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Advanced Technology Development Program
For Lithium-Ion Batteries:

Gen 2 Performance Evaluation Interim Report

February 2003

Idaho National Engineering and Environmental Laboratory
Idaho Falls, ID 83415
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FreedomCAR & Vehicle Technologies Program

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Gen 2 Performance Evaluation Interim Report

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ABSTRACT

The Advanced Technology Development Program is currently evaluating the performance of the second generation of Lithium-ion cells (i.e., Gen 2 cells). The 18650-size Gen 2 cells consist of a baseline chemistry and one variant chemistry. These cells were distributed over a matrix consisting of three states-of-charge (SOC) (60, 80, and 100% SOC), four temperatures (25, 35, 45, and 55°C), and three life tests (calendar-, cycle-, and accelerated-life). The calendar-life cells are clamped at an open-circuit voltage corresponding to 60% SOC and undergo a once-per-day pulse profile. The cycle-life cells are continuously pulsed using a profile that is centered around 60% SOC. The accelerated-life cells are following the calendar-life test procedures, but using the cycle-life pulse profile. Life testing is interrupted every four weeks for reference performance tests (RPTs), which are used to quantify changes in capacity, resistance, and power. The RPTs consist of a $C_1/1$ and $C_1/25$ static capacity tests, a low-current hybrid pulse power characterization test, and electrochemical impedance spectroscopy at 60% SOC. Capacity-, power-, and electrochemical impedance spectroscopy-based performance results are reported.

EXECUTIVE SUMMARY

In conjunction with the Partnership for a New Generation of Vehicles (PNGV), the Advanced Technology Development (ATD) Program was initiated in 1998 by the U.S. Department of Energy Office of Advanced Automotive Technologies to find solutions to the barriers that limit the commercialization of high-power Lithium-ion batteries. In 2002, PNGV was superseded by FreedomCAR (Freedom Cooperative Automotive Research) and this work is now under the auspices of the FreedomCAR and Vehicle Technologies Program. This report documents the performance evaluation of the second generation of 18650-size ATD Lithium-ion cells (i.e., Gen 2 cells) that were calendar-life tested at the Argonne National Laboratory, cycle-life tested at the Idaho National Engineering and Environmental Laboratory, and accelerated-life tested at Sandia National Laboratories. The Gen 2 cells consist of a baseline chemistry and one variant chemistry (i.e., Variant C). The Variant C chemistry contains a higher concentration of aluminum dopant in the cathode.

All calendar- and cycle-life testing is performed at 60% state-of-charge (SOC). The calendar-life cells consist of a 55 and 45°C Baseline cell group and a 45°C Variant C cell group. The cycle-life cells consist of a 25 and 45°C Baseline cell group and a 45°C Variant C cell group. Accelerated-life testing was only performed on Baseline cells. These cells were distributed according to a matrix covering three SOCs (60, 80 and 100% SOC) and four temperatures (25, 35, 45, and 55°C) for special calendar-life testing. All cell groups were initiated with standard characterization tests as defined in the *PNGV Battery Test Manual*, Revision 3, and the cell-specific test plans. These tests primarily include the $C_1/1$ static capacity test, the $C_1/25$ static capacity test, the low-current hybrid pulse power characterization (L-HPPC) test, and electrochemical impedance spectroscopy (EIS). These four tests are also a part of the reference performance tests (RPTs) that are performed every 4 weeks (i.e., every 28 days for the calendar- and accelerated-life cells and every 33,600 cycles for the cycle-life cells) during aging. From the RPTs, the capacity and power fades and EIS growth at the semicircle trough, normalized to the characterization RPT, are calculated and used as measures of cell degradation.

For all Baseline cell groups, the average fades (i.e., $C_1/1$ and $C_1/25$ capacity fades and power fade) and growth (i.e., EIS growth at the semicircle trough), generally increase with increasing temperature and SOC. The Baseline cells generally follow a square root of time dependence followed by a linear time dependence. Once the second mechanism dominates, the fade and growth rates generally increase. The breakpoints between mechanisms generally occur earlier, with increasing test temperature. The 60% SOC $C_1/25$ capacity fades show only a square root of time dependence, with no apparent change in mechanism, which is primarily due to the slower diffusion rate during the $C_1/25$ test. However, mechanistic changes begin to appear at higher SOCs. For the 60% SOC Baseline cell groups, the capacity and power fades and EIS growth are generally lowest for the calendar-life cells, in the middle for the cycle-life cells, and highest for the accelerated-life cells.

The 45°C Variant C cells also generally show an initial square root of time dependence followed by linear time dependence. As seen with the Baseline cells, the calendar-life Variant C cells generally show lower degradation rates than the cycle-life cells. These cells show significantly less $C_1/1$ and $C_1/25$ capacity fade than do the comparable Baseline cells. The power fade and EIS growth rates were initially much higher than the Baseline cells, but have since slowed down significantly. The different behavior of the Variant C cells indicates that they may be following an alternate time dependency. Consequently, they were also modeled using a natural log of time dependence, which generally did not show any mechanistic changes.

The remaining Baseline calendar- and cycle-life cells have completed 52 weeks (364 days and 436,800 cycles, respectively). The remaining Variant C calendar- and cycle-life cells have completed 32 weeks (224 days and 268,800 cycles). These cells will continue testing until the end-of-test (EOT) criteria are met for the last pair of cells. For the 25°C cycle-life Baseline cells, EOT is one fade increment beyond 30% power fade. The other Baseline and Variant C calendar- and cycle-life cells will continue testing until the last pair of cells reach 50% power fade. The remaining 25°C accelerated-life Baseline cells have completed 40 weeks (280 days) of testing. The remaining 35 and 45°C accelerated-life cells have completed 36 weeks (252 days) of testing. These cells will continue until they reach 50% power fade. All 55°C accelerated-life cells have already been removed from test.

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ACRONYMS

ALT	accelerated-life test
ANL	Argonne National Laboratory
ASI	area-specific impedance
ATD	Advanced Technology Development
BL	Baseline cells
BNL	Brookhaven National Laboratory
BOL	beginning-of-life
BSF	battery size factor
CalLT	calendar-life test
CycLT	cycle-life test
DOD	depth-of-discharge
DOE	Department of Energy
EIS	electrochemical impedance spectroscopy
EOT	end of test
FreedomCAR	Freedom Cooperative Automotive Research
Gen	Generation
INEEL	Idaho National Engineering and Environmental Laboratory
LBNL	Lawrence Berkeley National Laboratory
L-HPPC	low-current hybrid pulse power characterization
LLC	Limited Liability Company
OCV	open-circuit voltage
OSPS	operating set point stability
PNGV	Partnership for a New Generation of Vehicles
RPT	reference performance test
RTD	resistance temperature detector
SEI	solid electrolyte interface
SOC	state-of-charge
SNL	Sandia National Laboratories
VARC	Variant C cells

Advanced Technology Development Program for Lithium-Ion Batteries:

Gen 2 Performance Evaluation Report

1. INTRODUCTION AND BACKGROUND

In conjunction with the Partnership for a New Generation of Vehicles (PNGV), the U.S. Department of Energy (DOE) initiated the Advanced Technology Development (ATD) Program in 1998 to address the technical barriers impeding the commercialization of high-power Lithium-ion batteries for hybrid electric vehicle applications. These barriers include insufficient calendar life, high production costs, and poor response to abuse scenarios. The ATD Program is organized into four areas: long life, low cost, abuse tolerance, and technology transfer. A full description of the program is provided in Reference 1. (In 2002, PNGV was superceded by the formation of a new program between the U.S. Government and the U.S. Council for Automotive Research, called FreedomCAR (Freedom Cooperative Automotive Research). Also in 2002, the U.S. DOE Office of Energy Efficiency was reorganized and this work is now sponsored by the FreedomCAR and Vehicle Technologies Program.)

The ATD Program has engaged five DOE laboratories to address these critical barriers. Argonne National Laboratory (ANL) has overall programmatic and technical lead responsibilities, including cell chemistry. The Idaho National Engineering and Environmental Laboratory (INEEL) has lead responsibility for cell testing and aging, in collaboration with ANL and Sandia National Laboratories (SNL). SNL has lead responsibility for the investigation of abuse tolerance. Lawrence Berkeley National Laboratory (LBNL) is the lead diagnostic laboratory, in concert with Brookhaven National Laboratory (BNL), ANL, SNL, and INEEL. These five national laboratories are working in close coordination to:

- Identify and quantify the factors responsible for power fade through data analysis of aged cells
- Provide aged cells and analyzed performance data to enable correlation against diagnostic results and facilitate selection of the most useful analytical tools
- Develop aging protocols and explore new tests, analyses, and modeling methodologies relating to calendar life and provide results to battery developers and other laboratories.

1.1 Performance Testing Overview

1.1.1 Gen 2 Cells

Concurrent testing and analysis of the second generation of cells (i.e., Gen 2 cells) at the INEEL, ANL, and SNL are now being performed, with oversight by the DOE FreedomCAR and Vehicle Technologies Program. The 18650-size Lithium-ion Gen 2 cells consist of a baseline chemistry and one variant chemistry (referred to as Variant C) containing an increased concentration of aluminum dopant in the cathode. The ATD Program purchased 195 Gen 2 cells (165 Baseline cells and 30 Variant C cells) for testing. INEEL received 45 cells (30 Baseline cells and 15 Variant C cells) for cycle-life testing. ANL received 30 cells (15 Baseline and Variant C cells each) for calendar-life testing and 7 Baseline cells for archiving. SNL received 62 Baseline cells for accelerated-life testing and 48 Baseline cells for thermal abuse. Each diagnostic laboratory (LBNL, ANL, and BNL) received 1 Baseline cell without aging.

Testing and analyses are performed in accordance with the procedures outlined in the *PNGV Battery Test Manual,* Revision 3 (Reference 2), and as detailed in the cell-specific test plans. INEEL cycle-life and ANL calendar-life testing procedures are outlined in the *PNGV Test Plan for Advanced Technology Development Gen 2 Lithium-Ion Cells* (Attachment 1). SNL accelerated-life testing procedures are outlined in the *SNL ATD Gen 2 Test Plan* (Attachment 2). All Gen 2 cells are testing against the PNGV Power Assist goals (Reference 2).

1.1.1.1 Cell Chemistry

The 18650-size Gen 2 cells were manufactured by Quallion, LLC, to ATD specifications, as developed by ANL. The 195 cells were manufactured in batches over a period of 7 months in various-size lots (Appendix 2). The Gen 2 baseline cell chemistry is defined in Reference 3 and summarized in Table 1.

Table 1. Gen 2 baseline cell chemistries.

	Gen 2 Baseline Cells
Positive Electrode	8 wt% PVDF binder 4 wt% SFG-6 graphite 4 wt% carbon black 84 wt% $LiNi_{0.8}Co_{0.15}Al_{0.5}O_2$
Negative Electrode	8 wt% PVDF binder 92 wt% MAG-10 graphite
Electrolyte	1.2 M $LiPF_6$ in EC:EMC (3:7 wt%)
Separator	25 μm thick PE (Celgard)

The Variant C cell chemistry differs from the Gen 2 Baseline chemistry by an increase to the aluminum dopant from 5 to 10% and a decrease to the cobalt from 15 to 10% in the cathode (i.e., $LiNi_{0.8}Co_{0.1}Al_{0.1}O_2$). The purpose of the increased aluminum dopant was to stabilize the cathode to provide longer life and improved abuse tolerance. Otherwise, the Gen 2 Baseline and Variant C chemistries are identical. This change resulted in a 20% drop in the $C_1/1$ rated capacity (0.8 A·h) at beginning-of-life (BOL) compared to the Baseline cell-rated capacity of 1.0 A·h and impacted capacity- and power-fade, as detailed below.

1.1.1.2 Calendar-Life Testing

All calendar-life testing (Section 3.2.1) is performed at ANL. ANL received 22 Baseline cells on January 10, 2001 and initiated testing between January 16 and March 13, 2001. ANL received 15 Variant C cells on July 26, 2001, and began testing on September 12, 2001. Seven Baseline cells were archived, and 15 cells began calendar-life testing at 45°C. Due to low power fade after 4 weeks of aging (Appendix 2), the temperature was raised to 55°C. For continuity, two Baseline cells were removed from archive and began calendar-life testing at 45°C on May 16, 2001. The Variant C cells are calendar-life testing at 45°C. All calendar-life testing is performed at 60% state-of-charge (SOC). This report marks the completion of 280 days of calendar life on the 55°C Baseline cells, 364 days on the 45°C Baseline cells, and 224 days on the 45°C Variant C cells. Two 45°C Baseline cells and five Variant C cells remain on test and will continue until the specified end-of-test (EOT) criteria are met (Section 3.4). All 55°C Baseline cells were removed from test after 280 days.

1.1.1.3 Cycle-Life Testing

All cycle-life testing (Section 3.2.2) is performed at INEEL. INEEL received 30 Baseline cells on January 8, 2001 and initiated testing between January 23 and February 2, 2001. INEEL received 15 Variant C cells on July 30, 2001, and began testing on August 16, 2001. The Baseline cells were split into two groups of 15, with one group cycle-life testing at 25°C and the other at 45°C. The 15 Variant C cells are cycle-life testing at 45°C. All cycle-life testing is performed at 60% SOC. This report marks the completion of 436,800 cycles on the Baseline cells and 268,800 cycles on the Variant C cells. Eight Baseline cells and four Variant C cells remain on test, and testing will continue until the specified EOT criteria are met.

1.1.1.4 Accelerated-Life Testing

All accelerated-life testing (ALT) is performed at SNL. SNL received 54 Baseline cells for testing on February 6, 2001 and initiated testing between March 5 and March 19, 2001. SNL also received 8 Baseline cells for special cycle-life testing, with changes to the pulse duration, amplitude and/or frequency of the standard cycle-life profile, and 48 Baseline cells for thermal abuse; testing results for these cells will be published in different reports.

Forty-two cells are undergoing special calendar-life testing. The cells have been distributed over a matrix of four temperatures (25, 35, 45, and 55°C) and three SOCs (100, 80, and 60%). The remaining 12 cells were either archived or failed prior to any testing (see Section A2.5.2 in Appendix 2). This report marks completion of 280, 252, and 252 days of special calendar-life testing at 25, 35, and 45°C, respectively, for all SOC groups. The 55°C Baseline cells have completed 224, 140, and 140 days of special calendar-life testing for the 60, 80, and 100% SOC cell groups, respectively. Eighteen special calendar-life cells (7 at 25°C, 8 at 35°C, and 3 at 45°C) remain on test and will continue until the specified EOT criteria are met. All 55°C special calendar-life cells have already been removed from test.

2. BATTERY INFORMATION

2.1 Battery Rating and Limitations

The following battery ratings and limitations were used for the testing:

	Baseline Cells	Variant C Cells
$C_1/1$ rated capacity	1.0 A·h	0.8 A·h
$C_1/1$ nominal capacity (average)	0.961 A·h	0.828 A·h
Cell nominal weight (average)	38.5 g	38.4 g
Battery size factor:	553	651
Temperature		
Operating Range	-20 to +60ºC (discharge)	
Storage	10°C ± 3°C	
Maximum (discharge)	60°C	
Maximum (charge)	40°C	
Voltage Limits		
Minimum discharge voltage	3.0 V (18-s pulse)	
	3.0 V (continuous)	
Maximum charge voltage	4.3 V (10-s pulse)	
	4.1 V (continuous)	
HPPC Calculation voltages		
Maximum	4.1 V	
Minimum	3.0 V	
Current Limits		
Maximum discharge current	8.0 A (18-s pulse)	
	2.0 A (continuous)	
Maximum charge current	8.0 A (10-s pulse)	
	1.0 A (continuous)	

2.2 Special Considerations

Special considerations for the calendar-, cycle-, and accelerated-life cells (such as the lot numbers, ATD labeling scheme, temperature control, tab issues, etc.) are presented in Appendix 2.

3. TESTING

Characterization and life testing were performed in accordance with the *PNGV Battery Test Manual*, Revision 3 (Reference 2) and the ATD Gen 2 test plans (Attachments 1 and 2). PNGV performance goals, procedures, analytical methodologies, and ATD specific testing requirements are detailed in these documents and are summarized below. Laboratory-specific testing details are presented in Appendix 2.

3.1 Characterization Testing

Characterization testing was performed on all cells prior to life testing to establish BOL performance parameters, including capacity, resistance, power, and energy. All characterization testing was performed at 25°C. Following a receipt inspection (Appendix 2), testing was initiated with five consecutive C_1 discharges at the $C_1/1$ rate, beginning with a fully charged cell (4.1 V) and terminating at the specified cutoff voltage of 3.0 V. Next, a $C_1/25$ discharge test was performed, beginning with a fully charged cell and terminating at 3.0 V. Following a 1-h rest, the calendar- and cycle-life cells were also fully charged to 4.1 V at a $C_1/25$ rate.

Following the static capacity tests, all cells underwent electrical impedance spectroscopy (EIS) tests. EIS begins by discharging the cells from a fully charged state to the specified open-circuit voltage (OCV) corresponding to the target SOC (Appendix D of Attachment 1). Following an 8 to 12-h rest at OCV, which allowed the cells to reach electrochemical equilibrium, the impedance is measured using a 4-terminal connection over a frequency range of 10 kHz to 0.01 Hz, with a minimum of 8 points per decade of frequency. This test was performed on all cells at 60% SOC.

The low-current hybrid pulse power characterization (L-HPPC) test was performed next. The test profile is shown in Figure 1. It consists of a constant-current discharge and regen pulse with a 32-s rest period in between, for a total duration of 60 s. The 18-s constant-current discharge pulse is performed at a $5C_1$ rate for the ATD Gen 2 cells (i.e., 5 A for the Baseline cells and 4 A for the Variant C cells). The 10-s regen pulse is performed at 75% of the discharge rate (i.e., 3.75 A for the Baseline cells and 3 A for the Variant C cells). This profile is repeated at every 10% depth-of-discharge (DOD) increment, with a 1-h rest at OCV at each DOD increment to ensure that the cells have electrochemically and thermally equilibrated (Reference 2).

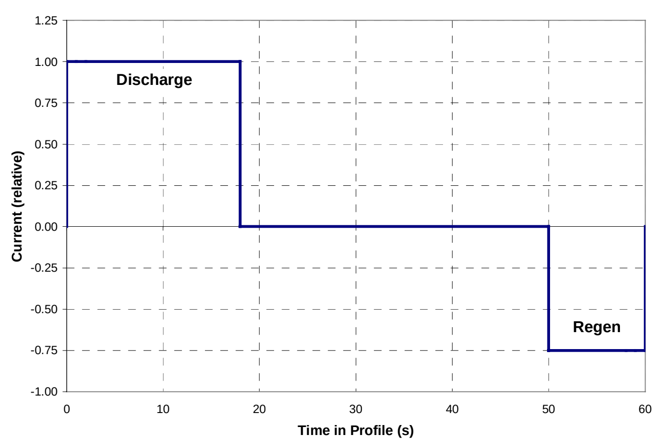

Figure 1. PNGV L-HPPC pulse profile.

3.2 Life Testing

3.2.1 Calendar-Life Testing

All ATD Gen 2 calendar-life cells are being tested at a clamped voltage corresponding to 60% SOC. Additionally, a once-per-day standard calendar-life test pulse profile is executed, as defined in Reference 2 and shown in Figure 2. Its purpose is to calculate daily pulse resistances and powers during the time at the target calendar-life SOC. The profile consists of constant current discharge and regen pulses with interspersed rest periods centered around 60% SOC. For the Gen 2 cells, a $3C_1$ discharge current (i.e., 3 A for the Baseline cells and 2.4 A for the Variant C cells) is used. The cumulative length of a single profile is 120 s and constitutes one cycle. This cycle is repeated once every 24 h during life testing, but is interrupted every 28 days (4 weeks) for reference performance tests (RPTs), as described in Section 3.3. The Gen 2 calendar-life Baseline cells began testing at 45°C. However, due to low power fade, the temperature was raised to 55°C after the first 4 weeks (Appendix 2). For data continuity, ANL also took two Baseline cells from archiving and began calendar-life testing them at 45°C. The Variant C cells are calendar-life testing at 45°C. For each cell group, a calendar-life pulse is also performed at 25°C at the beginning and end of each 4-week interval (see Attachment 1).

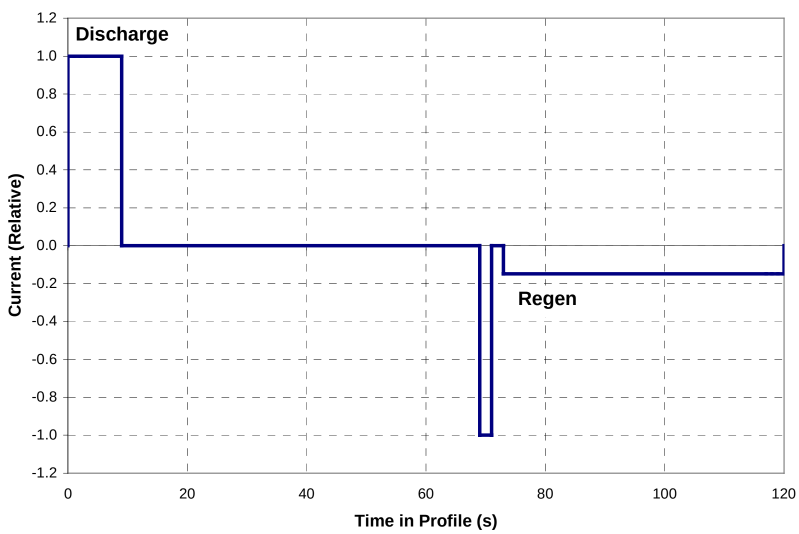

Figure 2. PNGV pulse-per-day calendar-life profile.

3.2.2 Cycle-Life Testing

All ATD Gen 2 cycle-life cells are being tested using the standard PNGV 25-W·h Power Assist cycle-life profile, as defined in Reference 2 and shown in Figure 3. It consists of a constant power discharge and regen pulse with interspersed rest periods. The cumulative length of a single profile is 72 s and constitutes one cycle. For Gen 2 testing, the pulses were centered around 60% SOC. This cycle is repeated continuously during life testing, but is interrupted every 33,600 cycles (4 weeks) for RPTs. Based on the scaling factor (Section 4.2.1.2), the constant power pulse during the 9-s discharge is 18.08 W for the Baseline cells and 15.36 W for the Variant C cells. The Gen 2 cycle-life Baseline cells were split into two groups of 15, with one group cycle-life testing at 25°C, and the other at 45°C. The 15 cycle-life Gen 2 Variant C cells are cycle-life testing at 45°C.

Cycling stability at the target SOC was established by performing the operating set point stability (OSPS) test just prior to commencing cycle-life testing. The OSPS test consists of 100 consecutive cycle-life profiles. The requirement is that at its completion, the actual SOC should be within ±2% of the target SOC (60% SOC), based on the OCV following a 1-h rest at the beginning and end of the 100 pulses. If the SOC is charge positive or charge negative (i.e., unstable), then a control voltage at the end of the discharge pulse is established, and the OSPS test is repeated until stable cycling occurs.

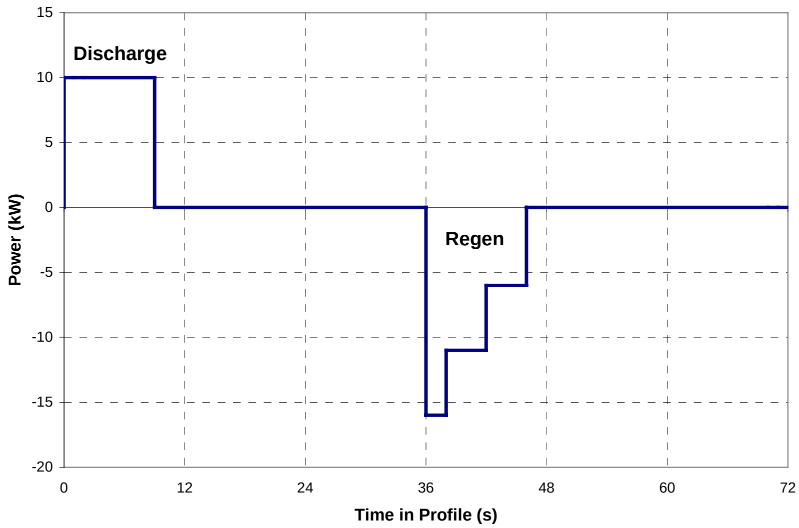

Figure 3. PNGV 25-W·h Power Assist cycle-life profile.

3.2.3 Accelerated-Life Testing

Special calendar-life testing is performed on 42 ALT Baseline cells. The cells were distributed according to the matrix shown in Table 2. The parameter values of SOC and temperature cover the range of expected use and allow for interpolation of measured power and capacity fade rates to the nominal use conditions (i.e., 25°C and 60% SOC). These cells undergo the standard PNGV 25-W·h Power Assist cycle-life pulse (Figure 3) once every 24 h, with a voltage control step on the third regen pulse. The control step was established based on an OSPS test performed before special calendar-life testing began. The cells are voltage-clamped at 60% SOC in between each pulse.

Table 2. Calendar-life matrix for the accelerated-life test.

SOC	25°C	35°C	45°C	55°C	Total
60%	3	3	3	3	12
80%	3	3	3	5	14
100%	3	3	5	5	16
Total	**9**	**9**	**11**	**13**	**42**

3.3 Reference Performance Testing

Life testing for the calendar-, cycle-, and accelerated-life cells is interrupted every 4 weeks for RPTs, which are used to quantify changes in capacity, resistance, and power. RPTs consist of a $C_1/1$ static capacity test, a $C_1/25$ static capacity test, a L-HPPC test, and an EIS test at 60% SOC. In addition to these tests, the accelerated-life cells also include a $C_1/10$ discharge, which consists of two $C_1/1$ discharges followed by a $C_1/10$ discharge (see Appendix 3). All RPTs are performed at 25°C. *Capacity fade* is the percentage loss in the discharge capacity during the $C_1/1$ or $C_1/25$ test. *Power fade* is the percentage loss in the power at 300 W·h (Reference 2). The fades are normalized to the characterization RPT (i.e., at characterization, the capacity and power fades are both 0%).

Initially, the EOT criteria (Section 3.4) for the calendar- and cycle-life cells specified that only two cells would receive full RPTs every 4 weeks. The other cells would undergo full RPTs at characterization and EOT, and only partial RPTs (i.e., a $C_1/1$ and L-HPPC test) every 4 weeks in between. After assessing the first 12 weeks of aging data, the RPT criteria was changed to a full RPT every 4 weeks for each cell on test.

