 cells at 1C

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CHARGE–DISCHARGE CYCLE OF 1C AT 45 DEGREES

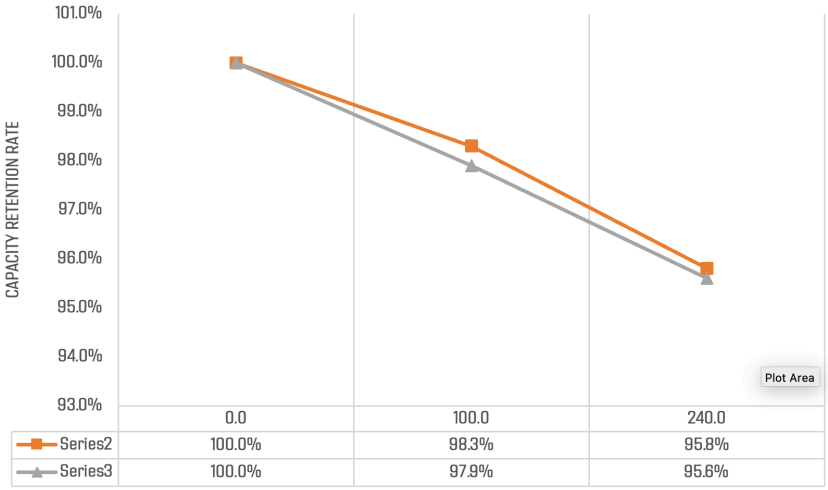
Steps followed:

1. Charge: 3.65V at 1C
2, Cut-off current: 0.05C
3. Set aside time: 600 seconds
4. Discharge: 2V at 1C
5. Set aside time: 600 seconds
6. Repeat steps 1-5 for 700 cycles

Judgement criteria: 700 times capacity retention rate > 80%

	INTERNAL RESISTANCE BEFORE CYCLE (M)	1ST CYCLE (MAH)	100 CYCLES (MAH)	100 TIMES CAPACITY RETENTION RATE	240 CYCLES (MAH)	240 TIMES CAPACITY RETENTION RATE	1000 CYCLES (MAH)	1000 TIMES CAPACITY RETENTION RATE
1	16.9	3187.0	3133.3	98.3%	3053.3	95.8%		0.0%
2	17.0	3185.0	3118.3	97.9%	3043.4	95.6%		0.0%

45°C AT 1C CHARGE–DISCHARGE CYCLE



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XTREME LOW TEMPERATURE LIFEPO4

FULLY CHARGED AND STORED AT 85 DEGREES FOR 4 HOURS AND DISCHARGE AT 0.9C DEGREES

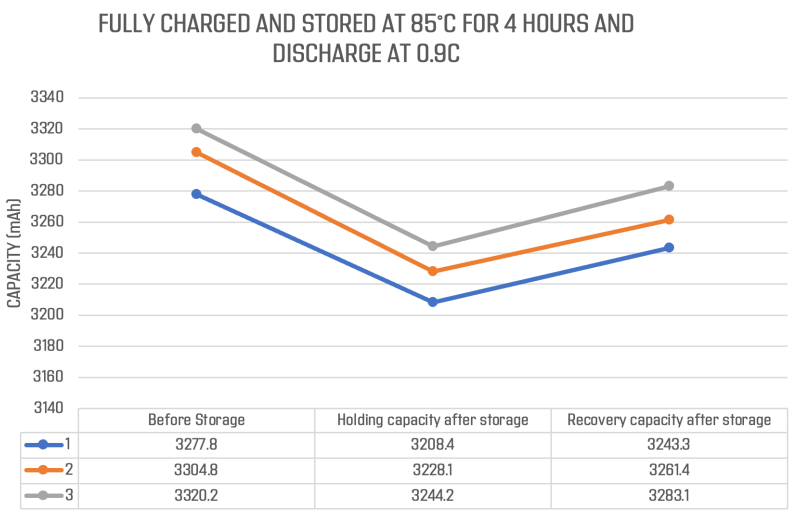
Steps followed:

1. The battery is tested at 25 degrees with a charge of 0.9C current.
2. Cut-off current: 0.05C
3. Set aside time: 4 hours at 85 degrees
4. Set aside time: 12 hours at 25 degrees
5. Discharge: 2V at 0.9C
6. The battery is tested and is recorded as “holding capacity”
7. Repeat the first step and record as “recovery capacity”

