**A Comparison of Battery Testing Protocols:
Those Used by the U.S. Advanced Battery Consortium* and Those Used in China**

**David C. Robertson,¹ Jon P. Christophersen,² Taylor Bennett,²
Lee K. Walker,² Fang Wang,³ Shiqiang Liu,³ Bin Fan,³ and Ira Bloom^{1,†}**

¹Chemical Sciences and Engineering Division

Argonne National Laboratory

9700 South Cass Avenue

Argonne, IL 60439

²Battery Test Center

Idaho National Laboratory

P.O. Box 1625

Idaho Falls, ID 83415

³China Automotive Technology and Research Center

No. 68, East Xianfeng Road, Dongli District

Tianjin, 300300 China

* The U.S. Advanced Battery Consortium consists of three U.S. automakers — Ford, General Motors, and Fiat Chrysler Automobiles — and the U.S. Department of Energy.

† Corresponding author: ira.bloom@anl.gov.

Abstract

Two testing protocols, QC/T 743 and those used by the U.S. Advanced Battery Consortium (USABC), were compared using cells based on LiFePO_4 /graphite chemistry. Differences in the protocols directly affected the data and the performance decline mechanisms deduced from the data. In all cases, the rate of capacity fade was linear with time. Overall, the testing protocols produced very similar data when the testing conditions and metrics used to define performance were similar. The choice of depth of discharge and pulse width had a direct effect on the apparent rate of resistance increased and estimated cell life. At greater percent depth of discharge (%DOD) and pulse width, the estimated life was shorter than at lower %DOD and shorter pulse width. This indicates that cells which were at the end of life based on the USABC protocol were not at end of life based on the QC/T 743 protocol by a large margin.

Keywords: battery testing, test protocols, lithium-ion batteries

1. Introduction

Advanced automotive batteries are currently tested in a laboratory setting to determine whether the measured performance of the batteries meet certain criteria, goals, or targets. A laboratory setting is mandatory to ensure that the results are obtained in a precise, prescribed, and controlled manner. Such battery testing is a time-consuming and expensive process.

1
2
3
4 Many organizations have started with the same fundamental understanding of electrochemical
5
6 processes but have developed independent battery testing protocols. The protocols are designed
7
8 to determine performance parameters (such as capacity, energy, resistance, and power) and
9
10 determine how they change with time and use. Each set of testing protocols is also associated
11
12 with a test philosophy. For example, one philosophy might be to test the batteries to absolute
13
14 failure (that is, to a point at which they no longer meet the performance targets), while another
15
16 might be to test them just long enough to obtain sufficient data to allow for a projection of when
17
18 they will no longer meet the goals.
19
20
21
22
23
24
25

26 Currently, parallel battery testing efforts for electric vehicle applications are taking place in the
27
28 United States and China. An international collaboration between the two countries might enable
29
30 them to leverage the resources available to them to their mutual advantage; for example,
31
32 establishing standardized, accelerated testing procedures that enable battery testing organizations
33
34 to cooperate in analyzing the resulting test data. The collaboration could then, in turn, accelerate
35
36 electric vehicle development and deployment.
37
38
39
40
41
42

43 Three organizations — Argonne National Laboratory (Argonne), Idaho National Laboratory
44
45 (INL), and China Automotive Technology and Research Center (CATARC) — collaborated to
46
47 answer the following questions: Do the protocols differ? If so, how? Are the data obtained from
48
49 these protocols comparable? To answer these questions, selected protocols from the appropriate
50
51 test manuals were chosen for this work. The tests from the United States came from the
52
53 U.S. Advanced Battery Consortium (USABC) *Electric Vehicle Battery Test Procedures*
54
55 *Manual* [1]. Those from China came from Automobile Standard QC/T 743-2006 [2]. The tests
56
57
58
59
60
61
62
63
64
65

1
2
3
4 were compared experimentally. The similarities and differences among the tests and the resulting
5
6 performance data are described.
7
8
9