3.4 End-of-Test Criteria

The Gen 2 EOT criteria for the calendar- and cycle-life cells are specified in Appendix C of Attachment 1. The cells are organized into groups of 15. One cell from each group is sent to a diagnostic laboratory for evaluation after characterization testing is complete. Following 4 weeks of aging, another two cells are removed from test and sent to the diagnostic laboratories. The EOT criteria for the remaining 12 cells are based on roughly equal power fade increments such that the penultimate pair of cells is sent for diagnostic evaluation when the power fade reaches 30%. The 25°C cycle-life and 55°C calendar-life Baseline cells will test to one power fade increment beyond 30%. The last pair of cells for all other calendar- and cycle-life cell groups (testing at 45°C) will continue testing until they reach 50% power fade.

The ALT cells are not removed from test in incremental stages. Rather, all 25, 35, and 45°C accelerated-life cells are removed from test when their power fades reach 50%. The 55°C accelerated-life cells continued testing until the L-HPPC test data were unable to yield useful power fade data.

3.5 Testing Status

3.5.1 Calendar-Life Testing

The 55°C Baseline cells met the EOT criteria after 40 weeks of calendar-life testing, with an average power fade of 32.6%. The two 45°C Baseline cells remain on test and have completed 52 weeks of aging with an average power fade of 31.9%. These cells will continue testing until they reach 50% power fade. Five 45°C Variant C cells remain on test and have completed 32 weeks of aging with an average power fade of 21.9%. Two cells will be removed at the next target power fade of 25.0%. Another two cells will be removed at 30% power fade, and the last cell will test until it reaches 50% power fade.

3.5.2 Cycle-Life Testing

Six 25°C Baseline cells and two 45°C Baseline cells remain on test and have completed 52 weeks of aging (436,800 cycles). The 25°C Baseline cells have an average power fade of 18.7%, with the next target power fade being 24.8%. The remaining two 45°C Baseline cells have an average power fade of 37.3% and will continue testing until they reach 50% power fade. Four 45°C Variant C cells remain on test and have completed 32 weeks of aging (268,800 cycles), with an average power fade of 26.2%. Two of these cells will be taken off test at 30% power fade; the remaining two will continue until they reach 50% power fade.

3.5.3 Accelerated-Life Testing

The number of cells remaining, average power fades, and weeks on test for the accelerated-life cells are summarized in Table 3.

Table 3. Test status for the accelerated-life cells.

		25°C	35°C	45°C	55°C
60% SOC	Cells Remaining	2	3	3	0
	Power Fade (%)	23.2	34.8	42.6	53.4
	Weeks	40	36	36	32
80% SOC	Cells Remaining	2	3	0	0
	Power Fade (%)	28.1	41.7	48.1	54.8
	Weeks	40	36	36	20
100% SOC	Cells Remaining	3	2	0	0
	Power Fade (%)	39.8	49.6	59.2	58.0
	Weeks	40	36	36	20

4. RESULTS

Due to the large number of Gen 2 data, only cell averages or results from representative cells are presented in this section. The $C_1/1$ capacity fade, power fade, and EIS resistance growth for each cell at each condition are presented in Appendix 1. Detailed results for all tests are available for all cells and are located at three different Web sites. Data for the Gen 2 cycle-life cells are available at http://atd.inel.gov. Data for the Gen 2 calendar-life cells are available at http://www.cmt.anl.gov/eadl/data/atd/default_.htm. Data for the Gen 2 ALT cells are available at https://mdesrv1.sandia.gov/mde/continue/usr/local/mde/ATD/atd.htm. Individual usernames and passwords are required for each site and can be requested on-line.

Since testing is performed at multiple temperatures and SOCs, a standard method of graphically representing data is used in this report. Unless otherwise stated on the figure legends, the data are presented using the format summarized in Table 4.

Table 4. Standard graphical convention.

Temperature (color)	Test (symbol)	Chemistry (symbol background)
25°C (blue)	calendar-life (circle)	Baseline cells (filled symbol)
35°C (red)	cycle-life (square)	Variant C cells (empty symbol)
45°C (purple)	accelerated-life (triangle)	
55°C (green)		

The Gen 2 data can be modeled in numerous ways. For this report, the fits to the data were selected based on an attempt to correlate with physical processes rather than arbitrary mathematical functions. A square root of time dependence can be related to a thermal diffusion process for the formation of a solid electrolyte interface (SEI) layer. Linear time dependence can be related to a steady-state formation of the SEI layer, where the electrolyte/salt decomposition reaction at the surface of the SEI layer determines the rate of SEI growth. The natural log of time dependence may be related to the transport of ions due to the electric fields present at the SEI layer (Reference 4).

4.1 Capacity

4.1.1 $C_1/1$ Capacity Fade and Model

Figure 4 (page 16) shows the average $C_1/1$ capacity fade for each cell group ("BL" for the Baseline cells and "VARC" for the Variant C cells) at 60% SOC for the calendar- ("CalLT"), cycle- ("CycLT"), and accelerated-life ("ALT") cells at 25, 35, 45, and 55°C. As expected, the Baseline cell capacity fade generally increases as a function of increasing test temperature. The Variant C cells show very slow fade rates in comparison to the Baseline cells. Within each temperature group and chemistry, the $C_1/1$ capacity fade rate is generally lowest for the calendar-life cells, in the middle for the cycle-life cells, and highest for the accelerated-life cells.

Figures 5 and 6 show the average $C_1/1$ capacity fade for the accelerated-life cells at 80 and 100% SOC, respectively. These data also show increased capacity fade with increasing test temperature. Except at 55°C, the accelerated life cells show the highest fade at 100% SOC and the lowest fade at 60% SOC (Figure 4). At 55°C, the 80% SOC cells show the highest fade, which may indicate that a higher-temperature mechanism has taken effect.

Figure 7 shows the average $C_1/1$ static capacity fade as a function of test time at 60% SOC for the Baseline calendar-, cycle- and accelerated-life cells. The 25°C cycle-life Baseline cells show a square root of time dependence through 52 weeks of testing. All other cell groups show a mechanistic change with an initial square root of time dependence, followed by a linear dependence. When the second mechanism takes effect, the $C_1/1$ capacity fade rate increases. The fade rate also increases with increasing temperature. The accelerated-life cells show the largest increase in the fade rate, and the calendar-life cells show the least increase in the fade rate. Within each life-test group (i.e., cycle-, calendar-, and accelerate-life), the breakpoints between mechanisms occur earlier at higher temperatures. The mechanism breakpoints and coefficients of determination (R^2) for the Baseline cells are summarized in Table 5.

Table 5. Baseline cell $C_1/1$ test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Cycle-Life	0 to 52 weeks	0.987	-	-
	Accelerated-Life	0 to 24 weeks	0.862	28 to 40 weeks	0.990
35	Accelerated-Life	0 to 20 weeks	0.926	24 to 36 weeks	0.931
45	Calendar-Life	0 to 28 weeks	0.931	32 to 52 weeks	0.982
	Cycle-Life	0 to 24 weeks	0.997	28 to 52 weeks	0.983
	Accelerated-Life	0 to 16 weeks	0.949	20 to 36 weeks	0.923
55	Calendar-Life	0 to 8 weeks	1.00	12 to 40 weeks	0.997
	Accelerated-Life	0 to 12 weeks	0.991	16 to 32 weeks	0.974

Figure 8 shows the $C_1/1$ static capacity fade as a function of test time at 60% SOC for the 45°C Variant C calendar- and cycle-life cells. As seen with the Baseline cells, the Variant C cells also show mechanistic changes, with the initial mechanism being square root of time dependent and the second mechanism being linearly dependent on test time. The cycle-life Variant C cells also show more fade than the calendar-life cells. Unlike the Baseline cells, when the second mechanism dominates, the Variant C cells show little or no capacity fade as a function of test time. The mechanism breakpoints and R^2 fits for the Variant C cells are summarized in Table 6.

Table 6. Variant C $C_1/1$ test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Calendar-Life	0 to 16 weeks	0.994	20 to 32 weeks	0.967
	Cycle-Life	0 to 8 weeks	0.983	12 to 32 weeks	0.958

Since the capacity fade rate significantly slows down as a function of test time, the Variant C cells may be following a different time dependence. The Variant C $C_1/1$ static capacity fade was also modeled with a natural log of time dependence, as shown in Figure 9. The logarithmic rate is typically seen in the low-temperature oxidation of metals (Reference 4). The cycle-life cells show no apparent mechanistic changes but the calendar-life cells still show a breakpoint, with a linear time dependence following 20 weeks of aging. The mechanistic breakpoints and R^2 fits for a natural log of time dependence are summarized in Table 7.

Table 7. Variant C $C_1/1$ natural log of time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	ln(t)-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Calendar-Life	0 to 20 weeks	0.915	24 to 32 weeks	0.952
	Cycle-Life	0 to 32 weeks	0.920	-	-

Figures 10 and 11 show the $C_1/1$ static capacity fade as a function of test time for the accelerated-life cells at 80 and 100% SOC, respectively. These data show the same general trends as the 60% SOC cell groups, with an initial square root of time dependence followed by a linear time dependence. The capacity fade increases as test temperature increases, as does the capacity fade rate when the second mechanism dominates. The breakpoints between mechanisms also occur earlier at higher temperatures. Except for the 55°C cells at 80% SOC, the average fade is highest at 100% SOC and lowest at 60% SOC. At 55°C, the 100% SOC fade is initially higher, but when the second mechanism takes effect, the 80% SOC fade rate increases more rapidly then the 100% SOC fade. The mechanism breakpoints and R^2 fits for the accelerated-life cells at 80 and 100% SOC are summarized in Tables 8 and 9, respectively.

Table 8. $C_1/1$ test time dependence for the accelerated-life cell groups at 80% SOC.

Temperature (°C)	Test	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 24 weeks	0.983	28 to 40 weeks	0.991
35	Accelerated-Life	0 to 20 weeks	0.834	24 to 36 weeks	0.936
45	Accelerated-Life	0 to 12 weeks	0.946	16 to 36 weeks	0.986
55	Accelerated-Life	0 to 8 weeks	0.981	12 to 20 weeks	1.00

Table 9. $C_1/1$ test time dependence for the accelerated-life cell groups at 100% SOC.

Temperature (°C)	Test	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 20 weeks	0.961	24 to 40 weeks	0.997
35	Accelerated-Life	0 to 16 weeks	0.943	20 to 36 weeks	0.968
45	Accelerated-Life	0 to 12 weeks	0.987	16 to 36 weeks	0.996
55	Accelerated-Life	0 to 8 weeks	0.992	12 to 20 weeks	0.995

4.1.2 $C_1/10$ Capacity Test

The accelerated-life cells began regular $C_1/10$ static capacity tests at each RPT after 8 weeks of aging (Appendix 3). As a result, a comparison between the $C_1/1$, $C_1/10$ and $C_1/25$ capacity fades cannot be made. However, Figures 12 through 14 show the available accelerated-life cell data for the average $C_1/1$, $C_1/10$ and $C_1/25$ capacities at 60, 80 and 100% SOC, respectively. As expected, the average capacities increase as the C-rate decreases. Also, as expected, the average capacities generally decrease faster with increasing temperature. The 60% SOC cell groups show higher capacities than the 80 and 100% SOC cell groups. The 100% SOC cell groups show the lowest $C_1/1$ capacities, but the $C_1/10$ and $C_1/25$ capacities are generally similar to the 80% SOC capacities.

4.1.3 C_1/25 Capacity Fade and Model

Figure 15 shows the average C_1/25 capacity fade for each cell group at 60% SOC for the calendar-, cycle- and the accelerated-life cells. As shown, the trends are similar to the C_1/1 capacity fade (Figure 4). The C_1/25 Baseline cell capacity fades increase as a function of increasing temperature. Except at 25°C, the order of increasing capacity fade generally shows that calendar-life is lowest, cycle-life is in the middle, and accelerated-life is the highest. At 25°C, the cycle-life cells show more fade than the accelerated-life cells. The 45°C Variant C C_1/25 capacity fade is similar to the 25°C Baseline cells.

Figures 16 and 17 show the average C_1/25 capacity fade for the accelerated-life cells at 80 and 100% SOC, respectively. These data also show increased capacity fade rate with increasing test temperatures. Both the 80 and 100% SOC fades are generally higher than the 60% SOC fades. The fade rates at 25 and 55°C are similar at 80 and 100% SOC. At 35 and 45°C, the 100% SOC fade rate is higher than those at 80% SOC.

Figure 18 shows the average C_1/25 capacity fade as a function of test time at 60% SOC for the Baseline calendar-, cycle- and accelerated-life cells. The fade rates within each temperature group are similar, and increase as a function of increasing test temperature. All cells show a square root of time dependence with no apparent mechanistic changes. This is primarily due to the slower diffusion rates during the C_1/25 test. The mechanism breakpoints and R^2 fits for the Baseline cells are summarized in Table 10.

Table 10. Baseline cell C_1/25 test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{½}$-Mechanism	
		Test Time	R^2 fit
25	Cycle-Life	0 to 52 weeks	0.987
	Accelerated-Life	0 to 40 weeks	0.961
35	Accelerated-Life	0 to 36 weeks	0.926
45	Calendar-Life	0 to 52 weeks	0.994
	Cycle-Life	0 to 52 weeks	0.988
	Accelerated-Life	0 to 36 weeks	0.964
55	Calendar-Life	0 to 40 weeks	0.991
	Accelerated-Life	0 to 32 weeks	0.984

Figures 19 and 20 show the average C_1/25 static capacity fade for the 45°C Variant C cells aged at 60% SOC as a function of the square root of time and the natural log of time, respectively. Table 11 shows the time dependence and R^2 fits for these cell groups. As shown, the Variant C cells do not show any obvious mechanistic changes with either time dependence fits. However, the coefficient of determination (R^2) is significantly better for the square root of time dependence. This may indicate that time dependence is related to the diffusion rate. Like the Baseline cells, the Variant C cells show similar fade rates through 32 weeks of testing.

Table 11. Variant C $C_1/25$ time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{½}$-Mechanism		ln(t)-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Calendar-Life	0 to 32 weeks	0.929	0 to 32 weeks	0.761
	Cycle-Life	0 to 32 weeks	0.982	0 to 32 weeks	0.913

Figures 21 and 22 show the $C_1/25$ static capacity fade as a function of test time for the accelerated-life cells at 80 and 100% SOC, respectively. Mechanistic changes appear at higher SOCs for the $C_1/25$ capacity fade. The 80% SOC $C_1/25$ capacity fades show mechanistic changes for the 35, 45, and 55°C temperature groups. At 100% SOC, all four temperature groups show mechanistic changes. As seen with the $C_1/1$ capacity fade, the mechanistic changes generally occur earlier at higher temperatures, and the fade rate increases once the second mechanism takes effect. The mechanism breakpoints and R^2 fits for the accelerated-life cells at 80 and 100% SOC are summarized in Tables 12 and 13, respectively.

Table 12. $C_1/25$ test time dependence for the accelerated-life cell groups at 80% SOC.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 40 weeks	0.979	-	-
35	Accelerated-Life	0 to 12 weeks	0.980	16 to 36 weeks	0.994
45	Accelerated-Life	0 to 12 weeks	1.00	16 to 36 weeks	0.987
55	Accelerated-Life	0 to 8 weeks	0.999	12 to 20 weeks	0.999

Table 13. $C_1/25$ test time dependence for the accelerated-life cell groups at 100% SOC.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 20 weeks	0.984	24 to 40 weeks	0.983
35	Accelerated-Life	0 to 16 weeks	0.829	20 to 36 weeks	0.949
45	Accelerated-Life	0 to 16 weeks	0.975	20 to 36 weeks	0.928
55	Accelerated-Life	0 to 8 weeks	0.999	12 to 20 weeks	0.956

4.1.4 $C_1/25$ Differential Capacity

The $C_1/25$ static capacity data are used to calculate the relative change in capacity as a function of the voltage, normalized to the average BOL $C_1/25$ capacity, Q_{BOL}. Its purpose is to gain further insights into the mechanisms operating during the degradation of cell performance. The $C_1/25$ discharge and charge data are first smoothed, then the differential capacity is calculated using Equation (1).

$$\text{Differential Capacity} = \frac{1}{Q_{BOL}} * \frac{d(A \cdot h)}{dV} \tag{1}$$

4.1.4.1 Baseline Cells

Figure 23 shows the Baseline cell $C_1/25$ differential capacity for G2.60L25.I114.25.52.19.G.T (see Appendix 2, Section A2.2 for a description of the ATD labeling scheme) through 52 weeks of cycle-life testing at 25°C. Its performance is similar to the cell group average and is therefore representative of all 25°C Baseline cycle-life cells. The average BOL $C_1/25$ capacity for the 25°C cycle-life Baseline cells [i.e., Q_{BOL} of Equation (1)] was 1.075 A·h. This figure shows that the differential capacity decreases as a function of cycle time. The integral of the differential capacity curve shows capacity losses within the peak regions, but virtually no capacity loss outside the peak regions. Therefore, the source of capacity fade predominately occurs at the three different SOC peaks (i.e., 9, 40, and 77% SOC from the BOL discharge curve). The locations of these peaks also increase slightly in SOC as a function of aging, as shown by small shifts to higher voltages. The point at which cycle-life testing is performed (60% SOC) is outside of a peak region and shows no significant capacity loss as a function of time.

Figure 24 shows the differential capacity for G2.60L45.I130.50.52.39.G.T, a representative 45°C Baseline cycle-life cell. As expected, the differential capacity through 52 weeks at 45°C decreases more rapidly than the 25°C Baseline cycle-life cells. The BOL location of the peaks occur at similar SOCs to the 25°C Baseline cells, and the capacity loss also occurs predominately at the location of the peaks. The shift in the peak locations is more pronounced at 45°C, with the charge differential capacity showing a greater shift than the discharge differential capacity.

Figure 25 shows the Baseline cell $C_1/25$ differential capacity for G2.60C45.A217.50.52.35.G.T through 52 weeks of calendar-life testing at 45°C. The BOL location of the peaks occur at similar SOCs to the cycle-life cells. Whereas the cycle-life cells show a small shift in the peak locations and a large drop in differential capacity (Figure 24), the calendar-life cells show a large shift in the peak locations and a small drop in differential capacity. The 40 and 80% SOC peaks appear to be shifting toward each other for both the cycle- and calendar-life cells. As a result, the middle peak appears to broaden as a function of test time. This could be attributable to the alteration of the crystalline lattice in the electrodes.

Figure 26 shows the differential capacity through 40 weeks for G2.60C55.A214.33.40.34.G.L, a representative 55°C Baseline calendar-life cell. The peak locations are similar to the other cell groups (Figures 23 through 25). As expected, the shift in the differential capacity peaks is greater at 55°C. The shift and broadening of the peak for the 55°C calendar-life cells, however, is similar to the 45°C calendar-life cells.

4.1.4.2 Variant C Cells

Figure 27 shows the differential capacity for G2C.60L45.I162.30.32.26.G.T, a representative 45°C Variant C cycle-life cell through 32 weeks of aging. The differential capacity for the Variant C cycle-life cells is missing the initial discharge peak (at approximately 8 to 10% SOC), and the charge peak at 5% SOC has a lower amplitude than the Baseline cycle-life cells (Figures 23 and 24). The rate of decrease and shift in the differential capacity for the 45°C Variant C cycle-life cells is similar to that of the 25°C Baseline cycle-life cells (Figure 23). This is consistent with the results seen in the $C_1/25$ capacity fade (Figure 15).

Figure 28 shows the differential capacity for G2C.60C45.A226.25.32.22.G.T, a representative 45°C Variant C calendar-life cell through 32 weeks of aging. As was seen with the Baseline calendar-life cells, the Variant C cells show less amplitude drop and more peak shifting than the Variant C cycle-life cells. Interestingly, the width of the middle peak region becomes narrower as the peak shifts to higher voltages as a function of test time. The third peak (78% SOC from the BOL discharge curve) develops into a set of two peaks as a function of test time. Unlike the Variant C cycle-life cells, the calendar-life cells have an initial discharge peak at 8% SOC that grows as a function of test time.

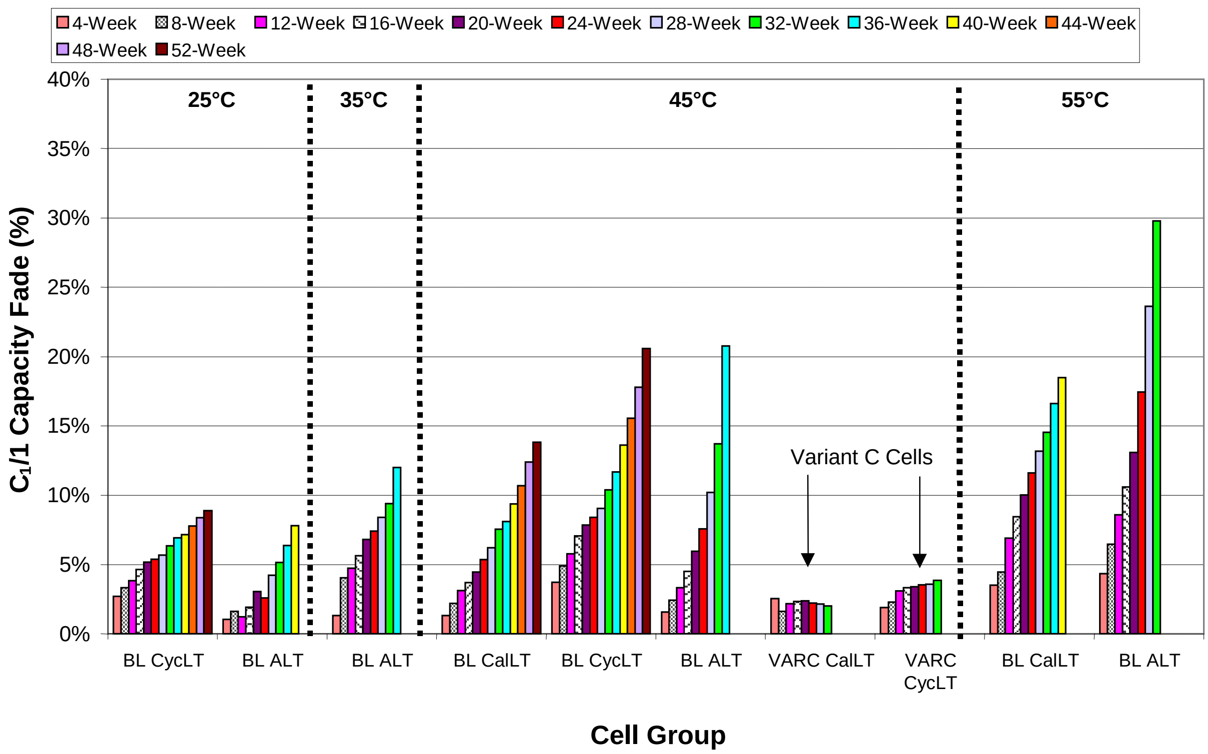

Figure 4. Average $C_1/1$ static capacity fade for each 60% SOC cell group.

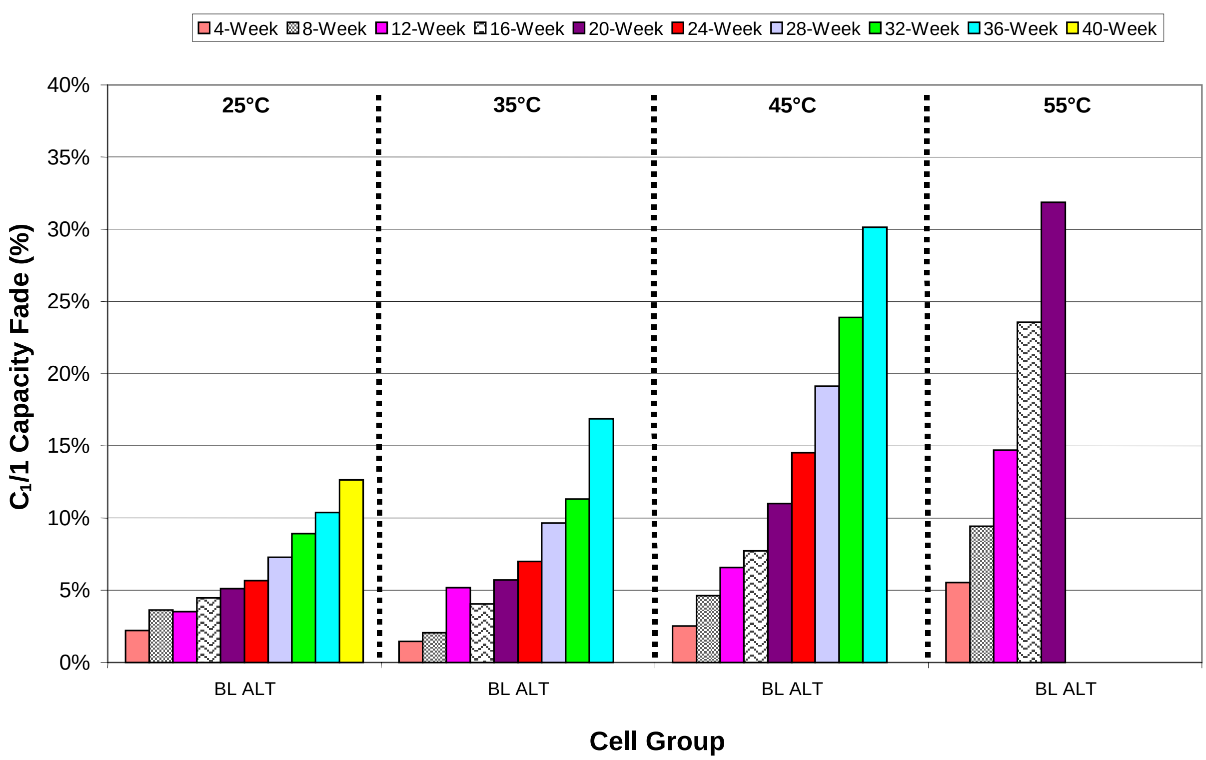

Figure 5. Average $C_1/1$ static capacity fade for each 80% SOC cell group.