Judgement criteria:
capacity holding rate > 95%
capacity recovery rate > 96%

	BEFORE STORAGE				AFTER STORAGE		
	VOLTAGE (V)	INTERNAL RESISTANCE BEFORE CYCLE (MΩ)	0.9 DISCHARGE CAPACITY (MAH)	VOLTAGE AFTER CYCLE (V)	INTERNAL RESISTANCE AFTER CYCLE (MΩ)	0.9C HOLDING CAPACITY (MAH)	0.9 RECOVERY CAPACITY (MAH)
1	3.349	13.2	3277.8	3.337	13.4	3208.4	3243.3
2	3.347	13.5	3304.8	3.338	13.7	3228.1	3261.4
3	3.358	13.5	3320.2	3.343	13.6	3244.2	3283.1

	PERFORMANCE			
	RETAINED CAPACITY	CAPACITY REMAINING	VOLTAGE DROP (V)	CELL RESISTANCE RISE (MΩ)
1	97.88%	98.95%	0.012	0.2
2	97.68%	98.69%	0.009	0.2
3	97.71%	98.88%	0.015	0.1



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XTREME LOW TEMPERATURE LIFEPO4

FULLY CHARGED AND STORED AT 60 DEGREES FOR 7 DAYS AND DISCHARGE AT 0.9 DEGREES

Steps followed:

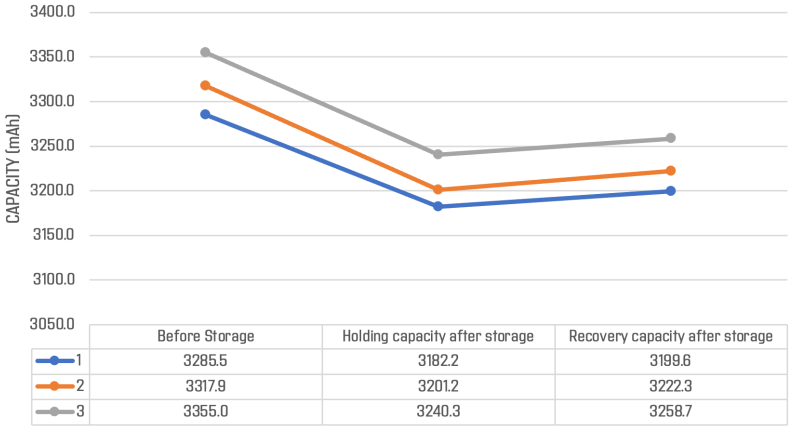
1. The battery is tested at 25 degrees with a charge of 0.9 degrees current.
2. Cut-off current: 0.05C
3. Set aside time: 7 days at 60 degrees
4. Set aside time: 12 hours 25 degrees
5. Discharge: 2V at 0.9 degrees
6. The battery is tested and is recorded as “holding capacity”
7. Repeat the first step and record as “recovery capacity”

Judgement criteria:
capacity holding rate > 90%
capacity recovery rate > 95%

	BEFORE STORAGE				AFTER STORAGE		
	VOLTAGE (V)	INTERNAL RESISTANCE BEFORE CYCLE (MΩ)	0.9 DISCHARGE CAPACITY (MAH)	VOLTAGE AFTER CYCLE (V)	INTERNAL RESISTANCE AFTER CYCLE (MΩ)	0.9 DEGREES HOLDING CA-PACITY (MAH)	0.9 RECOVERY CAPACITY (MAH)
1	3.346	13.6	3285.5	3.332	13.8	3182.2	3199.6
2	3.346	13.2	3317.9	3.329	13.5	3201.2	322.3
3	3.347	13.3	3355.0	3.332	13.6	3240	3258.7

	PERFORMANCE			
	HOLDING CAPACITY RATE	RECOVERY CAPACITY RATE	VOLTAGE DROP (V)	INTERNAL RESISTANCE RISE (MΩ)
1	96.86%	97.39%	0.014	0.2
2	96.48%	97.12%	0.017	0.3
3	96.58%	97.13%	0.015	0.3

FULLY CHARGED AND STORED AT 60°C FOR 7 DAYS AND DISCHARGE AT 0.9C



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XTREME LOW TEMPERATURE LIFEPO4