10 11 **2. Experimental** 12 13 14

15
16 **2.1 Materials.** Ten commercially-available lithium-ion cells based on LiFePO_4 /graphite
17 chemistry were used for this work. The format of the cells was rectangular prismatic and they
18
19 were in a hard metal case. The rated capacity of these cells was 7.5 Ah, and they were tested
20
21 using a MACCOR® battery tester. The distribution of cells is given in Table 1. The maximum
22
23 rated discharge currents were 75 A for continuous discharge and 225 A for a 10-s pulse.
24
25
26
27
28
29
30

31 A schematic of how the batteries were connected in the test channels are shown in Fig. 1. The
32
33 current was determined by measuring the voltage drop across a precision resistor, which was part
34
35 of the current-carrying circuit. The voltage drop was converted to current using Ohm's law.
36
37
38
39
40

41 **2.2 Performance characterization and cycling.** All tests were performed in environmental
42
43 chambers (Espec BTZ-575, dual compressor, 0.14 m^3 internal volume) with an ambient
44
45 temperature of 25°C , and all used the same charging algorithm. The cells were charged at the
46
47 $\text{C}_3/3$ rate (2.5 A) until the cell voltage reached 3.65 V. They were then held at 3.65 V until the
48
49 current decreased to below the $\text{C}/30$ rate (250 mA).
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

2.2.1 USABC. The initial performance of the cells was characterized using the USABC core tests, which consisted of capacity and peak power capability measurements and a 48-hour stand. Cell capacity was measured at the C/3, C/2, and C/1 rates between 3.65 and 2 V, corresponding to a 0% depth of discharge (DOD) and a 100% DOD, respectively. The capacity of the cell was also measured using the dynamic stress test (DST) [1] profile, shown in Fig. 2.

The peak power test consisted of 30-s pulses at increments of 10% from 0% to 90% DOD with no rest or regenerative breaking (i.e., charging) steps in between. This test used two current levels, referred to as base and peak. For these cells, the base current level was 0.467 A, and the peak current level for the pulses at each 10% DOD was 75 A. The 75-A current was based on removing the same capacity as in the QC/T 743 power density measurement (see below). Since the QC/T 743 protocol used the maximum rated current for 10 s, the USABC test used 1/3 of the current for three times as long. The base current was calculated from Eq. 1 [1]. The base current was used to remove capacity between pulses. Cell resistance, R , was calculated using Eq. 2 at each 10% DOD increment.

$$I_{base} = (12 \times C_{rated} - I_{high \text{ test current}}) \div 35 \quad \text{Eq. 1}$$

$$R = -\frac{V_{base} - V_{peak}}{I_{base} - I_{peak}} \quad \text{Eq. 2}$$

The cells were cycled by the repeated application of the DST profile from 0% to 80% DOD. Reference performance tests (RPTs) were conducted after every 50 charge/discharge cycles to determine the amount of performance change due to cycling. The RPTs consisted of two C/3 and one DST capacity measurements and a peak power test. Cycling then resumed. Cycling stopped

1
2
3
4 either when 1,000 DST cycles to 80% DOD had accrued or when the battery did not meet
5
6 performance goals [1].
7
8
9

10
11 **2.2.2 QC/T 743.** Characterization consisted of $C_3/3$ capacity measurements and a power density
12
13 (W kg^{-1}) measurement at 50% DOD. The capacity test was repeated up to five times or until a
14
15 consistent value was obtained. To obtain the power density measurement, a fully charged cell
16
17 was discharged at the $C/1$ rate for 1,800 seconds until the 50% DOD test point was reached.
18
19 A 10-s, 225-A pulse was then applied to the battery being tested. Cell resistance was calculated
20
21 using Eq. 1, where I_{base} was 7.5 A and I_{pulse} was 225 A.
22
23
24
25
26
27

28
29 Cycle life testing consisted of constant-current discharge cycles at the $C_3/2$ (3.75 A) rate until
30
31 80% of the rated capacity was removed. RPTs were performed after every 24 cycles. Here, the
32
33 RPT consisted of one $C_3/3$ capacity cycle and the 50% DOD power density test. Unlike what
34
35 occurred under the USABC test method, under the QC/T 743 method, the RPT was included in
36
37 the total number of cycles accrued.
38
39
40
41
42

43
44 Because the cycle count for this protocol included the power density measurement, the effect of
45
46 the measurement on cell performance was also included in the experiments. Here, two cells were
47
48 characterized and cycled using the above methods, but the power density measurement was
49
50 excluded.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

2.3 Data reduction and calculations. The data from all RPTs from using the test protocols were collected for analysis. The data were normalized to $t = 0$ before averaging.