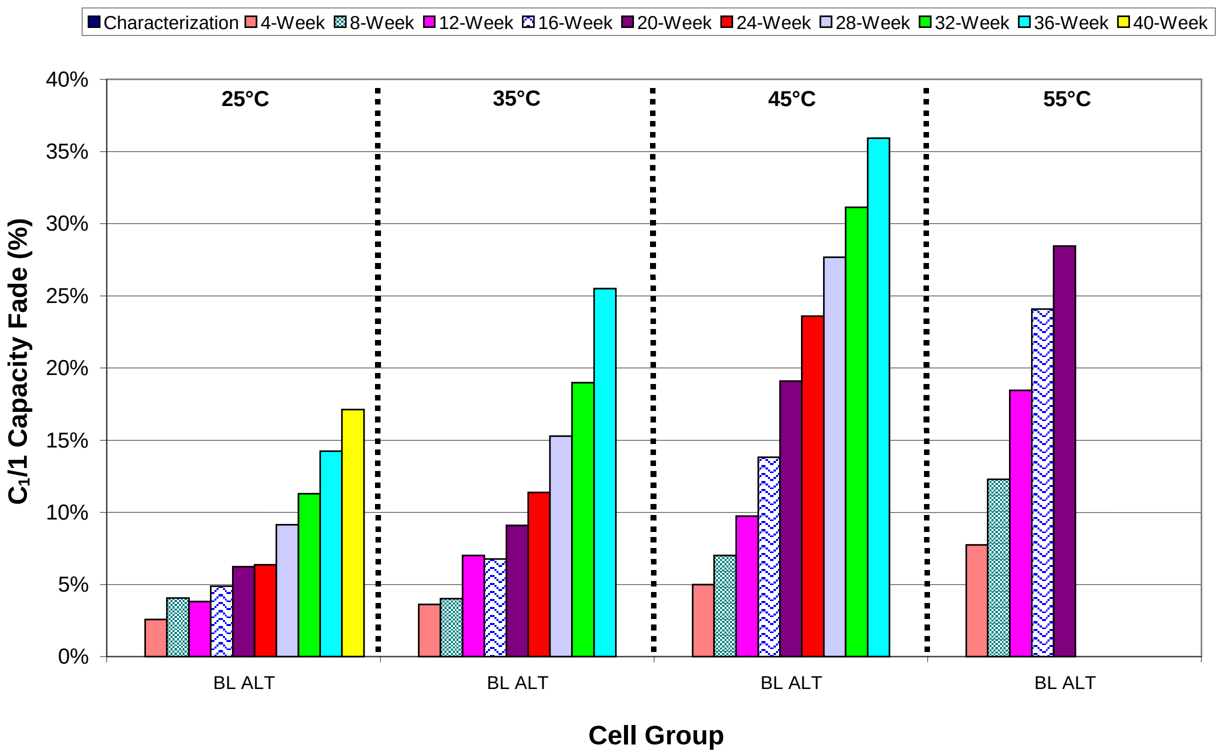

Figure 6. Average $C_1/1$ static capacity fade for each 100% SOC cell group.

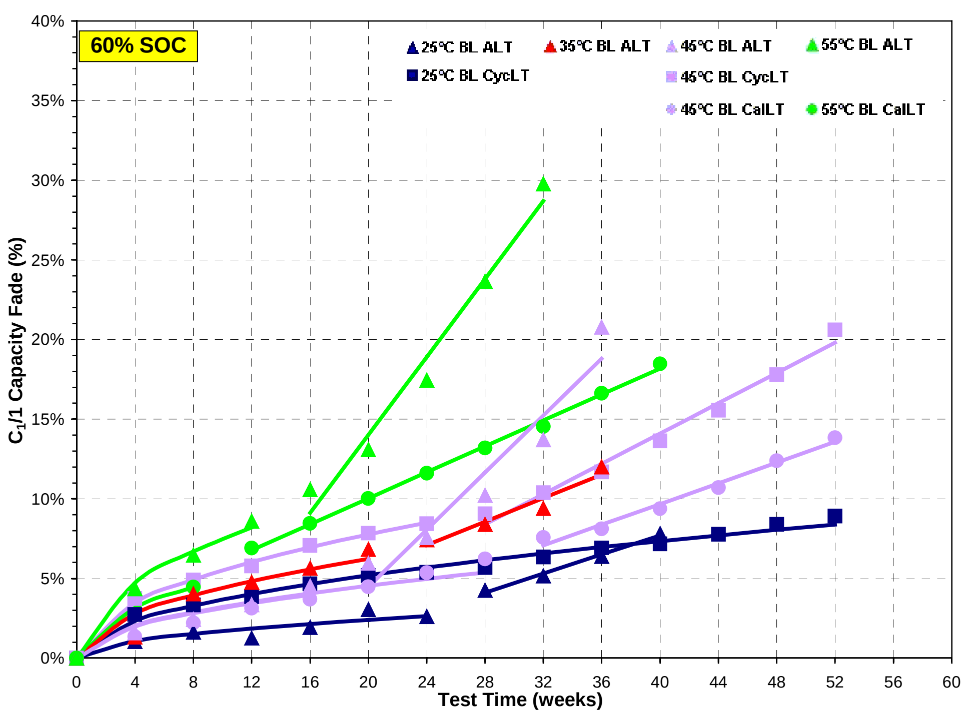

Figure 7. Average $C_1/1$ static capacity fade as a function of test time for the 60% SOC Baseline cells.

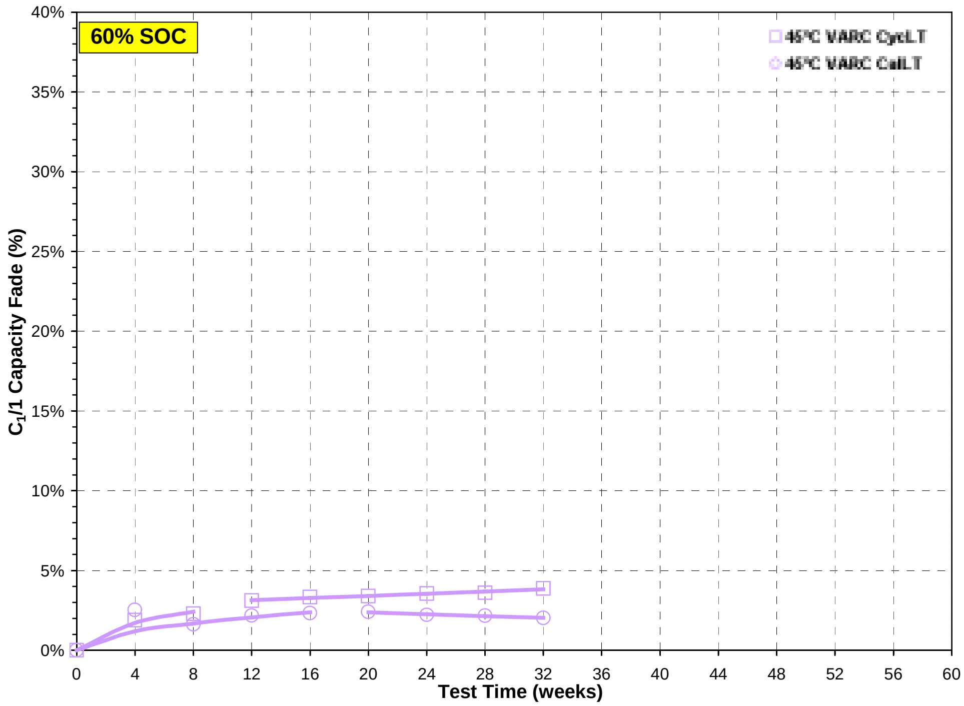

Figure 8. Average $C_1/1$ static capacity fade as a function of test time for the 60% SOC Variant C cells.

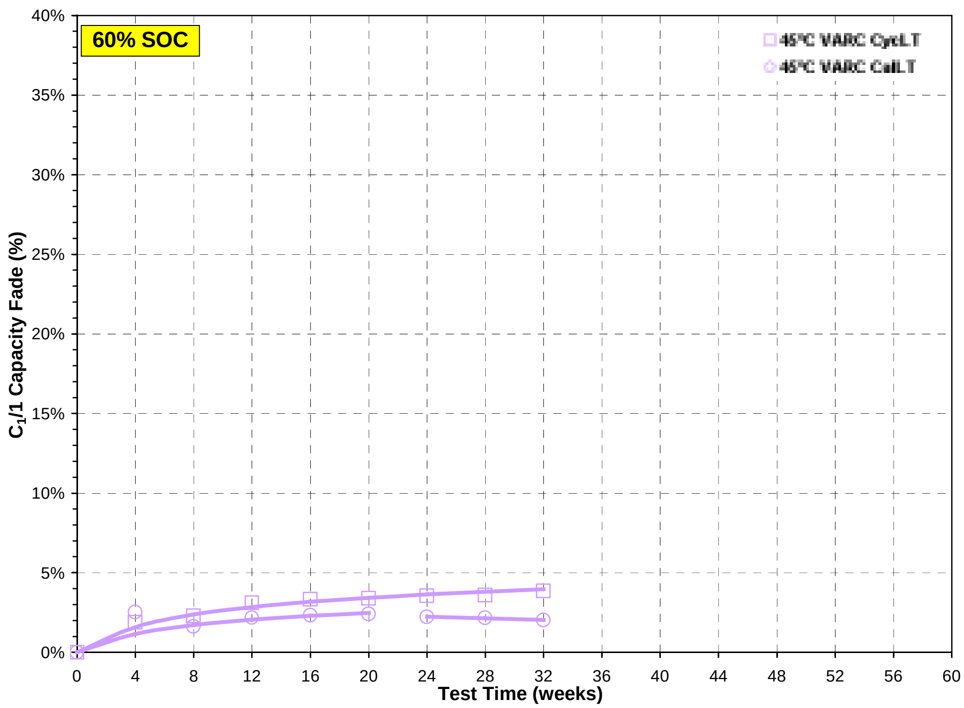

Figure 9. Average $C_1/1$ static capacity fade as a function of the natural log of time for the 60% SOC Variant C cells.

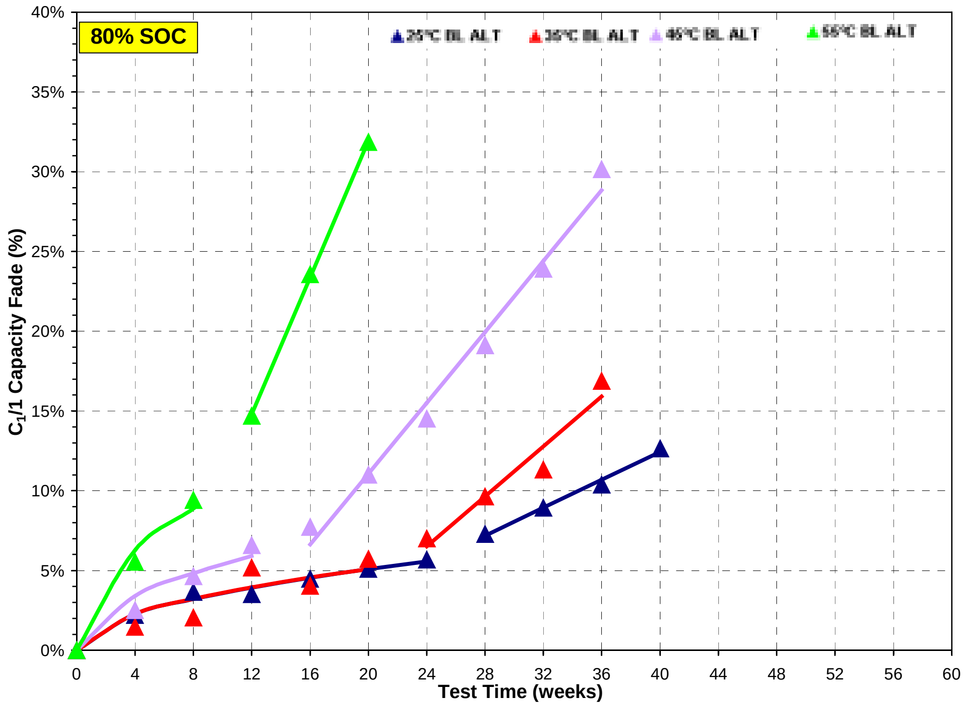

Figure 10. Average $C_1/1$ static capacity fade as a function of test time for the 80% SOC Baseline cells.

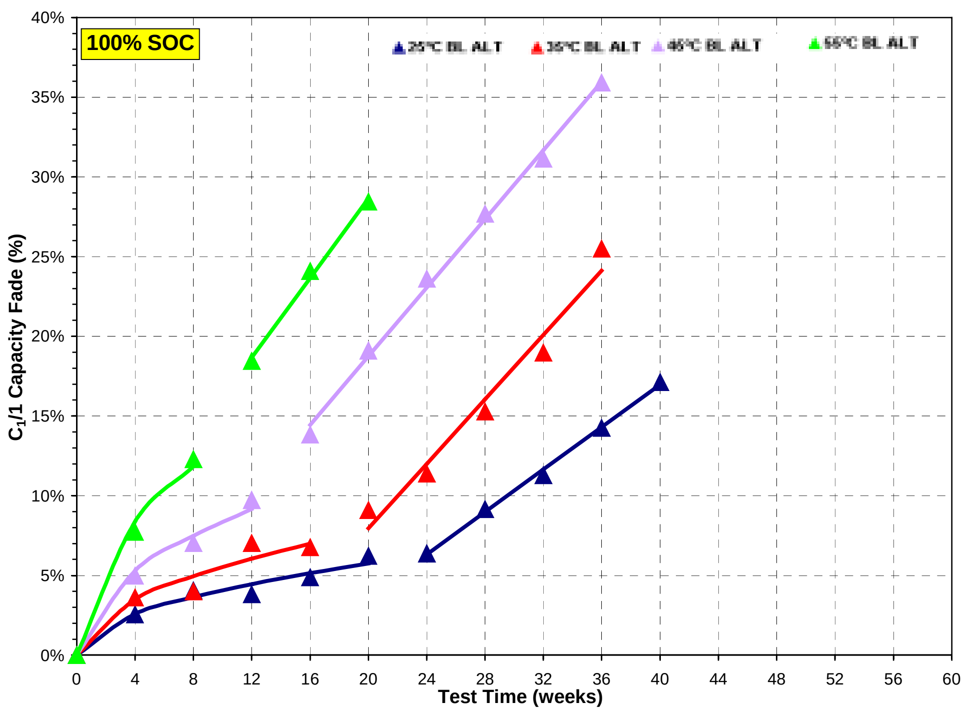

Figure 11. Average $C_1/1$ static capacity fade as a function of test time for the 100% SOC Baseline cells.

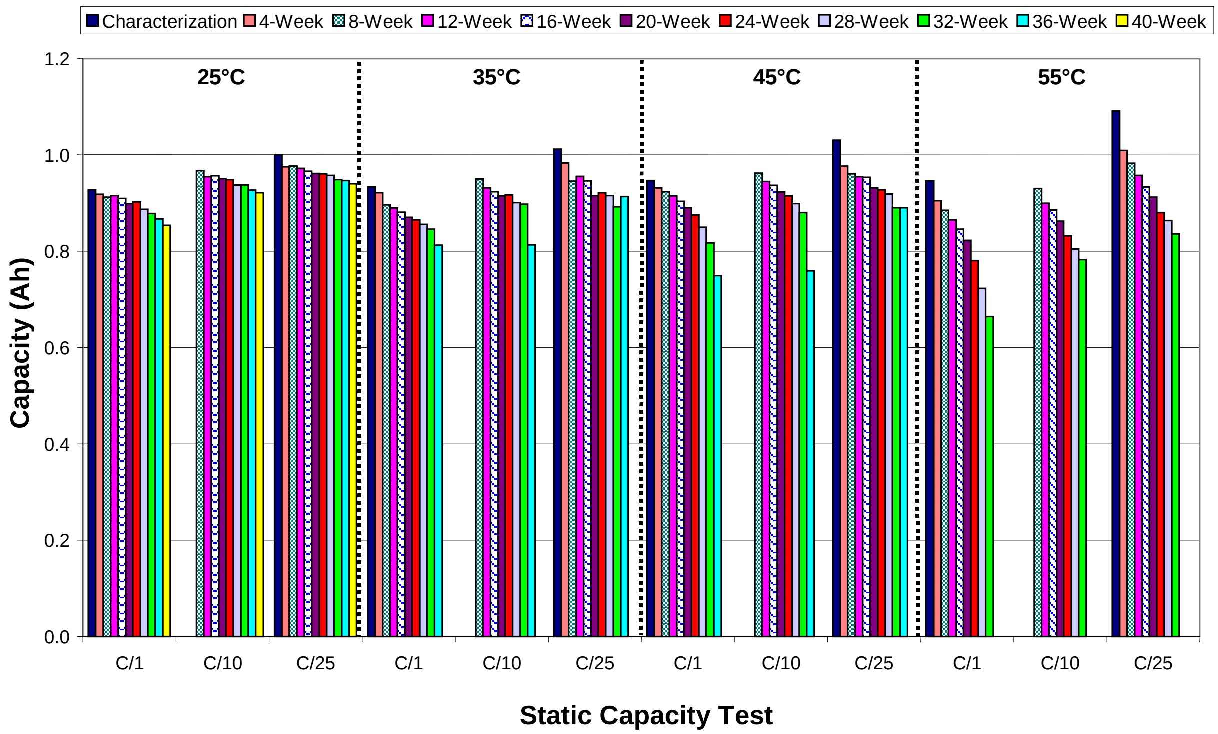

Figure 12. Static capacity tests for the accelerated-life cells at 60% SOC.

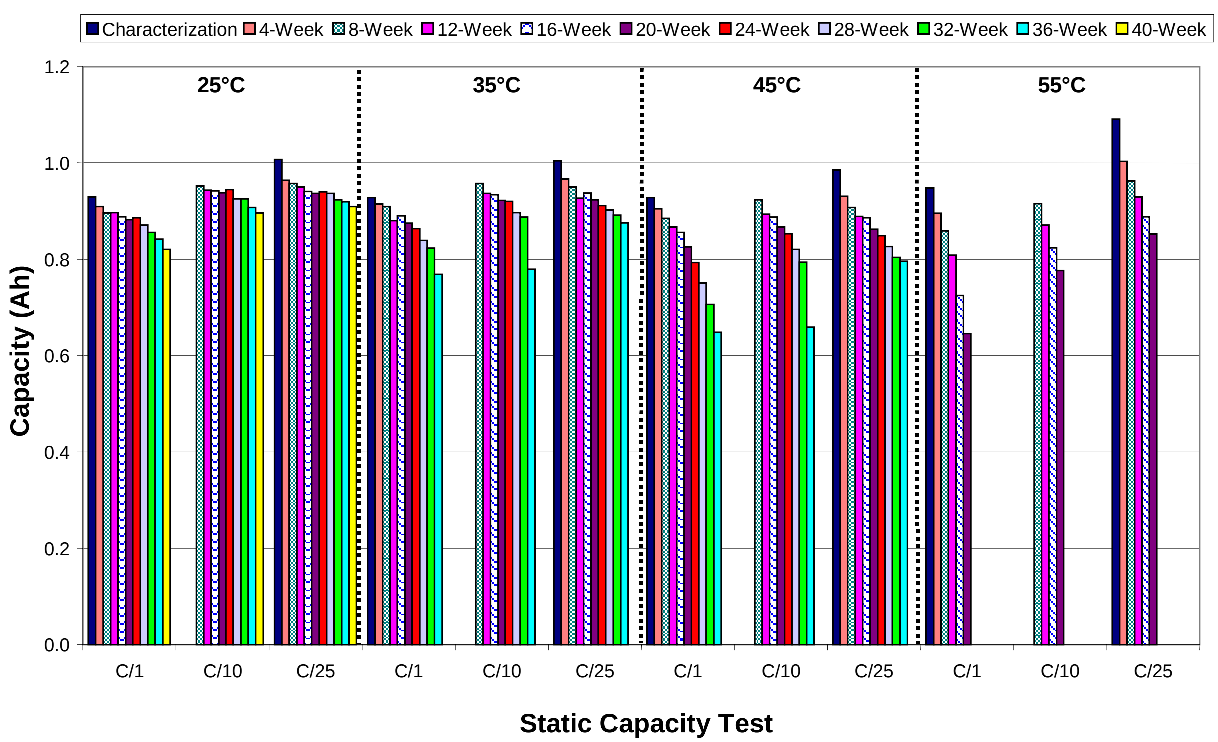

Figure 13. Static capacity tests for the accelerated-life cells at 80% SOC.

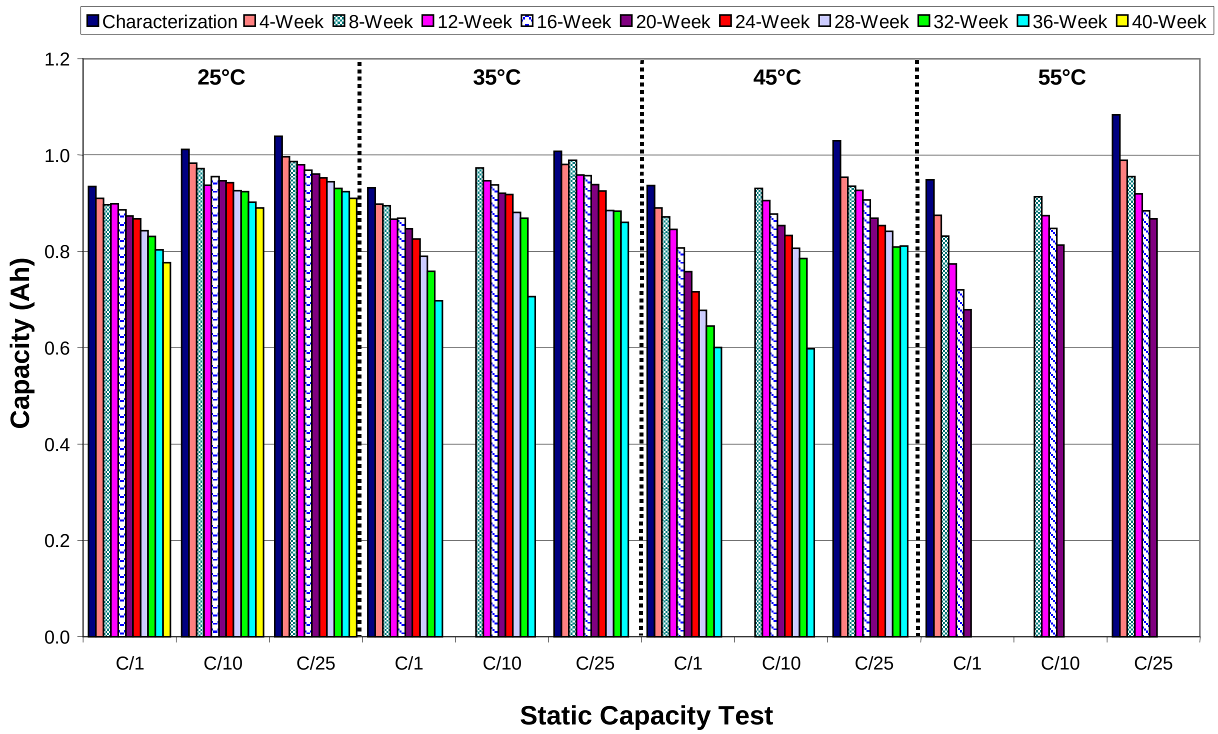

Figure 14. Static capacity tests for the accelerated-life cells at 100% SOC.

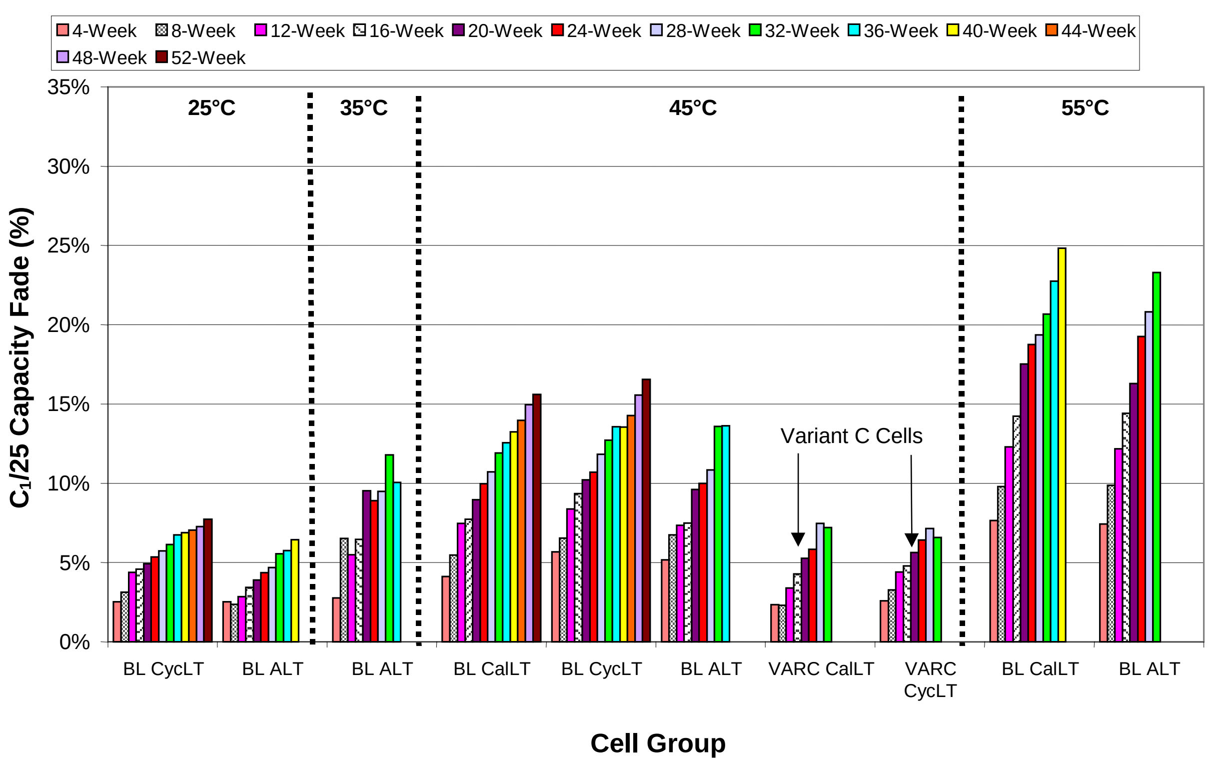

Figure 15. Average $C_1/25$ static capacity fade for each 60% SOC cell group.