FULLY CHARGED AND STORED AT 25 DEGREES FOR 28 DAYS AND DISCHARGE AT 0.9 DEGREES

Steps followed:

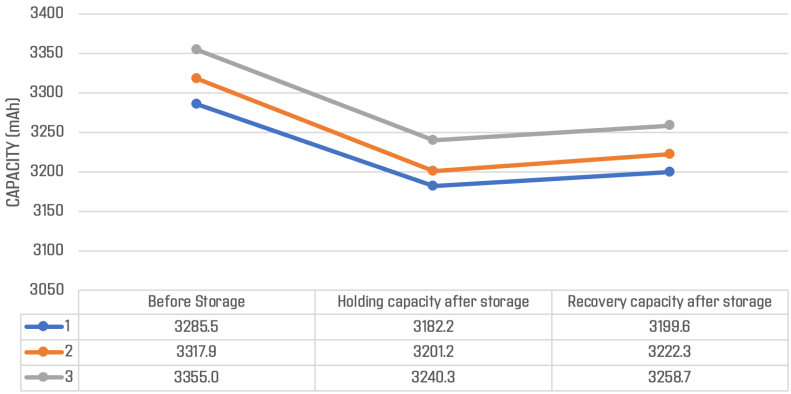
1. The battery is tested at 25 degrees with a charge of 0.9 degrees current.
2. Cut-off current: 0.05C
3. Set aside time: 28 days at 25 degrees
4. Discharge: 2V at 0.9 degrees
5. The battery is tested and is recorded as “holding capacity”
6. Repeat the first step and record as “recovery capacity”

Judgement criteria:
capacity holding rate > 95%
capacity recovery rate > 96%

	BEFORE STORAGE				AFTER STORAGE	
	VOLTAGE (V)	INTERNAL RESISTANCE BEFORE CYCLE (MΩ)	0.9 DISCHARGE CAPACITY (MAH)	VOLTAGE AFTER CYCLE (V)	INTERNAL RESISTANCE AFTER CYCLE (MΩ)	0.9 RECOVERY CAPACITY (MAH)
1	3.301	13.4	3302.5	3.299	13.4	3199.6
2	3.301	13.5	3285.3	3.299	13.4	322.3
3	3.299	13.2	3269.4	3.298	13.3	3258.7

	PERFORMANCE		
	RECOVERY CAPACITY RATE	VOLTAGE DROP (V)	INTERNAL RESISTANCE RISE (MΩ)
1	98.90%	0.002	0
2	98.67%	0.002	-0.1
3	98.63%	0.001	0.1

FULLY CHARGED AND STORED AT 25°C FOR 28 DAYS AND DISCHARGE AT 0.9C



	Before Storage	Holding capacity after storage	Recovery capacity after storage
1	3285.5	3182.2	3199.6
2	3317.9	3201.2	3222.3
3	3355.0	3240.3	3258.7

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50% SOC AND STORED AT 25 DEGREES FOR 90 DAYS AND DISCHARGE AT 0.9 DEGREES

Steps followed:

1. The battery is tested at 25 degrees with a charge of 0.9 degrees current.
2. Adjust the battery charge to 50% SOC
3. Set aside time: 90 days at 25 degrees
4. Discharge: 2V at 0.9 degrees
5. The battery is tested and is recorded as “holding capacity”
6. Repeat the first step and record as “recovery capacity”

Judgement criteria:
capacity recovery rate > 96%

	BEFORE STORAGE				AFTER STORAGE	
	VOLTAGE (V)	INTERNAL RESISTANCE BEFORE CYCLE (MΩ)	0.9 DISCHARGE CAPACITY (MAH)	VOLTAGE AFTER CYCLE (V)	INTERNAL RESISTANCE AFTER CYCLE (MΩ)	0.9 RECOVERY CAPACITY (MAH)
1	3.301	13.4	3302.5	3.299	13.4	3266.2
2	3.301	13.5	3285.3	3.299	13.4	3241.6
3	3.299	13.2	3269.4	3.298	13.3	3224.6

	PERFORMANCE		
	RECOVERY CAPACITY RATE	VOLTAGE DROP (V)	INTERNAL RESISTANCE RISE (MΩ)
1	98.90%	0.002	0
2	98.67%	0.002	-0.1
3	98.63%	0.001	0.1