Among other parameters, the USABC RPTs provided data on the change in cell capacity and resistance. According to Ref. 1, the USABC uses the performance at 80% DOD as its metric point. Performance characteristics were also calculated at 50% DOD and by using 10 s of the data from the 30-s pulse to facilitate comparisons to the results from the QC/T 743 protocol. Typical measuring points are shown in Fig. 3; resistance at 10 and 30 s were calculated using the cell potential and current values at t_0 and t_1 ; and at t_0 and t_2 , respectively, as shown in Eq. 1.

The average and standard deviation in each set of data were calculated using Microsoft Excel®. The changes in the normalized capacity data were analyzed for trends by modifying the LINEST function to include the biweight transformation [3, 4]. Here, each point was iteratively reweighted based on the residuals from the curve fit. The fit thereby became less sensitive to outlying values. The changes in the normalized resistance data were analyzed for trends using the unmodified LINEST function in Microsoft® Excel®.

The fits were used to estimate cycle life. Here, an assumed 30% increase in cell resistance was used as the end-of-life criterion for the sake of these calculations only. There were no stated end-of-life criteria based on resistance in either test protocol.

3 Results

3.1 Initial protocol comparison. In order to understand the similarities and differences between the two sets of protocols, several test parameters were collected and compared, as shown in Table 2. The test parameters had many similarities, including the energy window, test temperature, end-of-test criterion, and current used to measure capacity. However, many differences that might affect the measured battery performance were also observed. For example, the USABC cycle profile was dynamic and consisted of discharge and charge pulses. The root mean square (RMS) current, power, and energy throughput were higher in the USABC protocol than in the QC/T 743 protocol.

The power measurements were performed in different ways and at different places. The pulse current and pulse duration were not the same under the two protocols. The USABC method used a relatively longer and lower-magnitude pulse than did the QC/T method. The differences in time and magnitude affect the degree of electrode polarization and mass and charge transfer, which, in turn, affect the measured cell resistance.

3.2 Initial characterization. All cells were characterized in terms of C/3 capacity and resistance at 50% DOD (10 s) at the start of the experiment. The average values of these parameters and corresponding standard deviations are given in Table 3. For reference, the average values of resistance at other points, 50% DOD (30 s), 80% DOD (10 s), and 80% DOD (30 s), from the USABC protocol were also included. The average capacity of the entire population was 7.52 Ah (standard deviation or s.d. = 0.14).

The data in Table 3 also show the effect of %DOD and of time on measured resistance from the USABC protocol. As expected, increasing the effective measuring time increased the observed resistance. The increase was on the order of 19–37%, depending on %DOD. The value of average resistance increased when the %DOD was increased from 50 to 80%. In addition, the initial values of resistance at 50% DOD (10 s) were very similar when the results from the two protocols were compared.

3.3 Cycling. All cells were cycled to 80% DOD. As expected, cycling caused the performance of the cells to decline. The apparent amount of change depended on the test protocol and the parameter studied.

Since the RPT frequency (see Table 2) is different for the two methods, all performance degradation data will be given as functions of calendar days rather than cycle count. This will allow an equal determination of the effect of one protocol versus another on performance.

3.3.1 Capacity. Fig. 4 shows the effect of the cycling protocol on the average relative capacity fade of cells tested. The results from curve fitting (see Table 3 for the fitting parameters) indicated that the fits were good ($r^2 \geq 0.99$).

The results showed that the change in average, relative capacity followed similar kinetic rate laws. All appeared to follow a linear-with-time kinetic rate law, $\Delta C = at$. From the data in Table 4, the coefficient of time, a , for the QC/T 743 (no pulse) cycling method is very close to that from the USABC; indeed, the values are statistically ($\pm 2\sigma$) the same.

3.3.2 Resistance. Fig. 5 shows the dependence of cell resistance on %DOD and pulse-width time. From the figure, as expected, the values measured with a 10-s pulse width were lower than those measured using a 30-s pulse width (see Fig. 6a). In addition, all values followed a similar trend with %DOD; there was an apparent resistance minimum around 30% DOD.