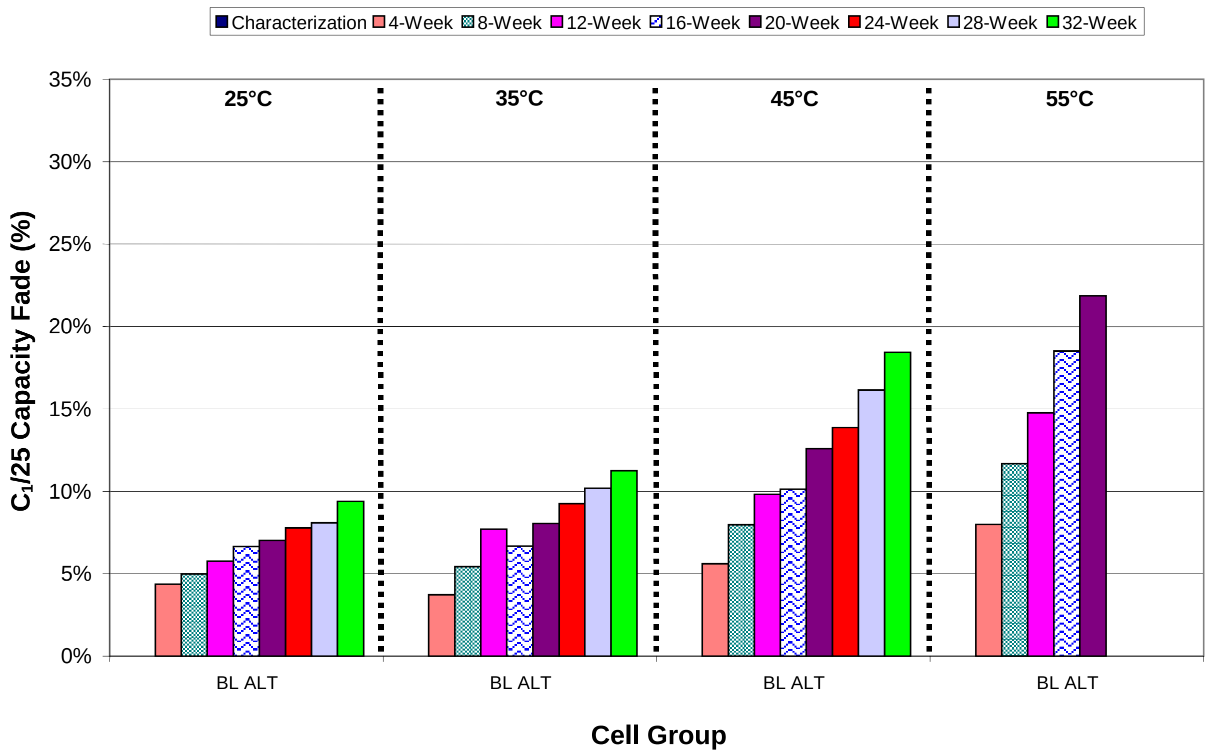

Figure 16. Average $C_1/25$ static capacity fade for each 80% SOC cell group.

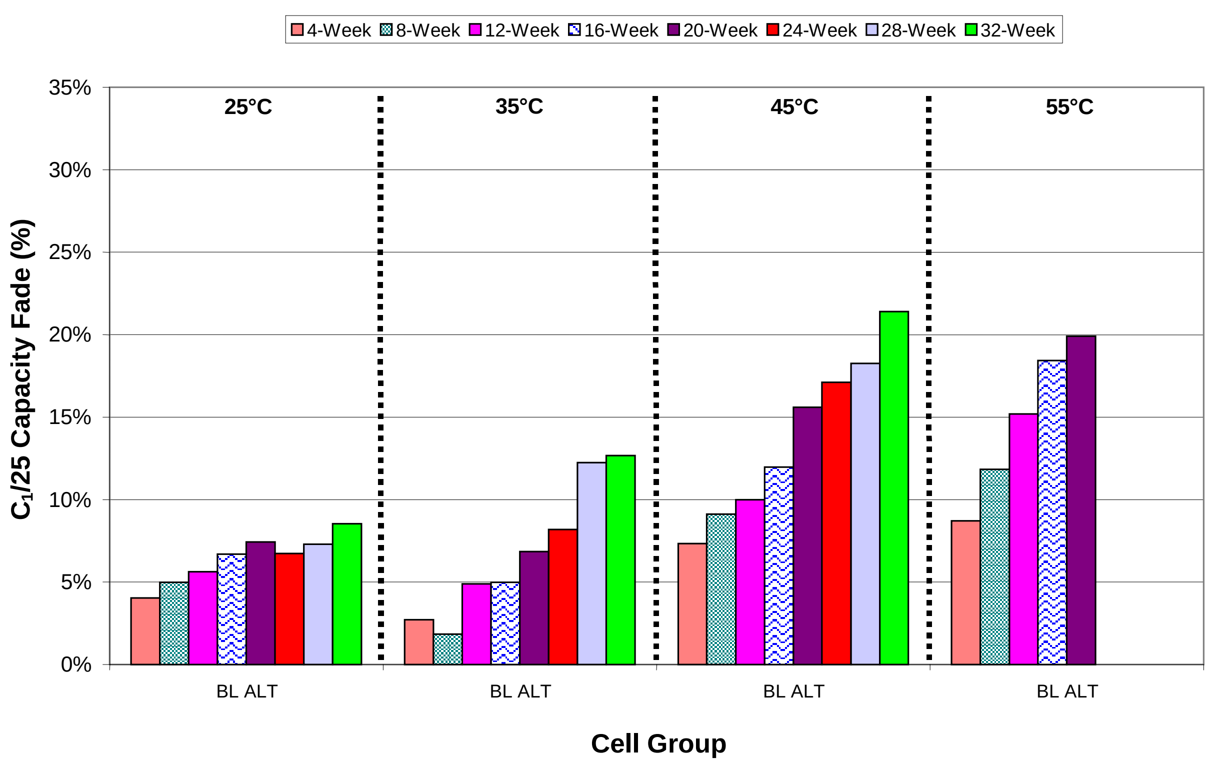

Figure 17. Average $C_1/25$ static capacity fade for each 100% SOC cell group.

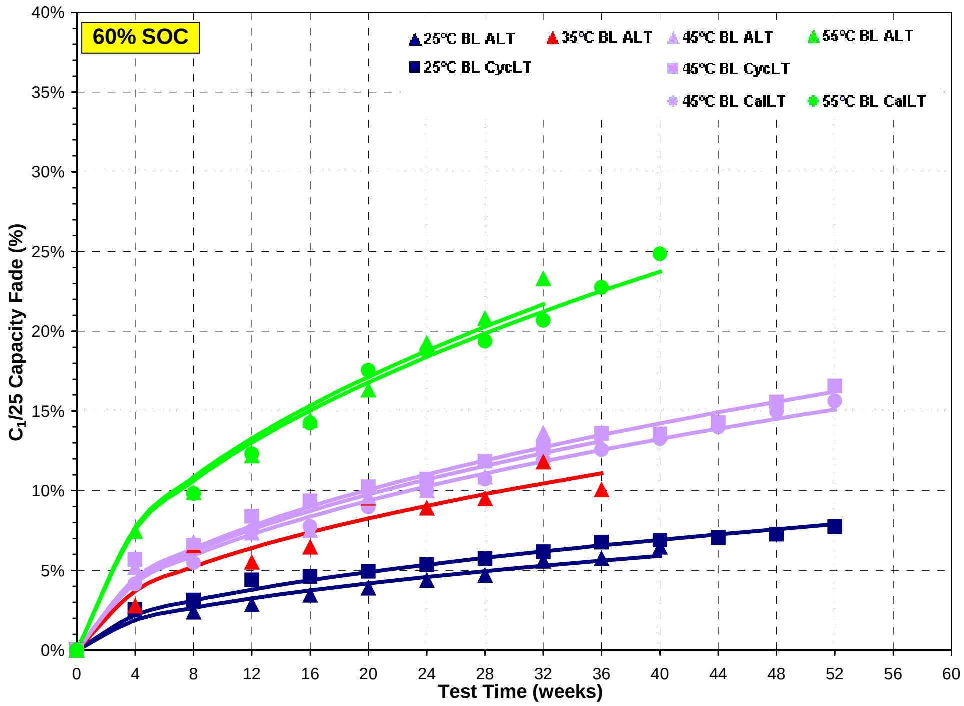

Figure 18. Average $C_1/25$ static capacity fade as a function of test time for the 60% SOC Baseline cells.

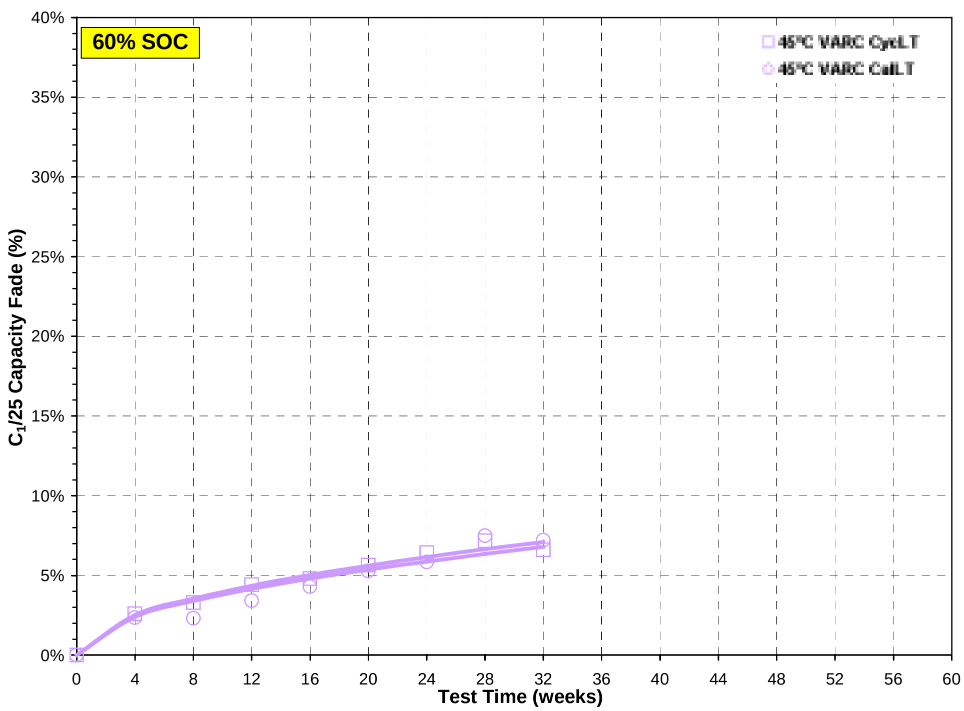

Figure 19. Average $C_1/25$ static capacity fade as a function of test time for the 60% SOC Variant C cells.

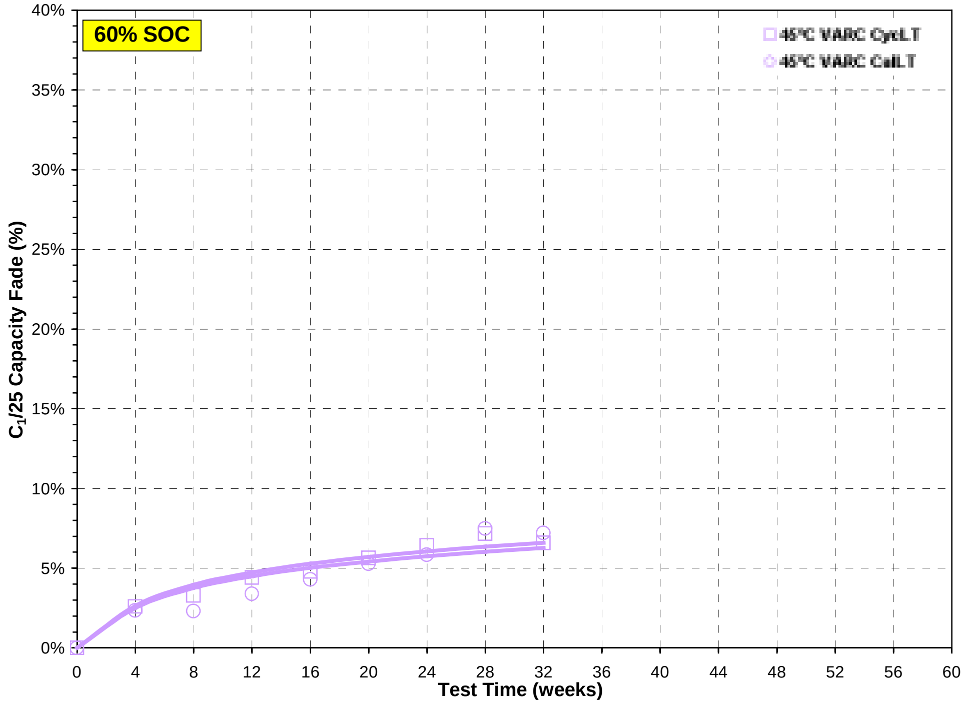

Figure 20. Average $C_1/25$ static capacity fade as a function of the natural log of time for the 60% SOC Variant C cells.

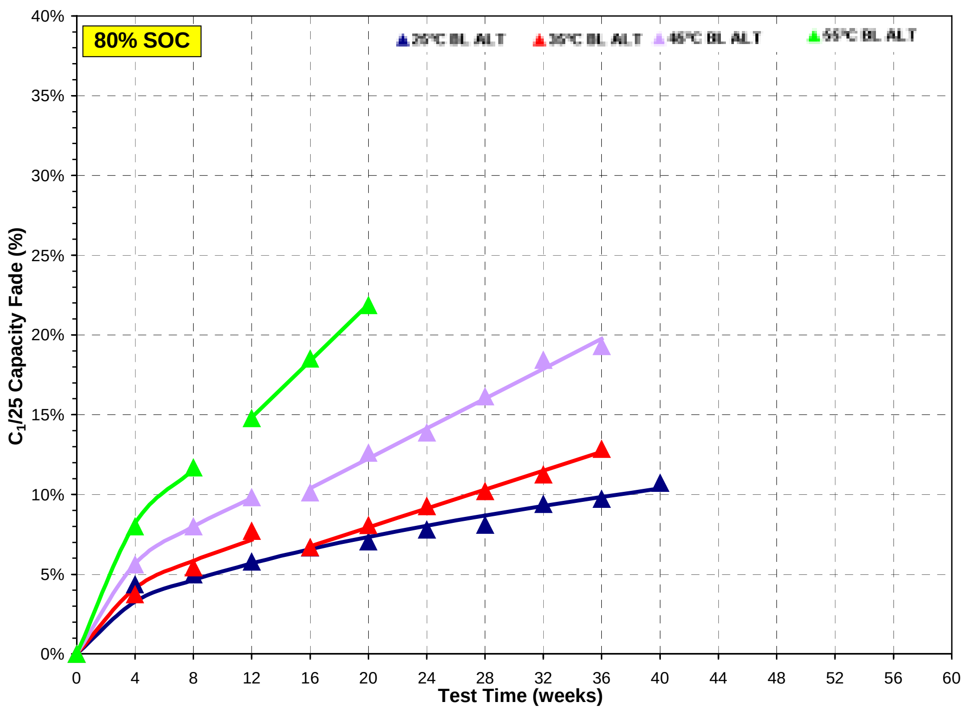

Figure 21. Average $C_1/25$ static capacity fade as a function of test time for the 80% SOC Baseline cells.

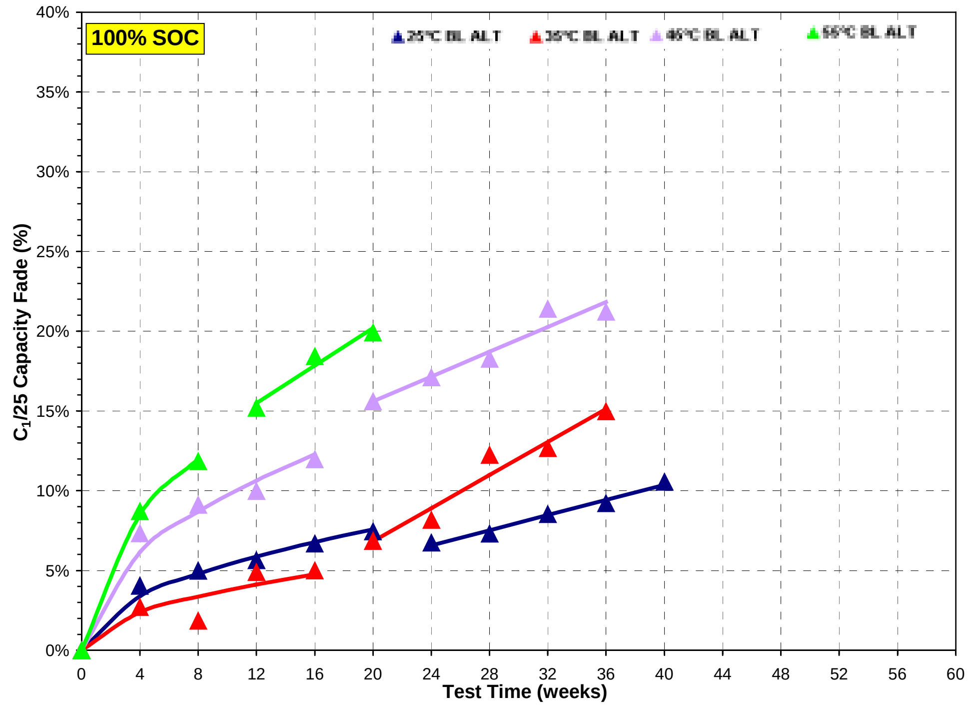

Figure 22. Average $C_1/25$ static capacity fade as a function of test time for the 100% SOC Baseline cells.

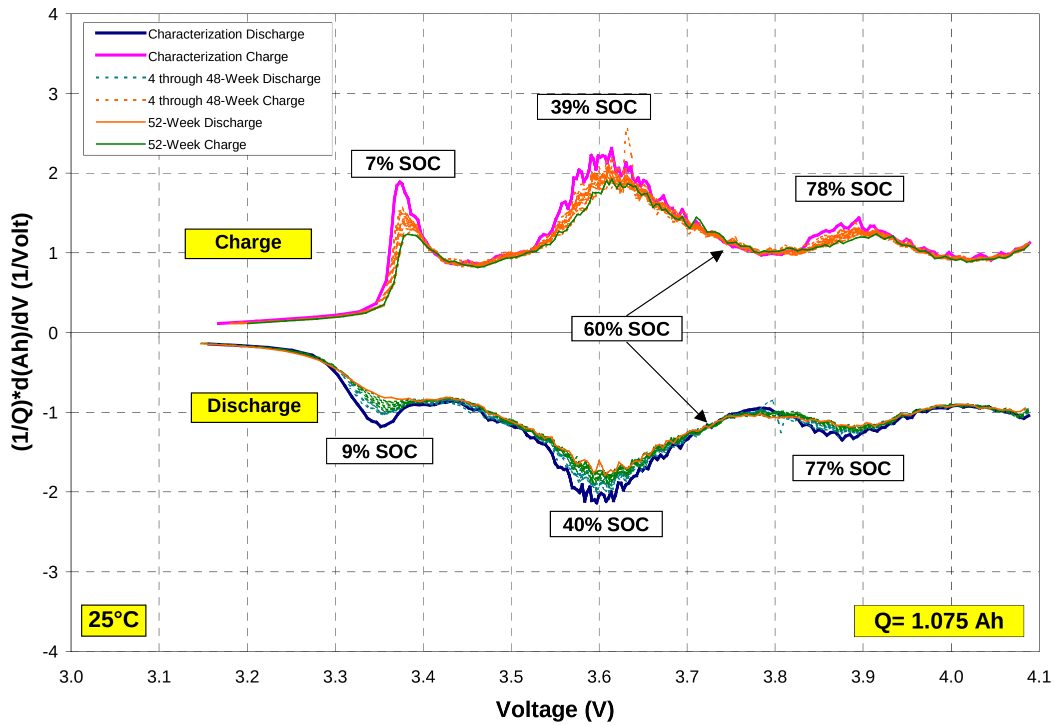

Figure 23. Differential capacity for G2.60L25.I114.25.52.19.G.T (25°C cycle-life Baseline cell).

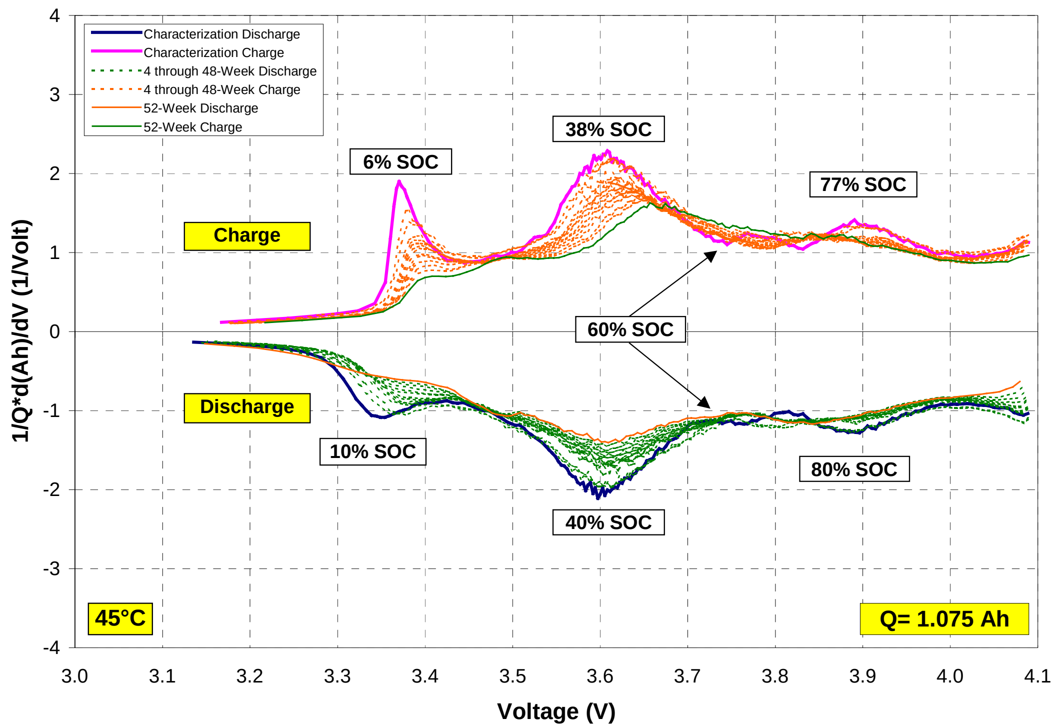

Figure 24. Differential capacity for G2.60L45.I130.50.52.39.G.T (45°C cycle-life Baseline cell).

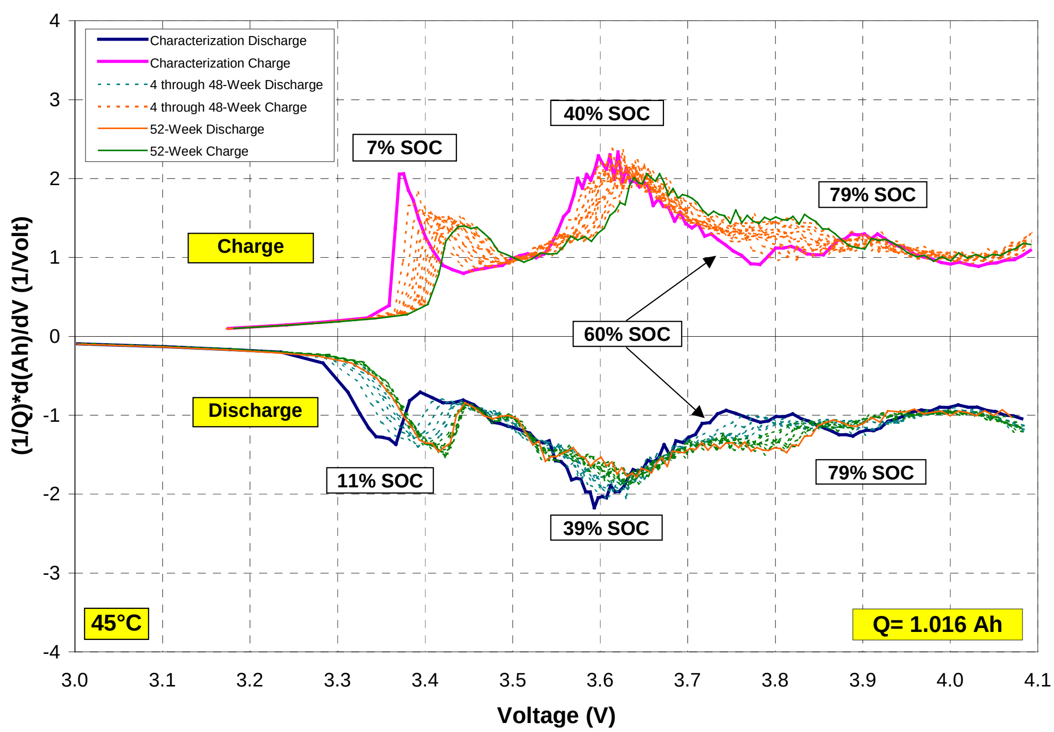

Figure 25. Differential capacity for G2.60C45.A217.50.52.35.G.T (45°C calendar-life Baseline cell).

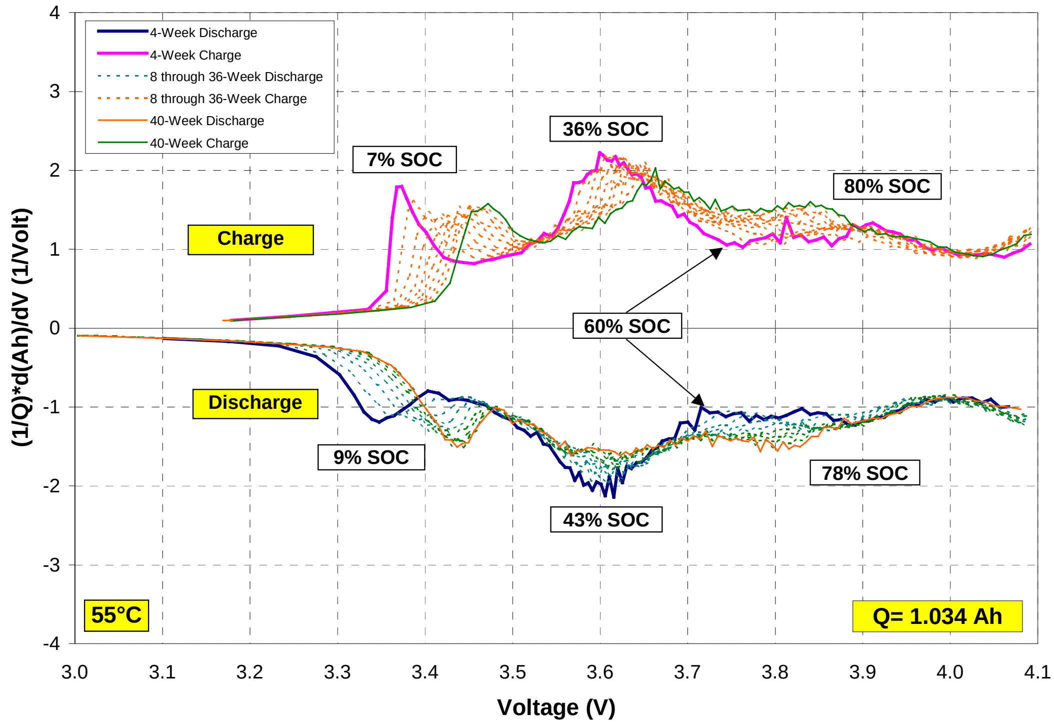

Figure 26. Differential capacity for G2.60C55.A214.33.40.34.G.L (55°C calendar-life Baseline cell).