Fig. 6b shows how the average, relative resistance changes with time based on results from both sets of protocols. Least-squares curve fitting shows that the data followed either linear-with-time, $\Delta R = at$, or mixed linear and parabolic, $\Delta R = at + bt^{1/2}$, rate laws. Based on the high values of r^2 , the fits were very good. The results from the least-squares fitting are given in Table 5.

The USABC results given in Fig. 6b and Table 5 show how %DOD and the width of the pulse affected the apparent resistance increase and mechanism of increase. The resistance increase was greater at 80% than at 50% DOD. It is interesting to note that the rate law also changed at 80% DOD, from linear to a mixed mechanism. Increasing the pulse width from 10 to 30 s also increased the apparent resistance increase at 50% DOD, but had little effect at 80% DOD.

From the 50% DOD, 10-s data, the rates of resistance increase from the two protocols were similar. Statistically, they were the same ($\pm 1\sigma$).

the estimated lifetime of the cells is dependent upon how the cell resistance is determined, which is influenced by the pulse amplitude and duration and the cell state of charge

Table 5 also shows the effect of %DOD and width of the pulse on estimated life of the cells. As the %DOD and pulse width increased, the estimated life of the cells tended to decrease, as expected. For example, at 50% DOD and 10-s pulse width the estimated life of the cells using the USABC protocol was about 537 days. At 80% DOD and 10-s pulse width, the estimated life decreased markedly to about 179 days, 33% of the previous value.

4. Discussion

Clearly, there were similarities and differences in the USABC and QC/T 743 testing protocols and in the data they produced. Taking capacity as an initial example, there was a distinct change in the rate law, depending on how the cells were cycled. The rate laws for all the cells tested indicated that capacity fade was linear with time, but inclusion of power density test in the QC/T 743 cells caused a change in the apparent rate. Most likely, this observation was caused by the additional i^2R heating on the cells caused by differences in the discharge rates between the normal cycling (C/3 rate) and power density test rate (C/1). Indeed, there was about a 3°C temperature increase when the power density test was used. During ordinary cycling, there was about a 1–2°C increase in temperature. The difference in temperature may have lowered the resistance of the cell, leading to apparently higher cell capacity and, thus, smaller changes.

The similarity between the USABC and QC/T 743 (no pulse) capacity results was not surprising. The RMS discharge current for the DST profile was about the C/3 rate, which was the same as that used in the QC/T 743 (no pulse) tests.

The rate of resistance increase was, within statistical error, the same for both the USABC and QC/T 743 protocols when using 50% DOD and 10 s as the basis for performance and yielded linear-with-time resistance-increase mechanisms. On the other hand, the USABC protocol uses 80% DOD for its metric. For this LiFeO₄-based cell chemistry, at 80% DOD, regardless of pulse width, there was a distinct change in the apparent mechanism of resistance increase. At 80% DOD, the mechanism was predominately parabolic with some linear contributions. This implies that pseudo-one dimensional diffusion was a significant factor here.

The estimated lifetime of the cells was dependent upon how the cell resistance was determined, which, in turn, were influenced by the pulse amplitude and duration and %DOD at which the resistance was measured. At greater %DOD and pulse width, the estimated life was shorter than at lower %DOD and shorter pulse width. Thus, using the resistance increase data, the USABC metric of 80% DOD and 30-s represented a more severe requirement on the battery than the QC/T 743 protocol did at 50% DOD and 10 s. This, in turn, indicates that cells that were at the end of life for the USABC protocol were not for the QC/T 743 protocol by a large margin.

Whether these results will affect change in the Chinese or USABC protocols will be a subject for further discussion between the two groups. The results described here provide a starting point for that discussion. They also show that, given the right combination of tests and metrics, the two protocols produce similar results.

5. Conclusion

Two testing protocols, QC/T 743 and those used by the U.S. Advanced Battery Consortium (USABC), were compared using cells based on LiFePO₄/graphite chemistry. Differences in the protocols directly affected the data and the performance decline mechanisms deduced from the data. In all cases, the rate of capacity fade was linear with time. Overall, the testing protocols produced very similar data when the testing conditions and metrics used to define performance were similar. The choice of depth of discharge and pulse width had a direct effect on the apparent rate of resistance increased and estimated cell life. At greater percent depth of discharge (%DOD) and pulse width, the estimated life was shorter than at lower %DOD and shorter pulse width. This indicates that cells which were at the end of life based on the USABC protocol were not at end of life based on the QC/T 743 protocol by a large margin.

Acknowledgment

The work at Argonne National Laboratory was performed under the auspices of the U.S. Department of Energy (DOE), Office of Vehicle Technologies, under Contract No. DE-AC02-06CH11357. The work at Idaho National Laboratory was performed under Contract No. DE-AC07-05ID14517. The work at China Automotive Technology and Research Center was supported by National High Technology Research and Development Program of China (863 Program): 2014AA052201.

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains

1
2
3
4 for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license
5
6 in said article to reproduce, prepare derivative works, distribute copies to the public, and perform
7
8 publicly and display publicly, by or on behalf of the Government.
9
10

11 12 13 14 **References**

- 15
16
17
18
19 1. BTP (Battery Test Procedure) Working Group, 1996, *Electric Vehicle Battery Test*
20
21 *Procedures Manual, Rev. 2*, U.S. Advanced Battery Consortium and U.S. Department of
22
23 Energy, January, http://www.uscar.org/commands/files_download.php?files_id=57.
24
25
- 26
27 2. National Development and Reform Committee of the People's Republic of China, 2006,
28
29 *Lithium-Ion Batteries for Electric Vehicles*, Auto Industry Standard QC/T 743-2006,
30
31 China Plan Publishing Company, March, [http://www.d1ev.com/uploadfile/newsfile/](http://www.d1ev.com/uploadfile/newsfile/20130819022042_547.pdf)
32
33 20130819022042_547.pdf (in Chinese).
34
35
- 36
37 3. Data Analysis and Regression, Addison-Wesley, Mosteller and Tukey, 1977; P. W.
38
39 Holland, R. E. Welsch, *Communications in Statistics: Theory and Methods* A6 (1977)
40
41 813–827.
42
- 43
44 4. B. Iglewicz, in: D. C. Hoaglin, F. Mosteller, J. W. Tukey (Eds.), *Understanding Robust*
45
46 *and Exploratory Data Analysis*, Wiley, New York, 1983, p. 417.
47
- 48
49 5. I. Bloom, S. A. Jones, V. S. Battaglia, G. L. Henriksen, J. P. Christophersen, R. B.
50
51 Wright, C. D. Ho, J. R. Belt, and C. G. Motloch, *J. Power Sources*, 124 (2003) 538–550.
52
- 53
54 6. J. Belt, V. Utgikar, and I. Bloom, *J. Power Sources*, 196 (2011) 10213–10221.
55
- 56
57 7. I. Bloom, B. W. Cole, J. J. Sohn, S. A. Jones, E. G. Polzin, V. S. Battaglia, G. L. Henriksen, C.
58
59 Motloch, R. Richardson, T. Unkelhaeuser and H. L. Case, *J. Power Sources* 101 (2001) 238–247.
60
61
62
63
64
65

8. E. Strauss, D. Golodnitsky, and E. Peled, *Electrochemical and Solid State Letters*, **2** (1999) 115–117.
9. G. Blomgren, *J. Power Sources*, 81-82 (1999) 112–118.

Table 1. Distribution of cells

Protocol Name	Count
USABC	4
QC/T 743 (pulse)	4
QC/T 743 (no pulse)	2

Table 2. Comparison of key attributes of the USABC and QC/T 743 protocols.

Attribute	USABC	QC/T 743
DOD (energy) window	0–80% DOD	0–80% DOD
Temperature, °C	25	25
Capacity measurement rate	C/3	C/3
End-of-test criterion, power-based	20% degradation	20% degradation
Metric point	80% DOD	50% DOD
Power pulse duration, s	30	10
Power pulse current, A	75	225
Cycle life profile time	5 h	5 h, 45 min
RPT frequency, cycles (days)	50 (10.5)	24 (6)
RMS power of life cycle, W	50–51	12–13
RMS current of life cycle, A	15–16	3.5–4
Average voltage of life cycle, V	3.17, fading with time	3.27, without fading
Energy throughput of life cycle, Wh	27	19.5

Table 3. Average performance parameters measured by using two protocols.