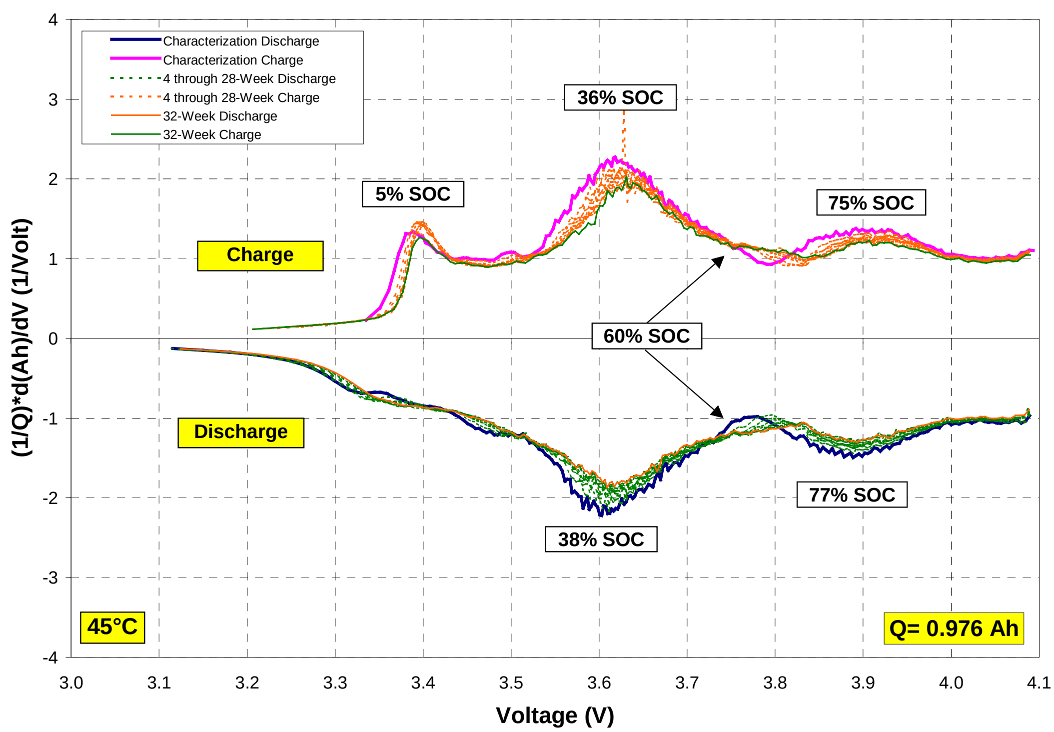

Figure 27. Differential capacity for G2C.60L45.I162.30.32.26.G.T (45°C cycle-life Variant C cell).

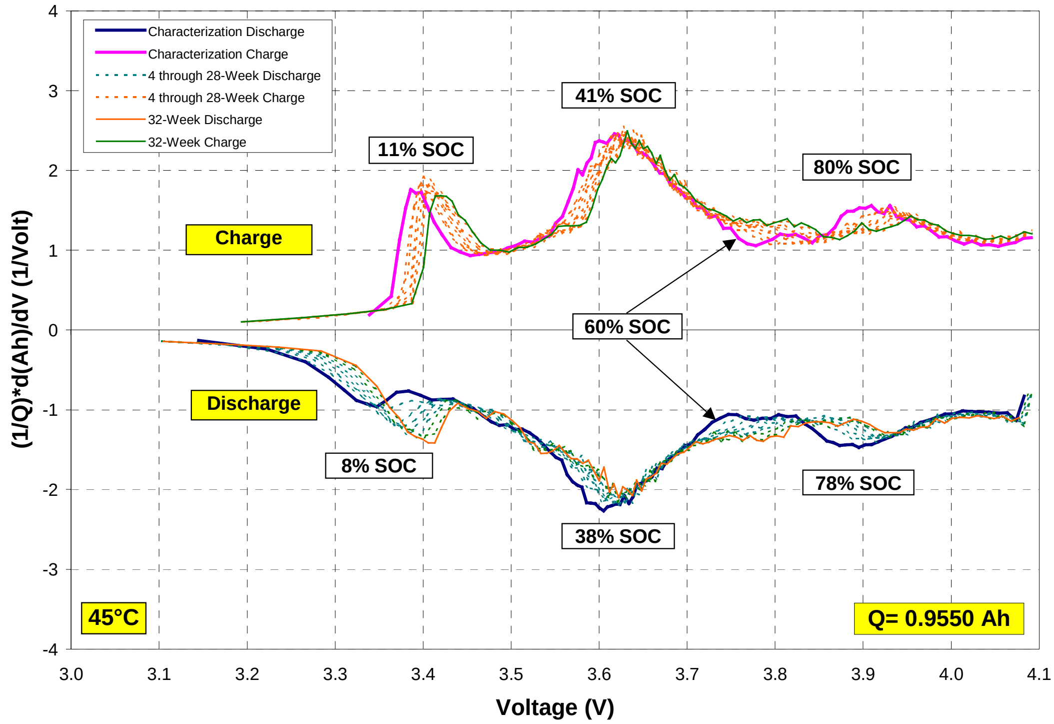

Figure 28. Differential capacity for G2C.60C45.A226.25.32.22.G.T (45°C calendar-life Variant C cell).

4.2 Power

4.2.1 Power Calculation Methodology

A standard measure of cell degradation for the ATD Program is the percent-fade in the power measured at 300 Wh from the L-HPPC test. A detailed description of the power calculation methodology is presented in Reference 2 and is summarized below.

4.2.1.1 Area Specific Impedance

From the L-HPPC test (Section 3.1), discharge and regen resistances are calculated as the ratio of the change in voltage (ΔV) divided by the change in current (ΔI) at specified times during the pulse at each 10% DOD increment, as shown in Equations (2) and (3).

$$R_{discharge} = \left. \frac{\Delta V_{18s}}{\Delta I_{18s}} \right|_{discharge} \quad (2)$$

$$R_{regen} = \left. \frac{\Delta V_{2s}}{\Delta I_{2s}} \right|_{regen} \quad (3)$$

Since the ATD Gen 2 cells are testing under the PNGV Power Assist goals, the data required include the 18-s discharge resistance and the 2-s regen resistance. Figure 29 (page 33) shows these resistances at each DOD increment as a function of OCV for a representative Baseline cell at BOL. As expected, the 18-s discharge resistances are consistently higher than the 2-s regen resistances. These resistances can also be scaled by the electrode area (846.3 cm^2 for the Gen 2 cells) to find the area specific impedance (ASI) in Ω-cm^2.

The resistance data are then used to calculate the discharge and regen pulse power capability ($P_{discharge}$ and P_{regen}) using Equations (4) and (5), respectively:

$$P_{discharge} = \frac{V_{min}(OCV - V_{min})}{R_{discharge}} \tag{4}$$

$$P_{regen} = \frac{V_{max}(V_{max} - OCV_{regen})}{R_{regen}} \tag{5}$$

where V_{min} and V_{max} are the specified L-HPPC voltage limits (3.0 and 4.1 V, respectively for the ATD Gen 2 cells), the OCV is the voltage immediately prior to the pulse, and $R_{discharge}$ and R_{regen} are the corresponding 18-s and 2-s discharge and regen resistances, respectively, calculated from Equations (1) and (2). Since the regen pulse occurs after a 32-s rest (see Figure 1), the voltage immediately prior to the pulse does not reflect the OCV at true equilibrium. Consequently, the OCV is linearly interpolated based on the discharge OCV at the current and next L-HPPC pulse (i.e., over a 10% DOD swing).

The pulse power capabilities at each DOD increment are then related to the corresponding amount of energy discharged at a $C_1/1$ rate to that point (i.e., the energy removed during the full $C_1/1$ discharge performed prior to the L-HPPC test). Figure 30 shows the discharge and regen pulse power capabilities versus the cumulative energy removed for the same representative cell shown in Figure 29. Note that the regen power is normalized to the discharge power through a scaling factor of 1.2 (i.e., the 30-kW Power Assist regen goal divided by the 25 kW Power Assist discharge goal).

4.2.1.2 Available Energy

From the pulse power capability curves (Figure 30), the available energy as a function of discharge power can be calculated by taking the difference in energy between the discharge power curve and regen power curve, as shown in Equation (6).

$$\text{Available Energy} = E_{discharge} - E_{regen}\,. \tag{6}$$

Figure 31 shows the resulting available energy curve for the same representative cell shown in Figures 29 and 30. The dashed-line in Figure 31 has a slope equal to the ratio of the PNGV Power Assist energy goal (i.e., 300 Wh) divided by the PNGV discharge power goal plus a 30% BOL power margin (i.e., 25 kW * 1.3). The point at which the dashed line intersects the available energy curve is where the PNGV goals are optimally met for this representative cell. This intersection point is used to calculate the battery size factor (BSF) by dividing the energy at this point by the PNGV energy goal (or, alternatively dividing the power at this point by the PNGV power goal with a 30% margin). This calculation was performed on each ATD Gen 2 cell. The Baseline cells have an average BSF of 553, and the Variant C cells have an average BSF of 651. The BSF is used to scale the cycle-life test profiles as well as all subsequent power and energy curves for direct comparison with the PNGV goals. A standard measure of cell degradation is to find the percent-fade in the power at 300 Wh, normalized to the BOL power at 300 Wh.

Figures 32 through 34 show the BSF-scaled available energies at each RPT for a representative calendar-, cycle- and accelerated-life cell, respectively, aged at 60% SOC and 45°C. The power and energy goals of 25 kW and 300 Wh are also shown by the bold lines. The available energy decreases steadily as a function of time. When the available energy curve intersects the cross-point between the two bold lines, the cell can no longer simultaneously meet the power and energy goals and has reached end-of-life. However, the diagnostic laboratories have requested that the cells continue testing beyond the power and energy cross-point in order to gain a better understanding of power fade (Section 3.4). The representative calendar-life cell, G2.60C45.A217.50.52.35.G.T (Figure 32), was unable to simultaneously meet the goals after 48 weeks (336 days). The representative cycle-life cell, G2.60L45.I130.50.52.39.G.T (Figure 33), was unable to simultaneously meet the power and energy goals at 36 weeks. Another concurrent requirement for cycle-life is completion of 300,000 cycles of the PNGV 25-Wh Power Assist profile (Figure 2). G2.60L45.I130.50.52.39.G.T just exceeded this requirement with 302,400 cycles at 36 weeks. The representative accelerated-life cell, G2.60A45.S438.NA.36.43.G.T (Figure 34), was unable to simultaneously meet the goals after 24 weeks (168 days). All three cells initially show a large decrease in available energy (between BOL and 4 weeks), but then show a steady and monotonic drop in power and energy.

4.2.2 Power Fade and Model

Figure 35 shows the average power fade for each cell group at 60% SOC for the calendar-, cycle- and accelerated-life cells. As seen with the capacity fade results (Figures 4 and 15), the power fade increases as a function of increasing test temperature for both the Baseline and Variant C cells. The order of increasing power fade is also lowest for the calendar-life cells, in the middle for the cycle-life cells, and highest for the accelerated-life cells.

Figures 36 and 37 show the power fade for the accelerated-life cells at 80 and 100% SOC, respectively. As shown, power fade increases with increasing test temperature and SOC. The cells at 100% SOC show the highest fades at each respective temperature. The higher-temperature mechanism affecting the $C_1/1$ capacity fades (Figures 5 and 6) is not visible in the power fade results.

Figure 38 shows the average power fade as a function of test time at 60% SOC for the Baseline calendar-, cycle- and accelerated-life cells. The 25°C cycle-life Baseline cells show a linear time dependence through 52 weeks of testing with no apparent mechanistic change. The 25°C $C_1/1$ and $C_1/25$ capacity fades showed only a square root of time dependence (Figures 7 and 18). All other cell groups show mechanistic changes with an initial square root of time dependence, followed by a linear dependence. The power fade rate increases when the second mechanism takes effect. Within each life-test group, the fade rate also increases with increasing temperature. Within each life-test group, the breakpoints between mechanisms generally occur earlier at higher temperatures. All of these trends are consistent with the $C_1/1$ capacity fade results shown in Figure 7. The mechanism breakpoints and R^2 fits for the Baseline cells are summarized in Table 14.

Table 14. Baseline cell power fade test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Cycle-Life	-	-	0 to 52 weeks	0.966
	Accelerated-Life	0 to 16 weeks	0.891	20 to 40 weeks	0.986
35	Accelerated-Life	0 to 8 weeks	0.994	12 to 36 weeks	0.923
45	Calendar-Life	0 to 28 weeks	0.970	32 to 52 weeks	0.986
	Cycle-Life	0 to 28 weeks	0.996	32 to 52 weeks	0.998
	Accelerated-Life	0 to 8 weeks	0.994	12 to 36 weeks	0.993
55	Calendar-Life	0 to 20 weeks	1.00	24 to 40 weeks	0.992
	Accelerated-Life	0 to 8 weeks	0.993	12 to 32 weeks	0.996

Figures 39 and 40 show the average power fade for the 45°C Variant C cells aged at 60% SOC as a function of the square root of time and the natural log of time, respectively, for the calendar- and cycle-life cells. As shown, the Variant C cells show an initial square root of time dependence followed by linear time dependence. However, the natural log of time fit shows no obvious breakpoints. The mechanism breakpoints and R^2 fits for the Variant C cells are summarized in Tables 15 and 16.

Table 15. Variant C power fade square root of time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Calendar-Life	0 to 12 weeks	0.976	16 to 32 weeks	0.999
	Cycle-Life	0 to 8 weeks	0.992	12 to 32 weeks	0.937

Table 16. Variant C power fade natural log of time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	ln(t)-Mechanism	
		Test Time	R^2 fit
45	Calendar-Life	0 to 32 weeks	0.943
	Cycle-Life	0 to 32 weeks	0.975

Figures 41 and 42 show the power fade as a function of test time for the accelerated-life cells at 80 and 100% SOC, respectively. These data also show the same general trends as the 60% SOC data. The fade rate increases with increasing temperature when the second mechanism takes effect. The breakpoints generally occur earlier with increasing temperature. The average fade is highest at 100% SOC, and lowest at 60% SOC. Although the 55°C cells at 100% SOC have higher fades than the 80% SOC cells, the linear slope at 80% SOC is higher. If testing had continued at 55°C, the 80% SOC cells would have eventually shown higher fades than the 100% SOC cells, which is the same trend observed for the $C_1/1$ capacity fade (Figures 10 and 11). The mechanism breakpoints and R^2 fits for the accelerated-life cells at 80 and 100% SOC are summarized in Tables 17 and 18, respectively.

Table 17. Power fade test time dependence for the accelerated-life cell groups at 80% SOC.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 20 weeks	0.904	24 to 40 weeks	0.995
35	Accelerated-Life	0 to 16 weeks	0.844	20 to 36 weeks	0.902
45	Accelerated-Life	0 to 8 weeks	0.999	12 to 36 weeks	0.994
55	Accelerated-Life	0 to 8 weeks	0.999	12 to 20 weeks	0.976

Table 18. Power fade test time dependence for the accelerated-life cell groups at 100% SOC.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Accelerated-Life	0 to 12 weeks	0.981	16 to 40 weeks	0.999
35	Accelerated-Life	0 to 8 weeks	0.994	12 to 36 weeks	0.994
45	Accelerated-Life	0 to 8 weeks	0.997	12 to 36 weeks	0.942
55	Accelerated-Life	0 to 4 weeks	1.00	8 to 20 weeks	0.982

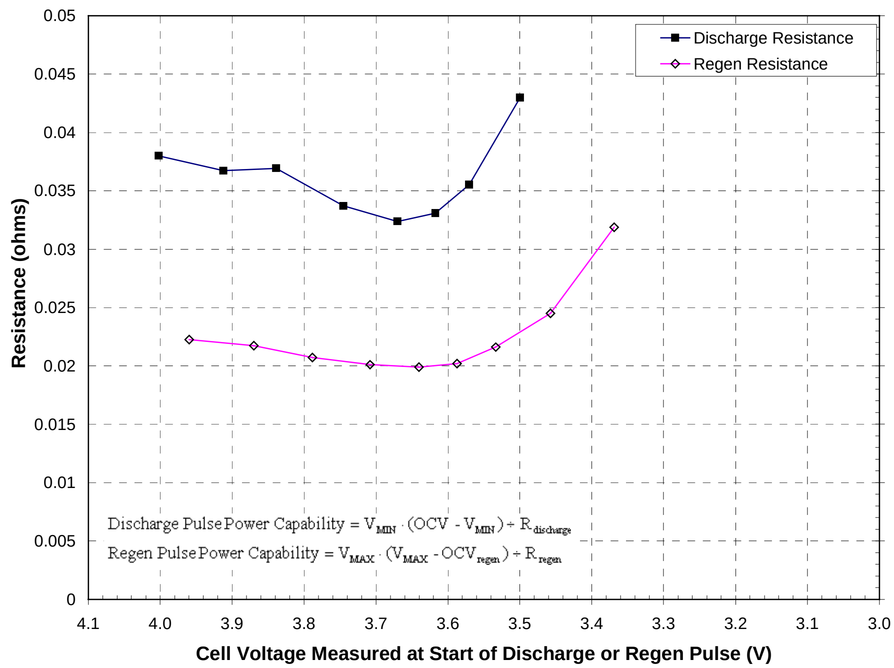

Figure 29. Resistance as a function of OCV for a representative Gen 2 Baseline cell.

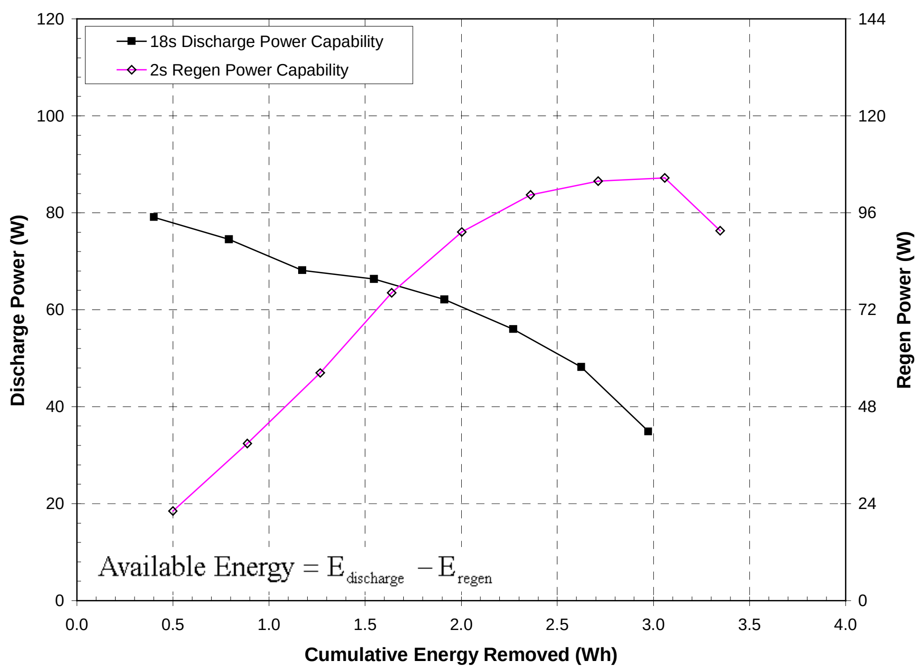

Figure 30. Discharge and regen pulse power capabilities versus the cumulative energy.

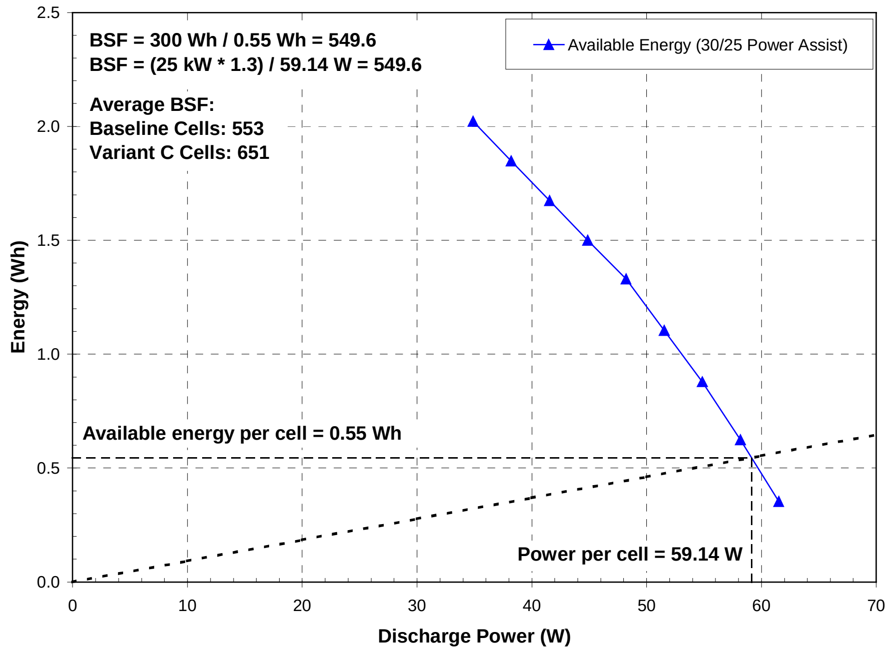

Figure 31. Available energy curve.

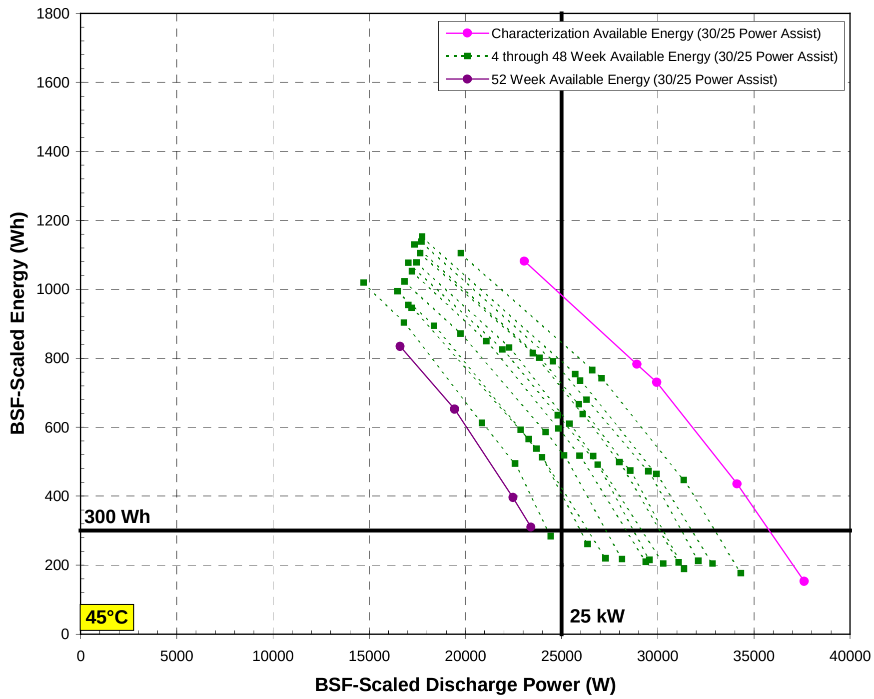

Figure 32. BSF-scaled available energy for G2.60C45.A217.50.52.35.G.T (45°C calendar-life Baseline cell).

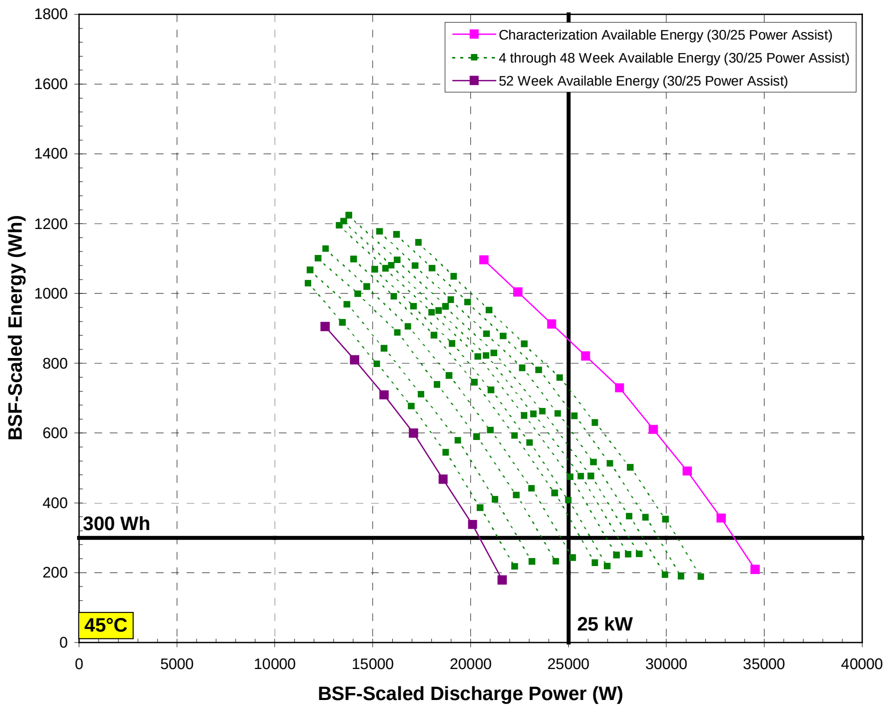

Figure 33. BSF-scaled available energy for G2.60L45.I130.50.52.39.G.T (45°C cycle-life Baseline cell).

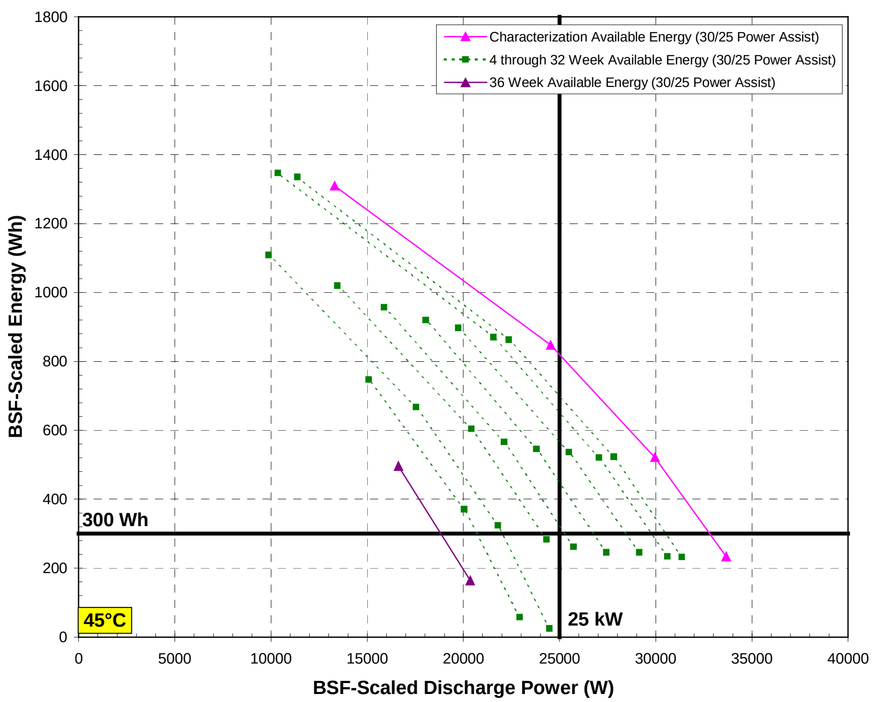

Figure 34. BSF-scaled available energy for G2.60A45.S438.NA.36.43.G.T
(45°C accelerated-life Baseline cell).

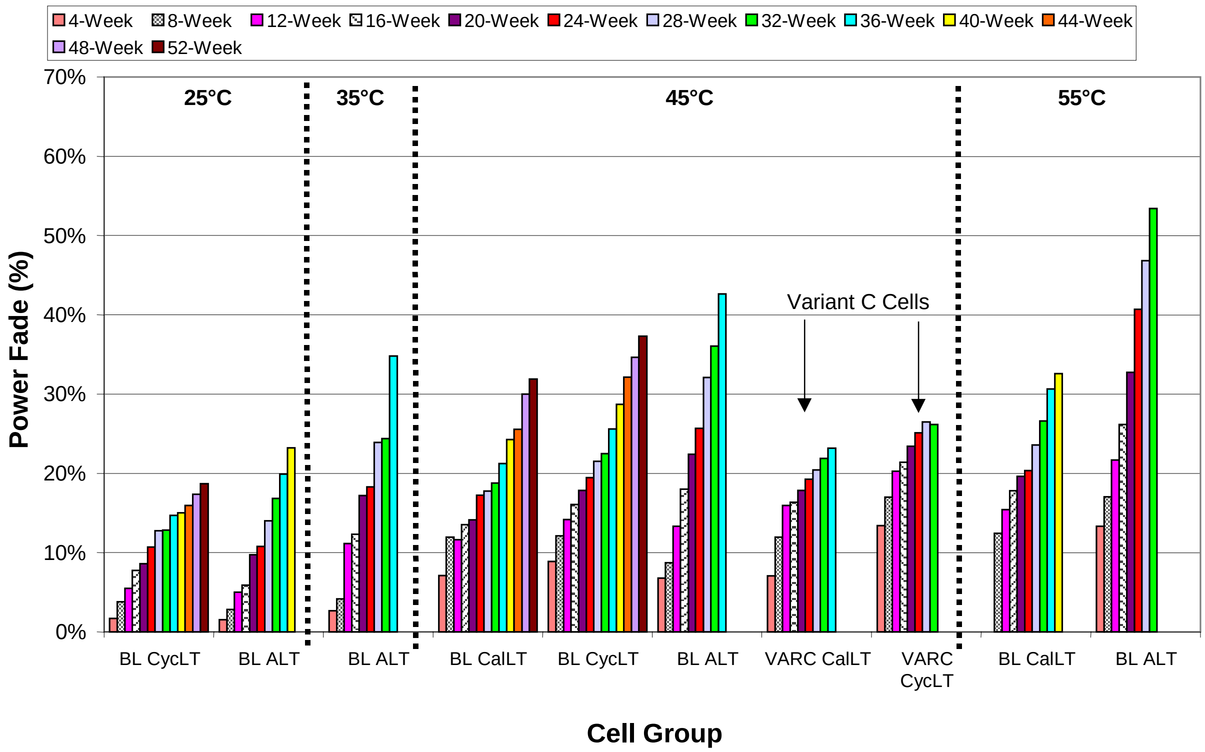

Figure 35. Average power fade for each 60% SOC cell group.

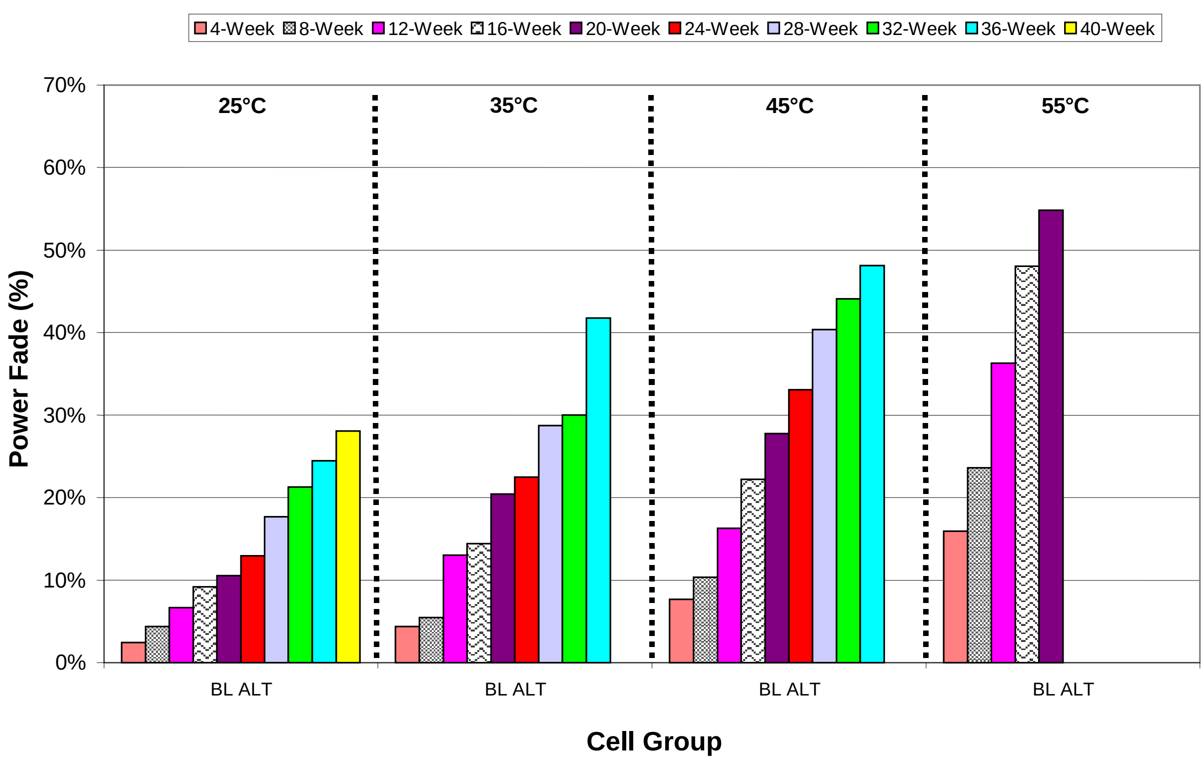

Figure 36. Average power fade for each 80% SOC cell group.

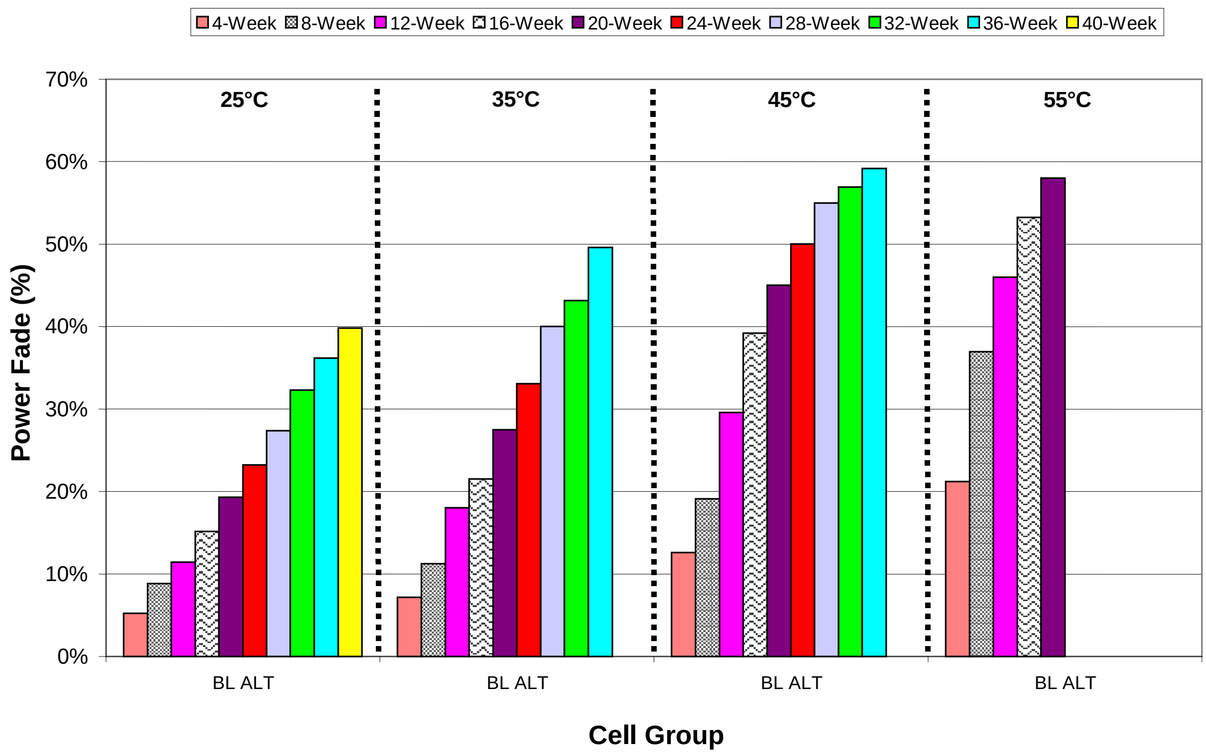

Figure 37. Average power fade for each 100% SOC cell group.

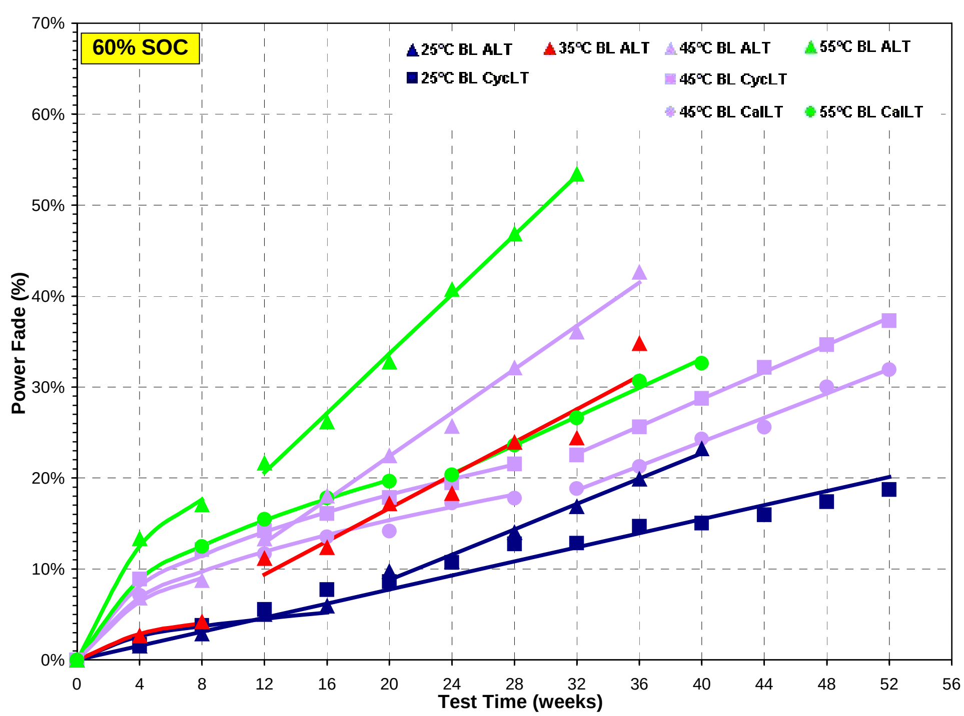

Figure 38. Average power fade as a function of test time for the 60% SOC Baseline cells.

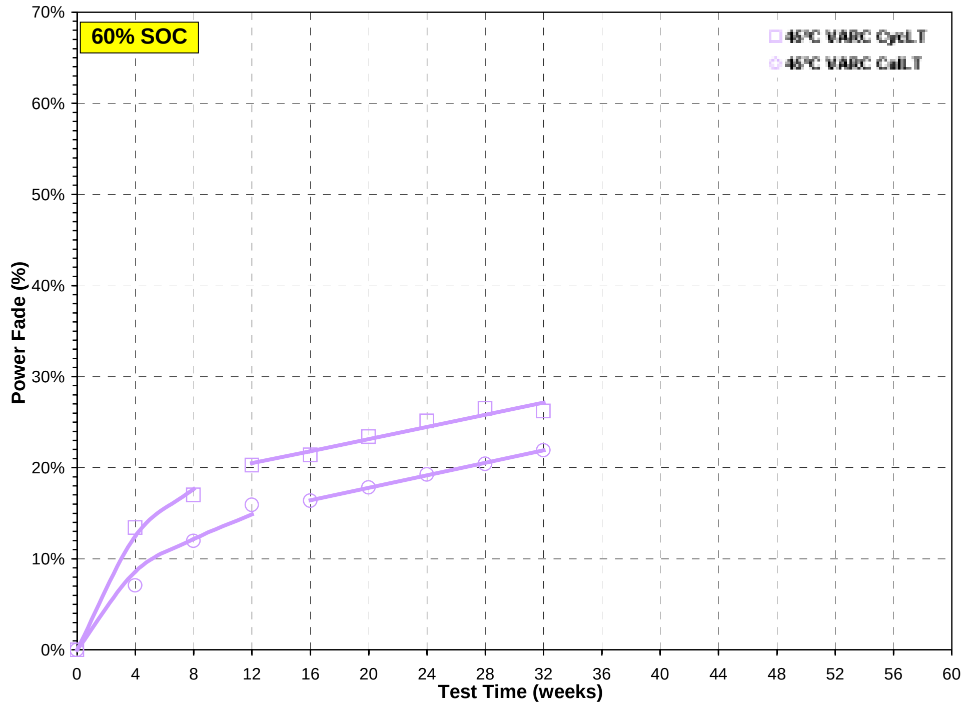

Figure 39. Average power fade as a function of test time for the 60% SOC Variant C cells.

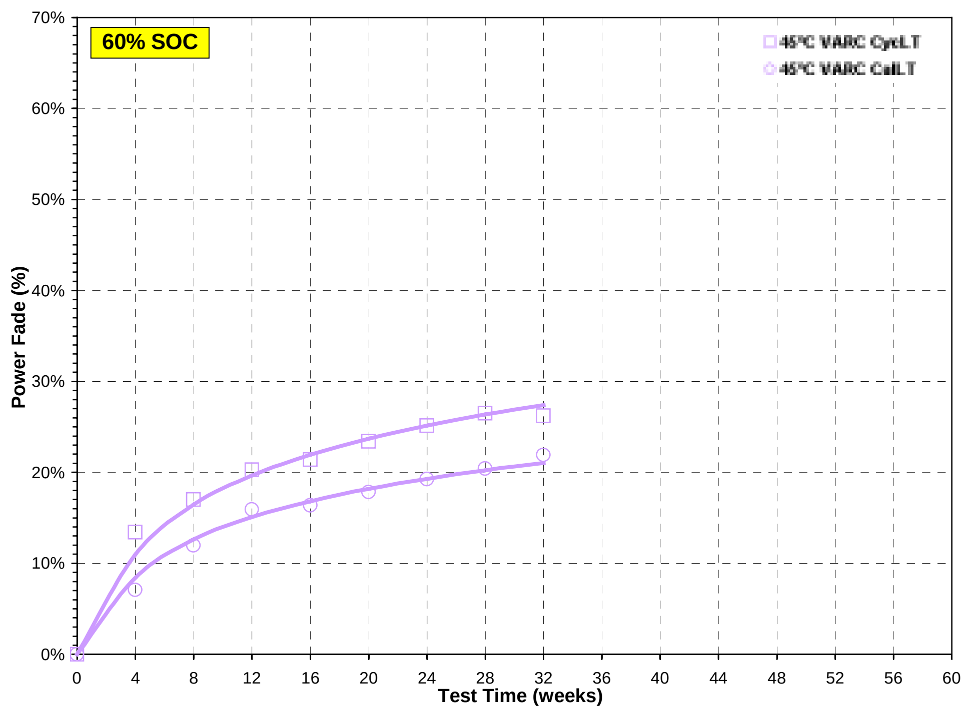

Figure 40. Average power fade as a function of the natural log of time for the 60% SOC Variant C cells.

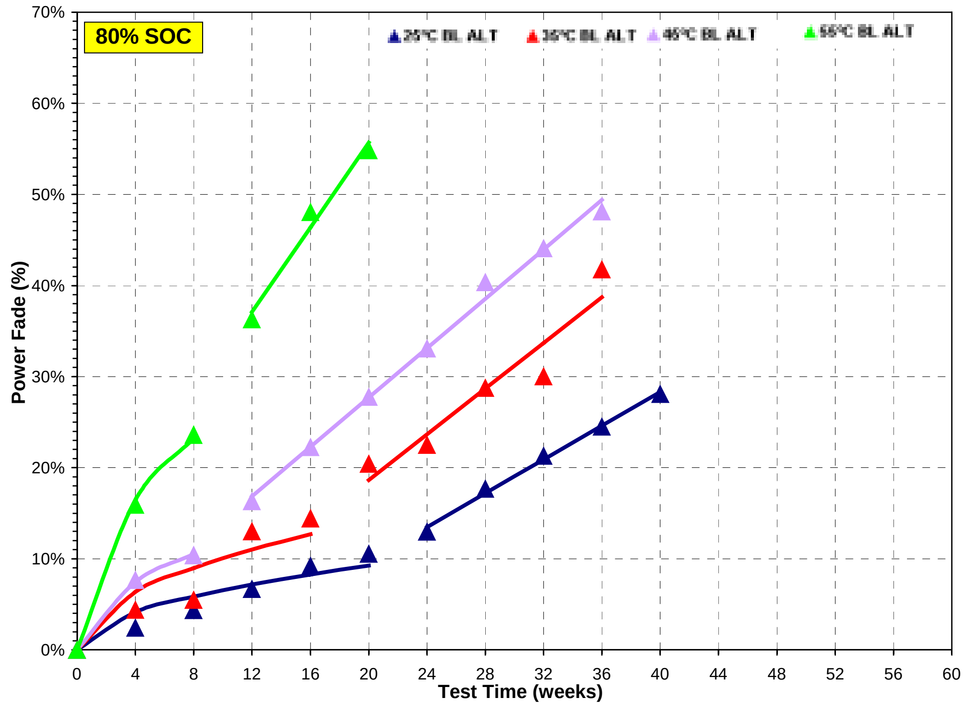

Figure 41. Average power fade as a function of test time for the 80% SOC Baseline cells.

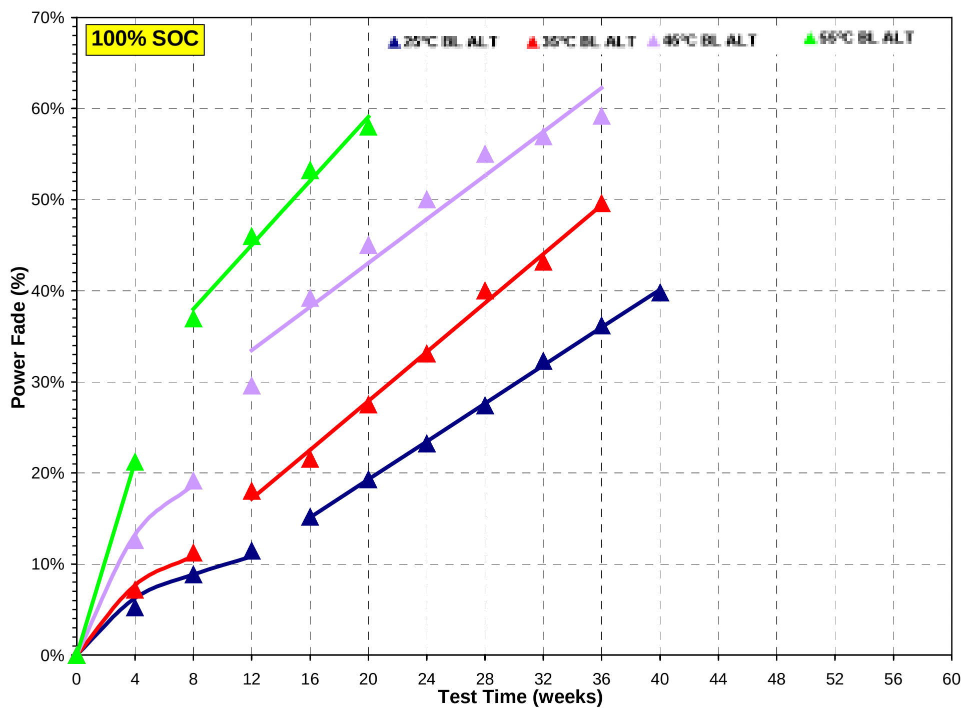

Figure 42. Average power fade as a function of test time for the 100% SOC Baseline cells.

4.3 Electrochemical Impedance Spectroscopy

4.3.1 Nyquist Plots

Figure 43 (page 44) shows the 60% SOC EIS Nyquist plot at each RPT increment from BOL to 52 weeks for G2.60C45.A217.50.52.35.G.T, a representative 45°C calendar-life Baseline cell. Figure 44 shows the 60% SOC EIS Nyquist plot for G2.60L45.I130.50.52.39.G.T, a representative 45°C cycle-life Baseline cell. Data in Figure 44 are only plotted over a frequency range of 2.5 kHz to 0.01 Hz to better show the changes in the semicircle trough frequency (the lowest point on the Nyquist curve) as a function of test time. Both figures show the steady and monotonic increase in impedance through 52 weeks of aging. As seen with capacity and power, the cycle-life impedance grows more rapidly than the calendar-life cells.

Figure 45 shows the 60% SOC EIS Nyquist plot at each RPT increment from BOL to 32 weeks for G2C.60C45.A226.25.32.22.G.T, a representative 45°C calendar-life Variant C cell. Figure 46 shows the EIS impedance for G2C.60L45.I162.30.32.26.G.T, a representative Variant C cycle-life cell. The Variant C cells also show a steady and monotonic growth through 32 weeks of aging. The Variant C cell impedance initially grows more rapidly than the Baseline cell impedance but has since slowed down. The 32-week calendar- and cycle-life Variant C cells showing similar impedances to their respective Baseline cells at 52 weeks.

4.3.2 EIS Modeling

The EIS data can be modeled using four parallel RC networks connected in series. Figure 47 shows the outputs of each individual RC network, resulting in four distinct curves, for G2.60L45.I130.50.52.39. G.T, a representative 45°C cycle-life cell at 52 weeks. Progressing from left to right, the first curve represents the high frequency capacitive tail (resulting from the 4-terminal connection), which is an artifact arising from apparatus contributions. The anode and cathode primarily influence the first and second semicircles, respectively (Reference 5). The leftmost curve is the Warburg impedance, which may represent a resistance caused by the diffusion of ions. The ideal method of measuring cell degradation is to track the growth of the two semicircles as a function of time. However, as shown in Figures 43 through 46, they are poorly resolved due to the influence of the high-frequency capacitive tail and the low-frequency Warburg impedance. Although they become progressively more distinct as the cells age, an alternative approach for measuring cell degradation needs to be identified.

4.3.2.1 Frequency Bands

The EIS results can be divided into three different frequency bands (high-, mid- and low-frequency). The break point between the mid- and low-frequency bands is clearly located at the trough frequency. The transition from the high- to mid-frequency band is more difficult to identify, since the capacitive tail highly influences the first and second semicircles. This transition was found by calculating the maximum rate of change of the slope of the EIS curve (i.e., where the third derivative equals zero) over a specified frequency range. The cycle-life cells were curve-fitted to a 4^{th} order polynomial fit over a frequency range of 1000 to 100 Hz. The calendar-life cells were curve fitted over a frequency range of 10,000 to 200 Hz. Figure 48 shows the curve-fit for G2.60L45.I130.50.52.39.G.T, a representative 45°C cycle-life cell, and G2.60C45.A217.50.52.35.G.T, a representative 45°C calendar-life cell, at 52 weeks.

Figures 49 and 50 show the resulting average delta impedance magnitudes at each frequency band at each RPT through 52 weeks of Baseline cell cycle-life testing at 25°C and 45°C, respectively. The delta impedance magnitude at the mid-frequency band was found by subtracting the magnitude at the trough by the magnitude of the high-frequency band, as calculated above. The low-frequency delta magnitude was found by subtracting the magnitude at 50 mHz by the initial average trough frequency (2.5 Hz). The mid-frequency band clearly shows the highest delta impedance growth with 152.2 and 370.6% growth from BOL for the 25 and 45°C cycle-life cells, respectively.

Figures 51 and 52 show the average delta impedance magnitudes at each frequency band for the calendar-life 45 and 55°C Baseline cells. The low-frequency band for the calendar-life cells was found by subtracting the magnitude at 50 mHz by the initial average trough frequency of 4.0 and 3.0 Hz for the 45 and 55°C Baseline cells, respectively. The calendar-life cells also show that the mid-frequency band shows the most growth, with 162.3 and 232.0% growth for the 45 and 55°C Baseline cells, respectively.

Figures 53 and 54 show the average delta impedance magnitudes for the 45°C Variant C calendar- and cycle-life cells, respectively. The low-frequency band was found by subtracting the magnitude at 50 mHz by the initial average trough frequency of 2.5 and 2.0 Hz for the calendar- and cycle-life cells, respectively. The mid-frequency bands show 112.6 and 169.4% growth from BOL for the calendar- and cycle-life cells, respectively.