Protocol	Parameter	Average value (s.d.)
USABC	C/3 capacity, Ah	7.46 (0.09)
	Resistance at 50% DOD (10 s), mΩ	3.97 (0.04)
	Resistance at 50% DOD (30 s), mΩ	4.71 (0.04)
	Resistance at 80% DOD (10 s), mΩ	5.41 (0.10)
	Resistance at 80% DOD (30 s), mΩ	7.45 (0.12)
QC/T 743 (no pulse)	C/3 capacity, Ah	7.74 (0.06)
QC/T 743 (pulse)	C/3 capacity, Ah	7.62 (0.12)
	Resistance at 50% DOD (10 s), mΩ	3.46 (0.03)

Table 4. Values of the fitting parameters from the data in Fig. 3.

Protocol	a (s.e.) [*]	r^2
USABC	3.62×10^{-4} (2.09×10^{-6})	>0.99
QC/T 743	3.12×10^{-4} (5.32×10^{-6})	0.99
QC/T 743 (no pulse)	3.73×10^{-4} (5.11×10^{-6})	0.99

^{*}s.e.=standard error

Table 5. Values of the fitting parameters from the data in Fig. 6 and estimated life.

Protocol and metric parameters	a (s.e.)	b (s.e.)	r^2	Estimated life, days
USABC (50% DOD, 10 s)	5.59×10^{-4} (1.26×10^{-5})		0.99	536.67
USABC (50% DOD, 30 s)	8.06×10^{-4} (1.54×10^{-5})		0.99	372.21
USABC (80% DOD, 10 s)	4.55×10^{-4} (1.03×10^{-4})	1.63×10^{-2} (1.14×10^{-3})	0.99	178.50
USABC (80% DOD, 30 s)	1.20×10^{-3} (1.07×10^{-4})	8.18×10^{-3} (1.19×10^{-3})	0.99	168
QC/T 743 (pulse)	5.90×10^{-4} (2.12×10^{-5})		0.99	510

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6a.

Fig. 6b.

Fig. 1. Schematic of the test channels used for this work. The labels, T, V, and I on the controller/data acquisition box in the schematic represent temperature, voltage, and current (as voltage drop across the resistor) sense inputs, respectively. The thermistor was placed on the center of one of the large faces of the prismatic cell. **The precision resistor was inside the battery tester.**

Fig. 2. DST profile from Ref. [1]. The DST profile was scaled to 500 W/kg at 80% DOD for use in the tests.

Fig. 3. Current and cell potential vs. time for a pulse during the USABC peak power test.

Fig. 4. **Average loss** in relative capacity vs. time for the three cycling protocols used in the experiments. The markers represent the data, and the solid curves, the least squares fit. The error bars represent the standard deviation at that point ($\pm 1\sigma$). If $1\sigma \leq \sim 5\%$ of the reported value, the error bar will not be visible.

Fig. 5. Resistance of a typical cell vs. %DOD and pulse width time at $t = 0$. The full, 30-s pulse did not complete at 90% DOD. There were sufficient data to calculate the 10-s resistance value, but not the 30-s one.

Fig. 6a. Increase in average resistance vs. time for cells tested using the USABC and QC/T 743 (pulse) protocols. The values from the former method were calculated at two values of %DOD and using two pulse widths to facilitate comparison with the values from QC/T 743 (pulse). Since the standard deviations ($\pm 1\sigma$) for the points shown were less than 2% of the reported value, error bars are not shown.

Fig. **6b**. Increase in average, relative resistance vs. time for the cells tested using the USABC and QC/T 743 (pulse) protocols. The values from the former method were calculated at two values of %DOD and using two pulse widths to facilitate comparison with the values from QC/T 743 (pulse). The error bars represent the standard deviation at that point ($\pm 1\sigma$). If $1\sigma \leq \sim 5\%$ of the reported value, the error bar will not be visible.