Figure 55 shows the average EIS delta magnitude growth of the mid-frequency region as a function of test time for the 45 and 55°C Baseline and 45°C Variant C calendar-life cells. The Baseline cells show a mechanistic change with an initial square root of time dependence followed by a linear dependence. As expected, the growth rate increases once the second mechanism takes effect. The Variant C cells show a square root of time dependence with no apparent mechanistic changes. These cells show a greater magnitude growth than the 45°C Baseline cells through 32 weeks, but the 45°C Baseline cells show a greater growth rate. The mechanism breakpoints and R^2 fits for the calendar-life cells are summarized in Table 19.

Table 19. Calendar-life cell mid-frequency growth test time dependence.

Temperature (°C)	Chemistry	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Baseline	0 to 20 weeks	0.995	24 to 52 weeks	0.981
	Variant C	0 to 32 weeks	0.969	-	-
55	Baseline	0 to 16 weeks	0.995	20 to 40 weeks	0.972

Figure 56 shows the average EIS delta magnitude growth of the mid-frequency region as a function of test time for the 25 and 45°C Baseline and 45°C Variant C cycle-life cells. The 25°C Baseline cycle-life cells show a linear time dependence, with no apparent mechanistic change, as seen with the power fade (Figure 38). The 45°C Baseline cycle-life cells show a mechanistic change between 28 and 32 weeks with an initial square root of time dependence followed by a linear time dependence. As expected, when the second mechanism dominates, the growth rate increases. The 45°C Variant C cells show a square root of time dependence with no apparent mechanistic changes. Unlike the calendar-life Variant C cells, the growth of the cycle-life Variant C cells are similar to the 45°C Baseline cells. The mechanism breakpoints and R^2 fits for the cycle-life cells are summarized in Table 20.

Table 20. Cycle-life cell mid-frequency growth test time dependence.

Temperature (°C)	Chemistry	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Baseline	-	-	0 to 52 weeks	0.967
45	Baseline	0 to 28 weeks	0.986	32 to 52 weeks	0.986
	Variant C	0 to 32 weeks	0.986	-	-

Figure 57 shows the impedance growth rate for the Variant C calendar- and cycle-life cells as a function of the natural log of time. As seen with the square root of time dependence, a natural log of time fit does not show a mechanistic change. The R^2 fits for the calendar- and cycle-life cells are 0.946 and 0.976, respectively.

4.3.2.2 Time Dependence

Figure 58 shows the average EIS magnitude growth at the semicircle trough for each cell group at 60% SOC for the cycle- and calendar-life cells. As seen with the capacity and power fade results (Figures 4, 15, and 35), the EIS growth increases as a function of increasing test temperature for both the Baseline and Variant C cells. The calendar-life cells show smaller EIS growth than the cycle-life cells.

Figure 59 shows the average EIS growth as a function of test time at 60% SOC for the Baseline calendar- and cycle-life cells. As seen with the power fade (Figure 38), the 25°C cycle-life Baseline cells show a linear time dependence with no apparent mechanistic change. The 45 and 55°C cell groups show mechanistic changes with an initial square root of time dependence followed by a linear time dependence. The growth rates also increase once the second mechanism takes effect, and the breakpoints occur earlier with increasing temperature. The mechanism breakpoints and R^2 fits for the Baseline cells are summarized in Table 21.

Table 21. Baseline cell EIS growth test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{½}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
25	Cycle-Life	-	-	0 to 52 weeks	0.994
45	Calendar-Life	0 to 28 weeks	0.984	32 to 52 weeks	0.977
	Cycle-Life	0 to 28 weeks	0.994	32 to 52 weeks	0.979
55	Calendar-Life	0 to 16 weeks	0.968	20 to 40 weeks	0.975

Figure 60 shows the average EIS growth as a function of the square root of test time at 60% SOC for the 45°C calendar- and cycle-life Variant C cells. These cell groups show a mechanistic change with a linear time dependence after the breakpoint. The Variant C cell groups show a higher average EIS growth than the Baseline cell groups at 45°C, but the growth rates are smaller. Unlike the power fade results (Figure 39), the calendar-life Variant C cells show a slightly higher EIS growth than the cycle-life cells. The mechanism breakpoints and R^2 fits for the Variant C cells are summarized in Table 22.

Table 22. Variant C EIS growth test time dependence for the 60% SOC cell groups.

Temperature (°C)	Test	$t^{1/2}$-Mechanism		t-Mechanism	
		Test Time	R^2 fit	Test Time	R^2 fit
45	Calendar-Life	0 to 16 weeks	0.952	20 to 32 weeks	0.983
	Cycle-Life	0 to 8 weeks	0.999	12 to 32 weeks	0.964

Figure 61 shows the average Variant C EIS growth as a function of the natural log of time. The logarithmic fit does not show any mechanistic changes. The R^2 fits for the calendar- and cycle-life cells are 0.906 and 0.976, respectively.

4.3.2.3 Power Fade Dependence

Figure 62 shows the power fade as a function of the EIS magnitude growth at the semicircle trough for the Baseline and Variant C calendar-and cycle-life cells. As shown, the EIS growth tracks linearly with the power fade with the intercept passing through zero. The correlation shows a minor temperature dependence, with the 25°C Baseline cycle-life cells showing the highest slope, and the 55°C Baseline calendar-life cells showing the lowest slope. The correlation also appears to be test independent, with the 45°C Baseline calendar- and cycle-life cells showing virtually identical slopes. The only anomalies to these general trends are the 45°C Variant C calendar-life cells. The correlation shows a lower slope than the 55°C Baseline calendar-life cells. This is primarily attributable to the EIS growth (Figures 60 and 61), which shows slightly greater EIS magnitude growth than the cycle-life cells. (This is opposite to the trends identified with capacity fade, Figures 8 and 9, and power fade, Figures 39 and 40.) This anomaly is still under investigation. The slopes and R^2 fits for the calendar- and cycle-life cells are summarized in Table 23.

Table 23. Power fade as a function of EIS magnitude growth at the trough.

Temperature (°C)	Chemistry	Test	Slope	R^2 fit
25	Baseline	Cycle-Life	0.623	0.977
45	Baseline	Calendar-Life	0.522	0.963
	Baseline	Cycle-Life	0.516	0.959
	Variant C	Calendar-Life	0.404	0.987
	Variant C	Cycle-Life	0.547	0.975
55	Baseline	Calendar-Life	0.448	0.950

4.4 Pulse Resistances

Figure 63 shows the daily discharge and regen pulse resistances for G2.60C45.A217.50.52.35.G.T, a representative 45°C calendar-life Baseline cell. The resistance grows steadily as a function of test time but shows a small drop every 28 days when life testing is interrupted for RPTs. Evidently, the RPTs cause a short-lived decrease in the resistances, which may be a result of "reconditioning" from the static capacity tests. This phenomenon has been observed for other Lithium-ion technologies as well. Figure 64 shows the discharge and regen pulse resistances for G2.60L45.I130.50.52.39.G.T, a representative 45°C cycle-life Baseline cell. Discharge and regen resistances are calculated for the first and last 100 pulses and every pulse in between. The cycle-life cells also show periodicity every 672 hours (4 weeks) when RPTs are performed. As expected, the cycle-life pulse resistance grows a little more rapidly than the calendar-life cells. Figure 65 shows the daily pulse resistances for G2.60A45.S438.NA.36.43.G.T, a representative 45°C accelerated-life cell. Also as expected, the accelerated-life cells show the fastest growth in pulse resistance.

Figure 66 shows the daily discharge and regen pulse resistance for G2C.60C45.A226.25.32.22.G.T, a representative 45°C calendar-life Variant C cell. Figure 67 shows the discharge and regen pulse resistances for G2C.60L45.I162.30.32.26.G.T, a representative 45°C cycle-life Variant C cell. The Variant C cell pulse resistances are higher than the Baseline cells (Figures 62 and 63), but the rate of resistance increase is obviously less than the 45°C Baseline cells.

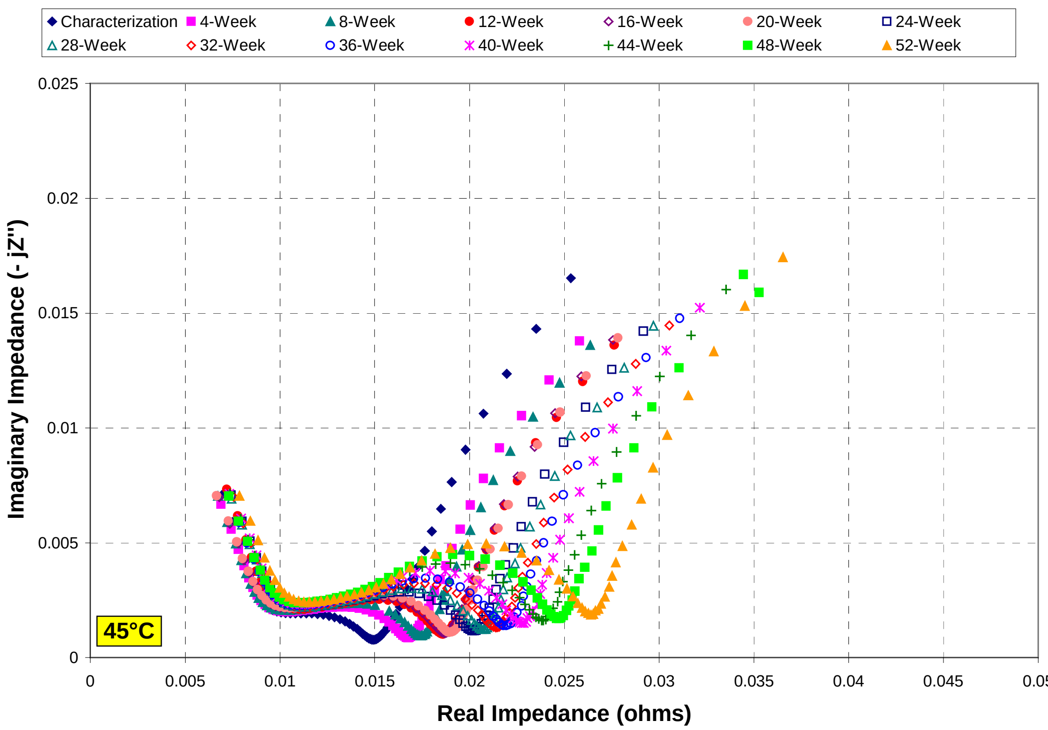

Figure 43. EIS Nyquist plot for G2.60C45.A217.50.52.35.G.T (45°C calendar-life Baseline cell).

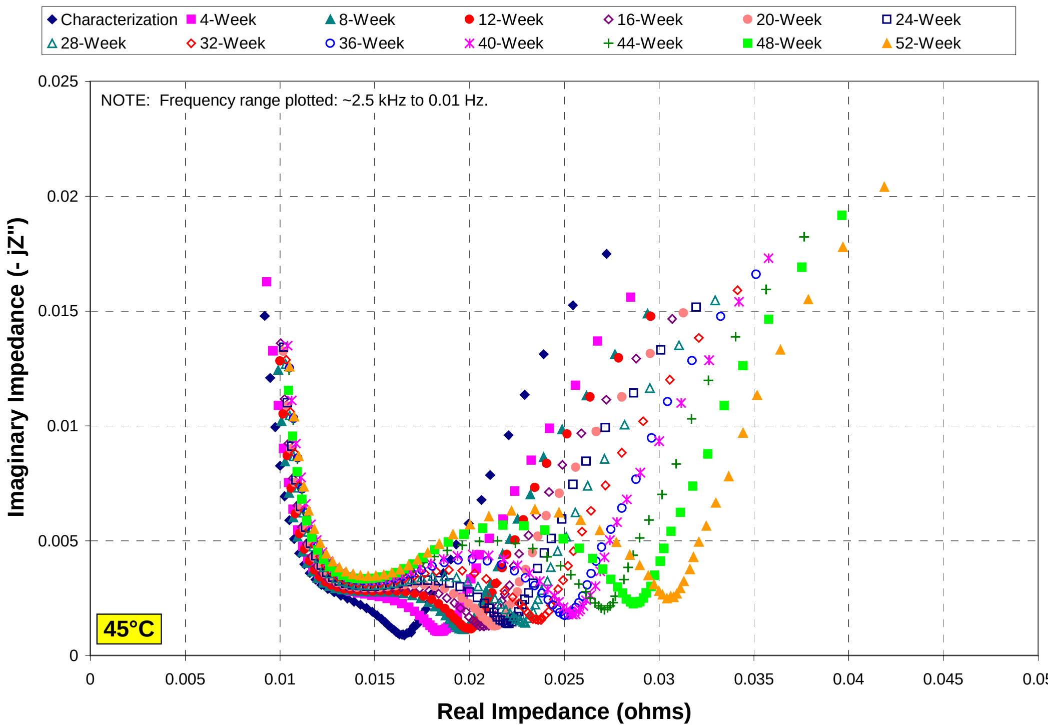

Figure 44. EIS Nyquist plot for G2.60L45.I130.50.52.39.G.T (45°C cycle-life Baseline cell).

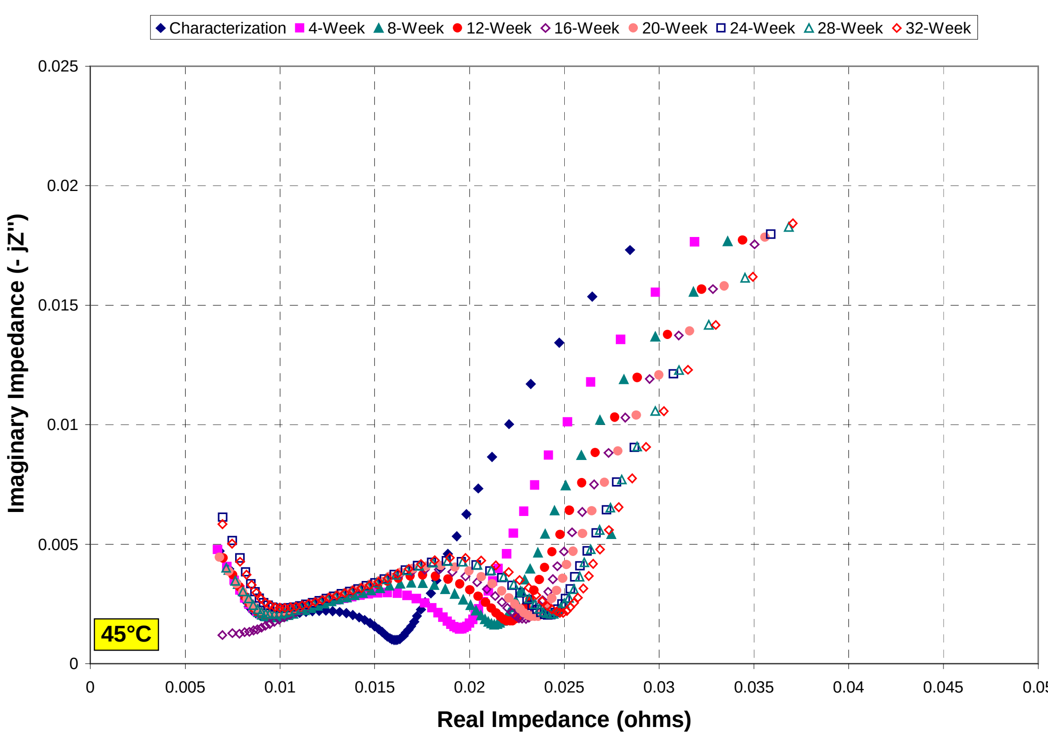

Figure 45. EIS Nyquist plot for G2C.60C45.A226.25.32.22.G.T (45°C calendar-life Variant C cell).

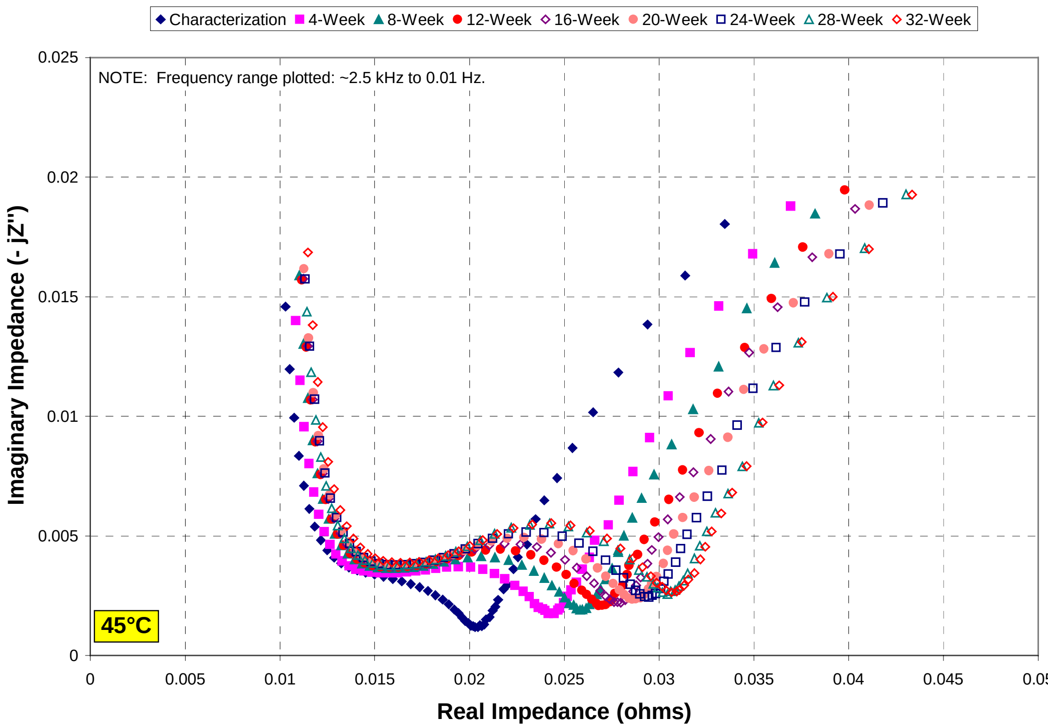

Figure 46. EIS Nyquist plot for G2C.60L45.I162.30.32.26.G.T (45°C cycle-life Variant C cell).

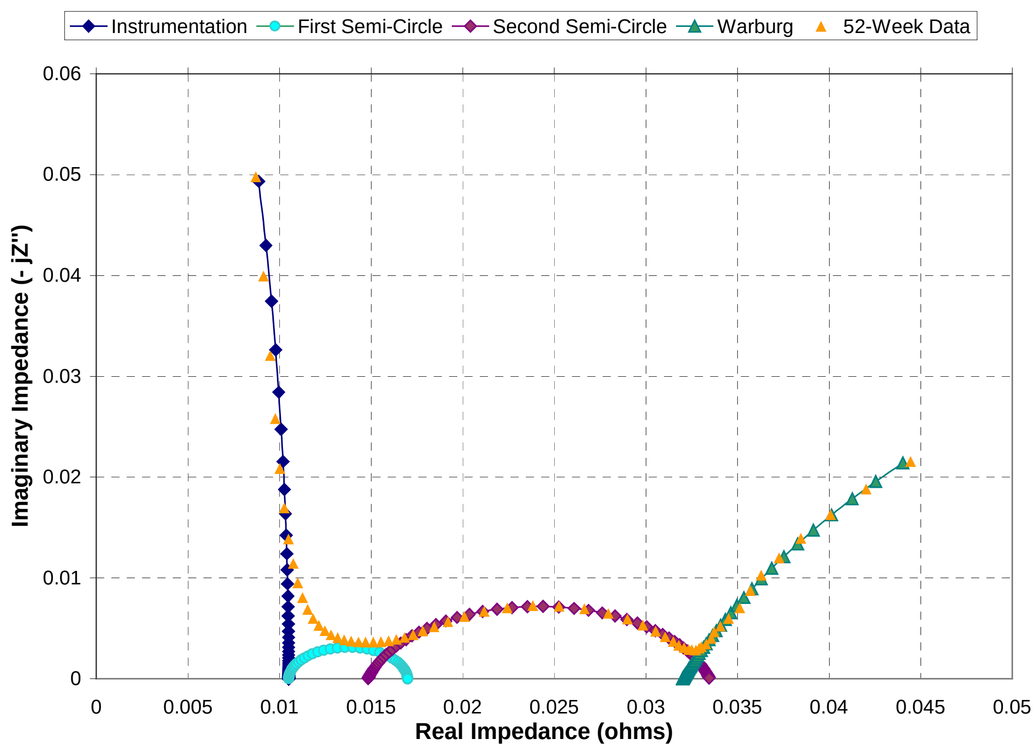

Figure 47. Nyquist plot for G2.60L45.I130.50.52.39.G.T
(45°C cycle-life Baseline cell) with the RC network model.

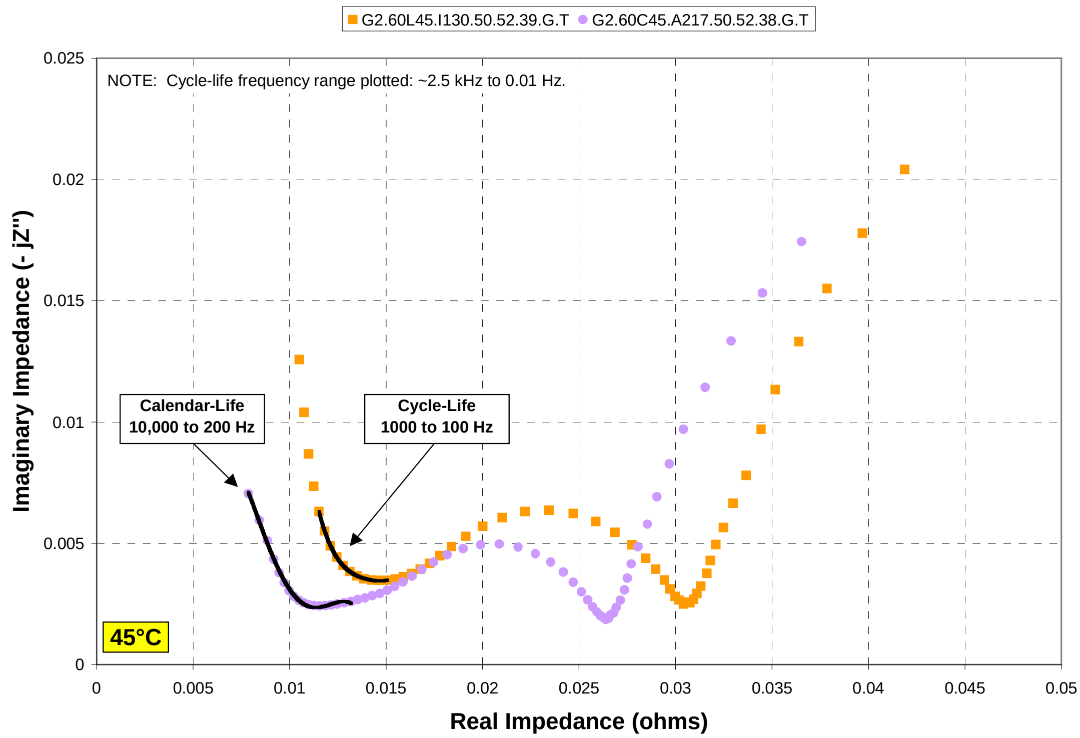

Figure 48. Fourth-order polynomial fit to identify the high- to mid-frequency band transition.

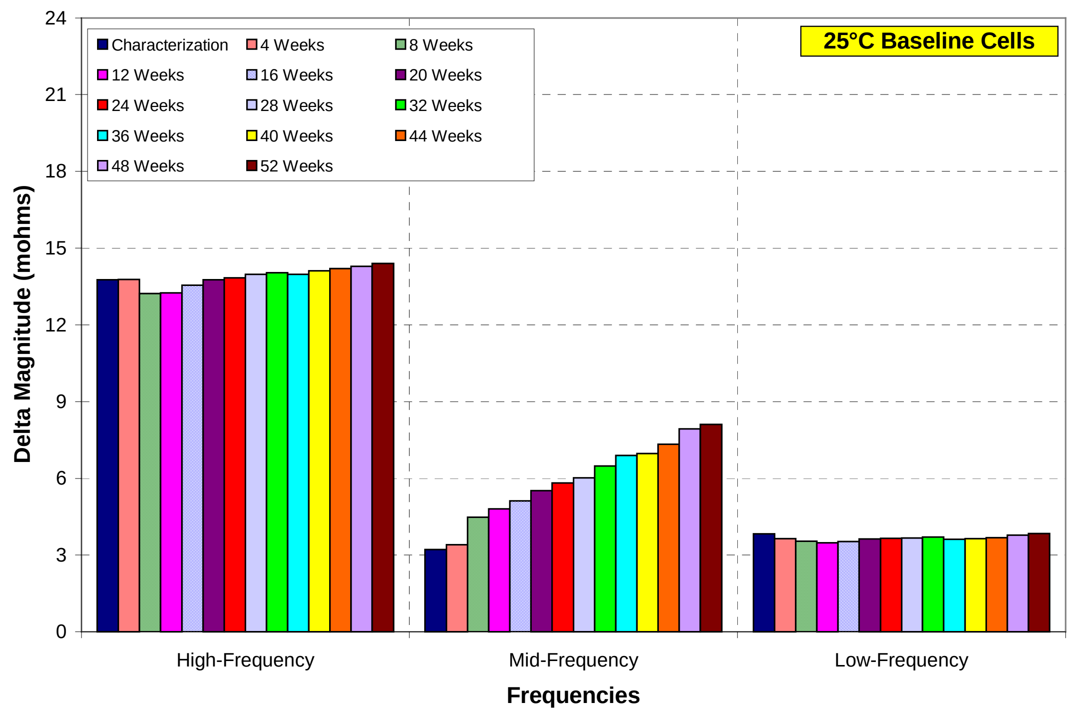

Figure 49. EIS frequency bands for the 25°C cycle-life Baseline cells.

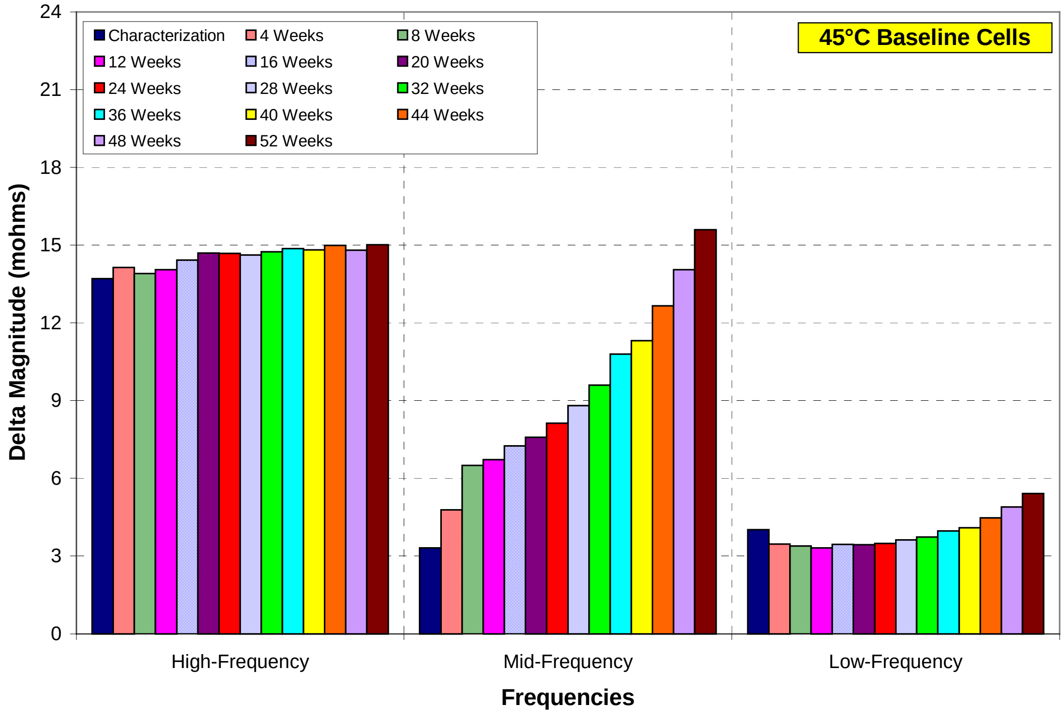

Figure 50. EIS frequency bands for the 45°C cycle-life Baseline cells.

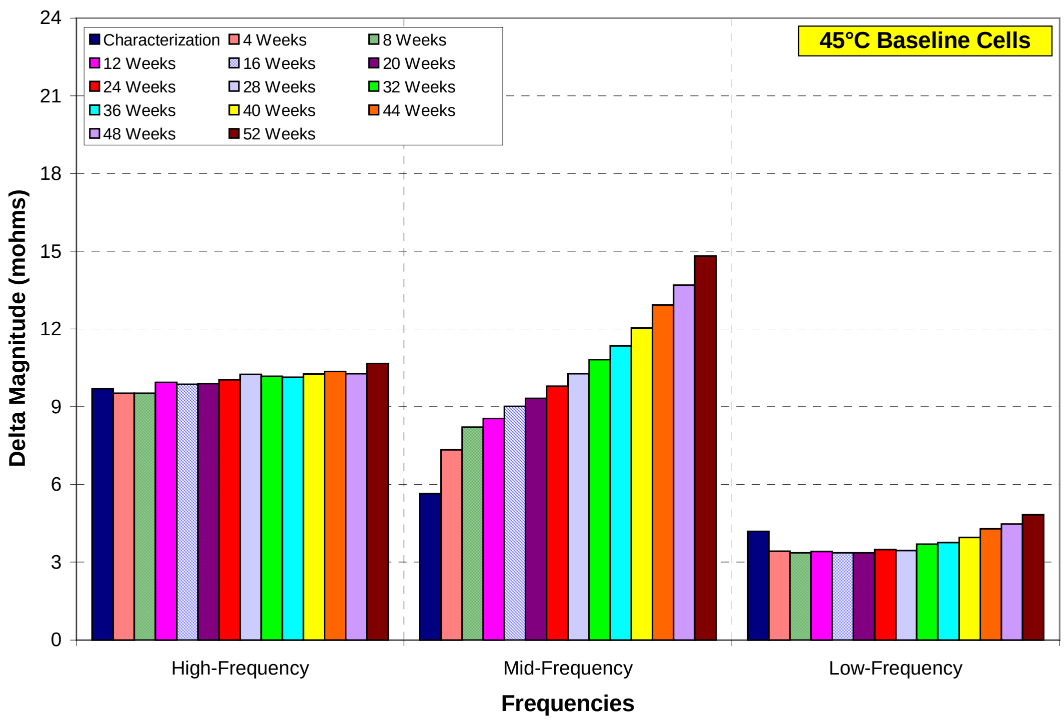

Figure 51. EIS frequency bands for the 45°C calendar-life Baseline cells.

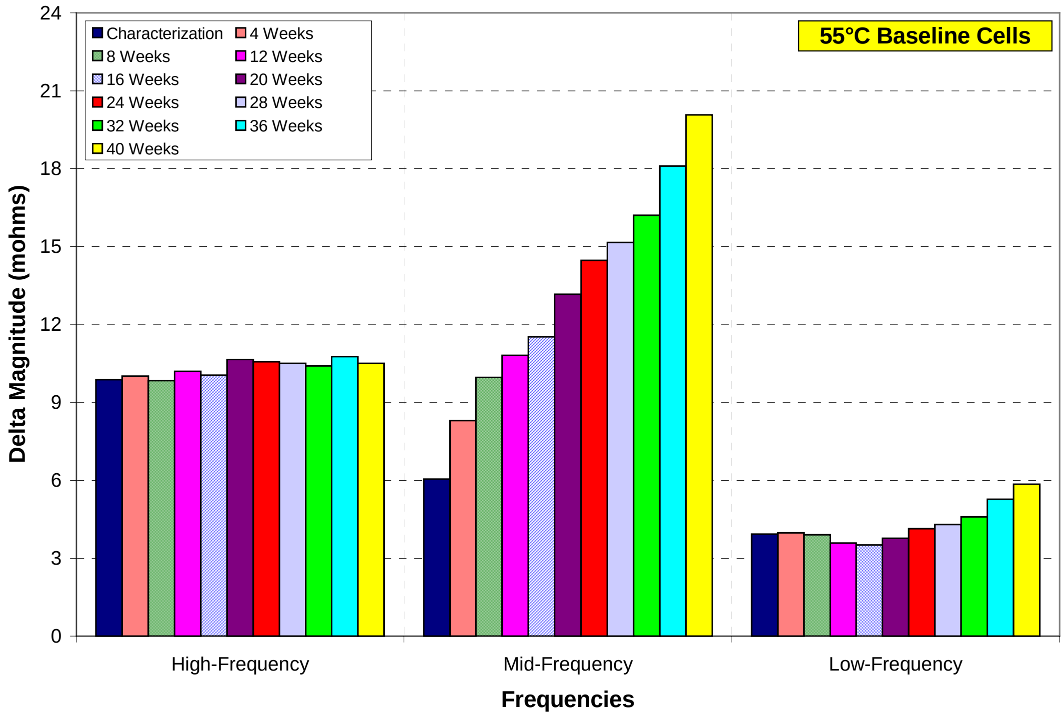

Figure 52. EIS frequency bands for the 55°C calendar-life Baseline cells.

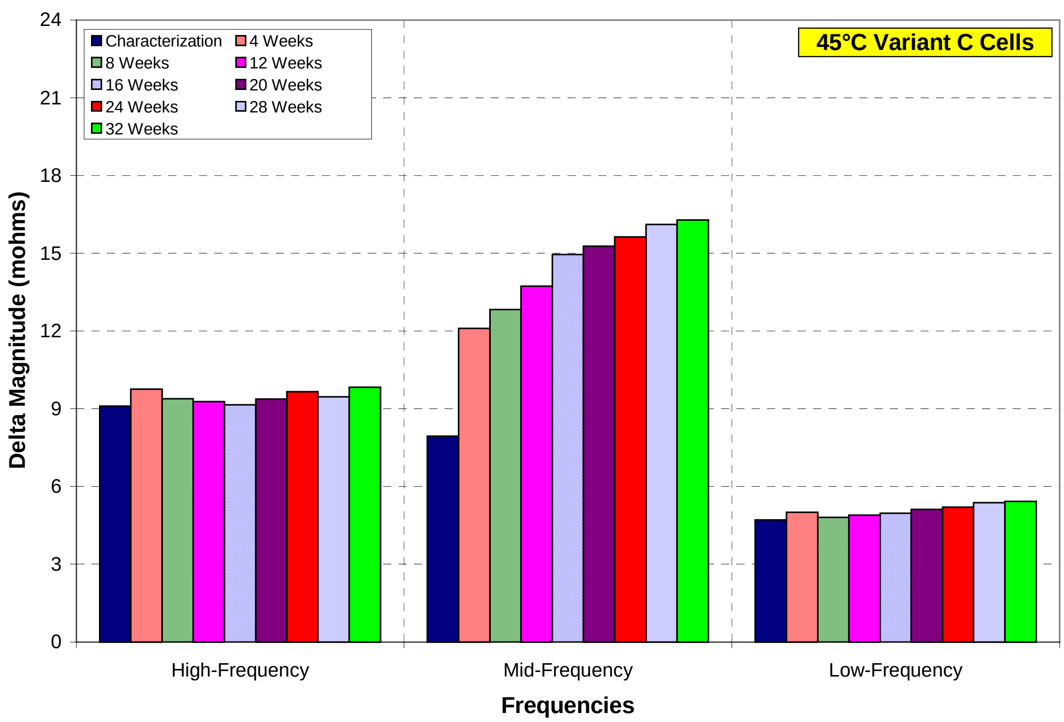

Figure 53. EIS frequency bands for the 45°C calendar-life Variant C cells.

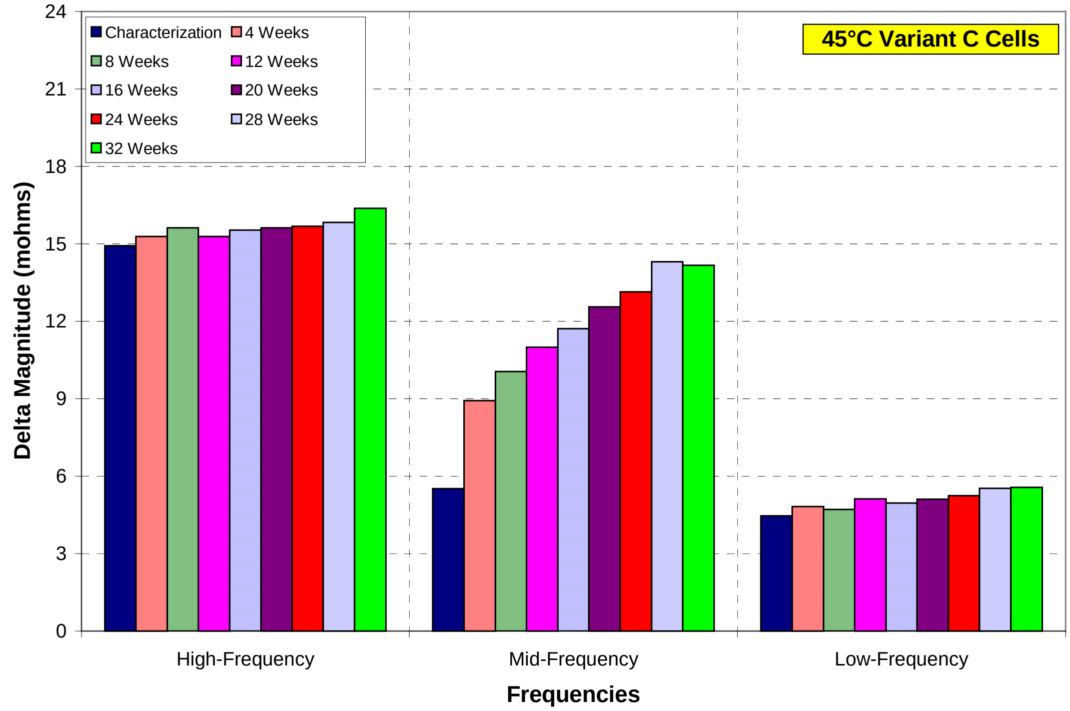

Figure 54. EIS frequency bands for the 45°C cycle-life Variant C cells.

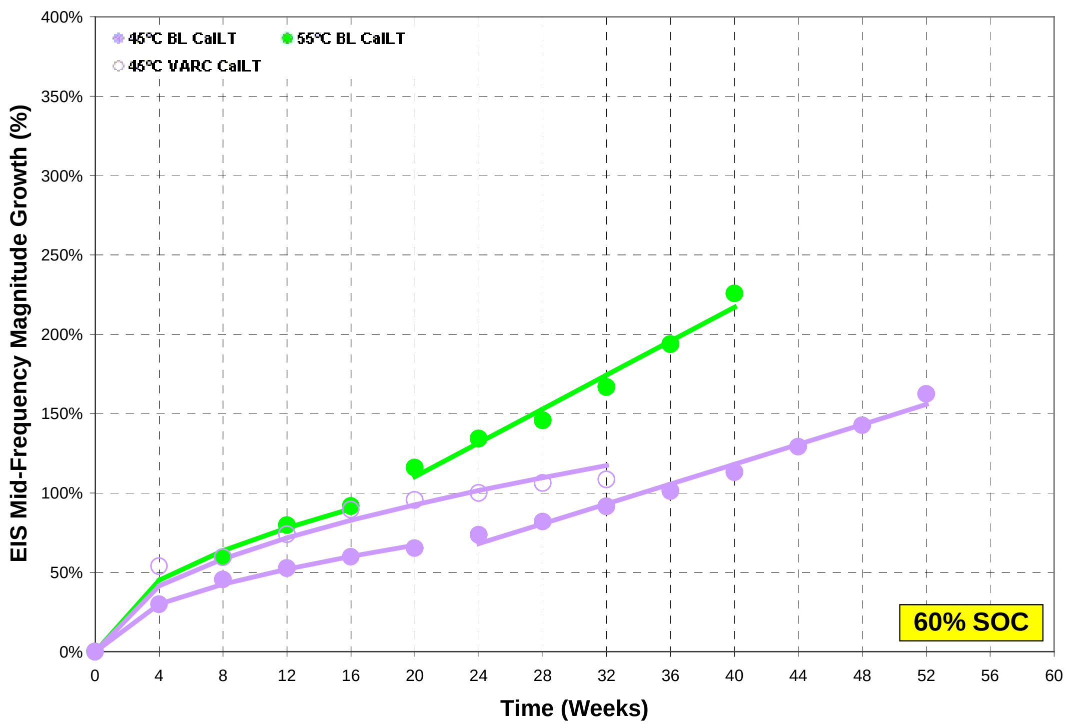

Figure 55. EIS delta magnitude growth of the mid-frequency region for the calendar-life cells.

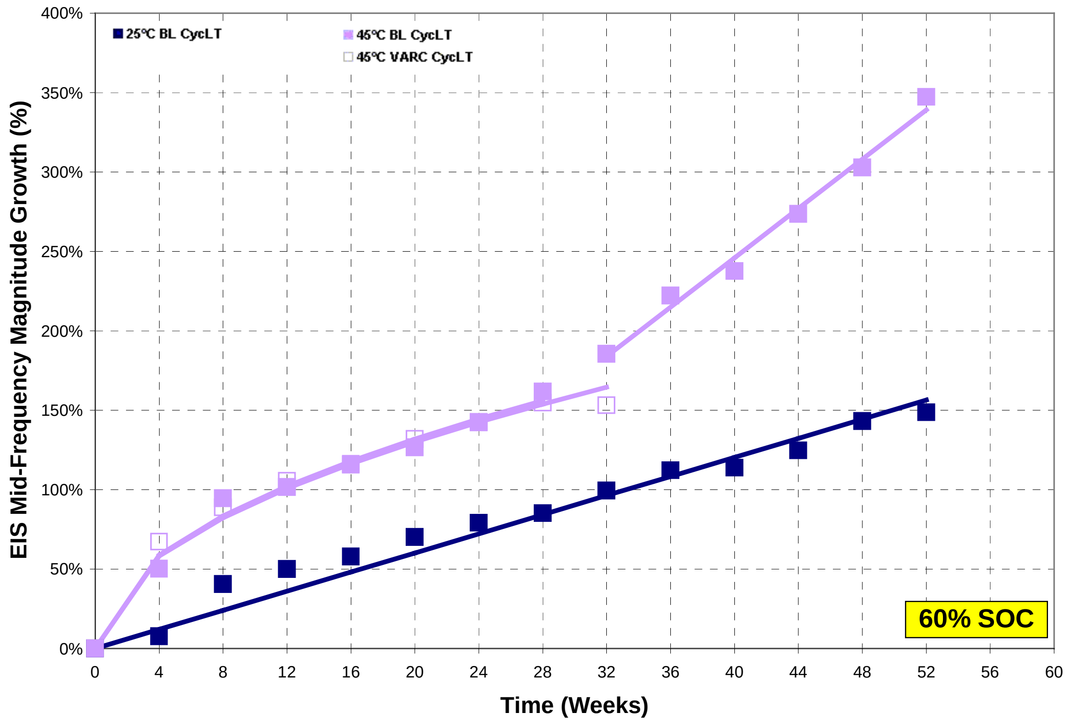

Figure 56. EIS delta magnitude growth of the mid-frequency region for the cycle-life cells.

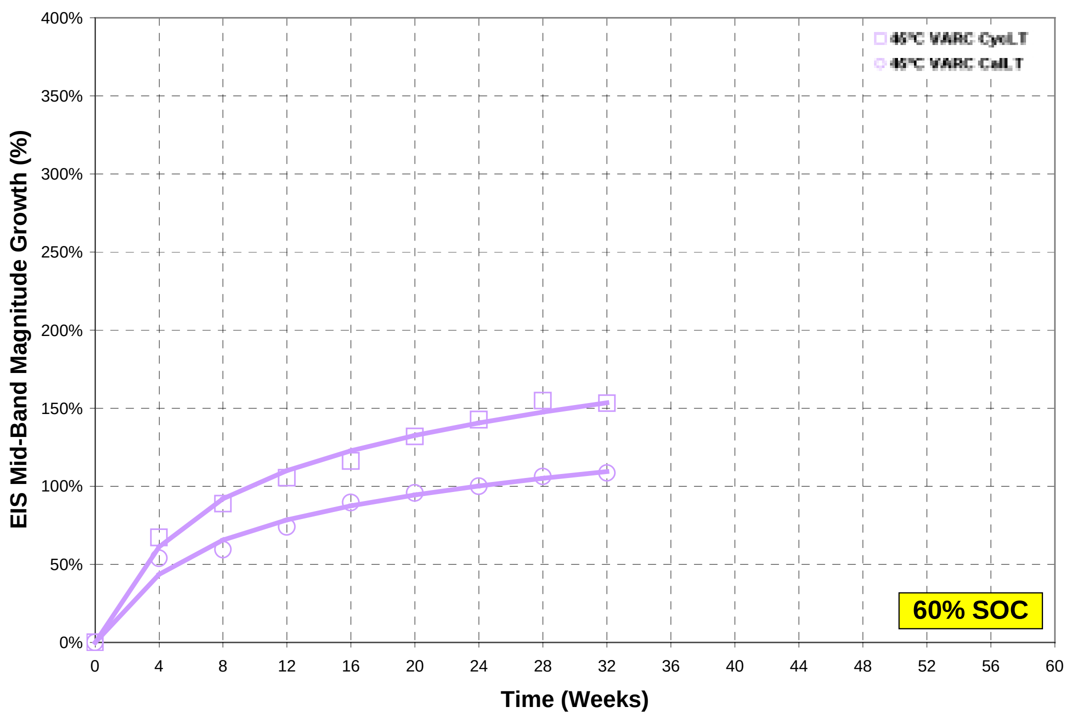

Figure 57. Variant C EIS delta magnitude growth with a natural log of time dependence.

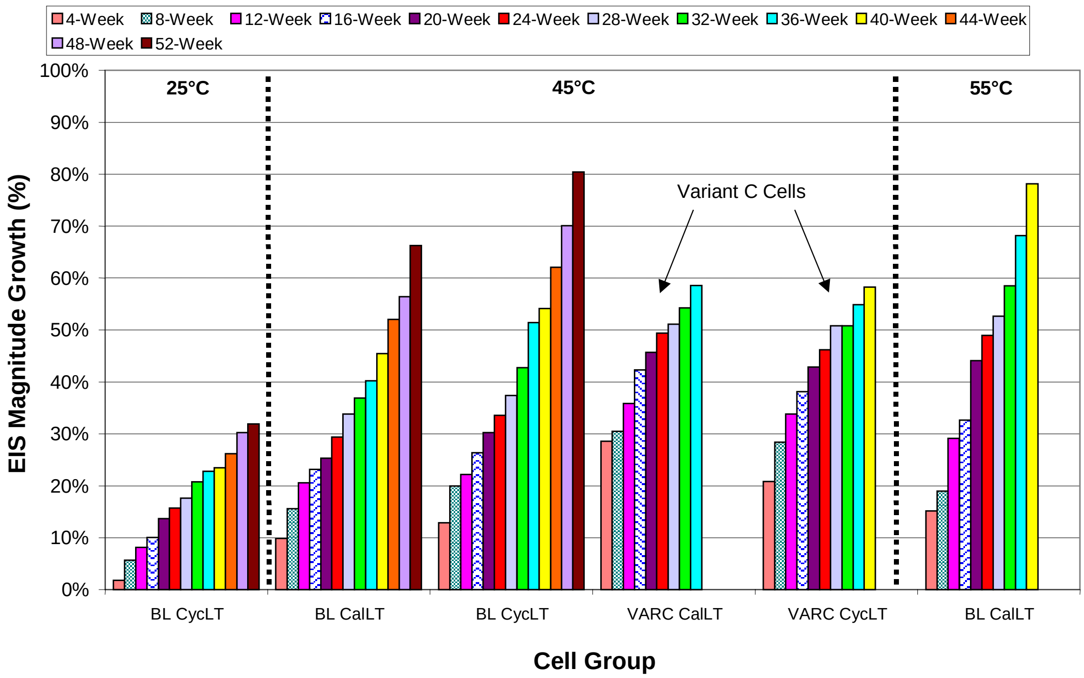

Figure 58. Average EIS magnitude growth at the semicircle trough for the 60% SOC calendar- and cycle-life Baseline and Variant C cells.

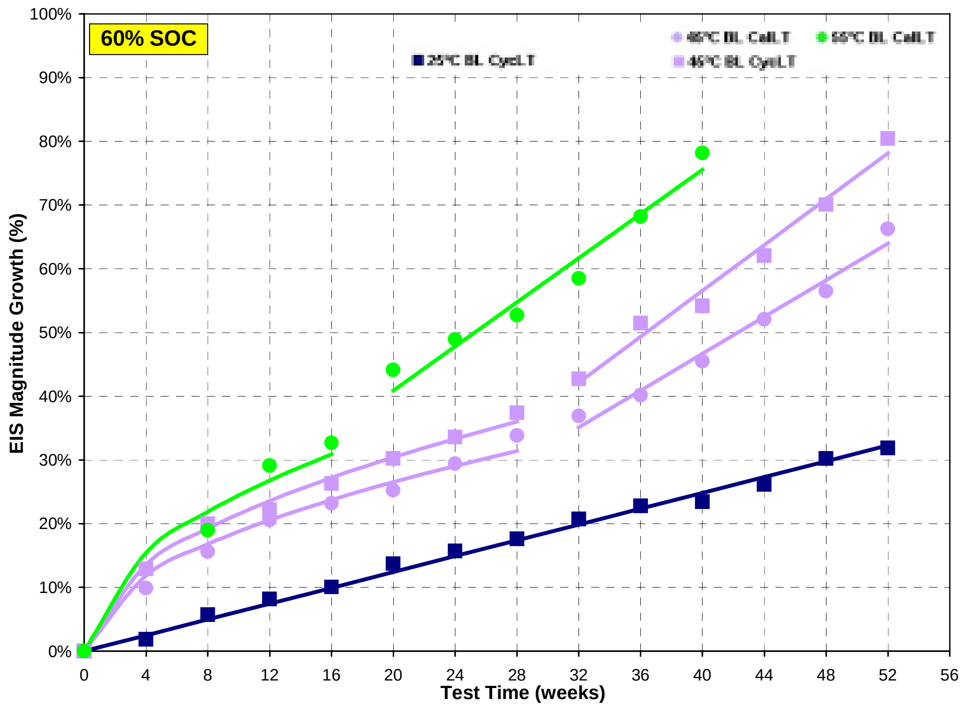

Figure 59. Average EIS magnitude growth at the semicircle trough as a function of test time for the 60% SOC calendar- and cycle-life Baseline cells.

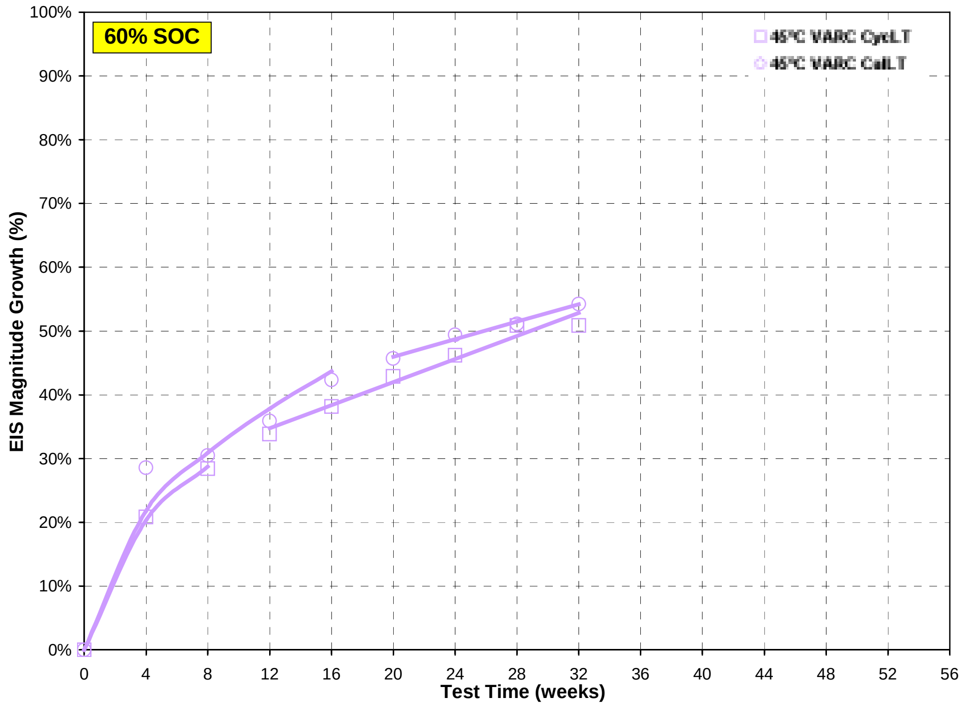

Figure 60. Average EIS magnitude growth at the semicircle trough as a function of test time for the 60% SOC calendar- and cycle-life Variant C cells.

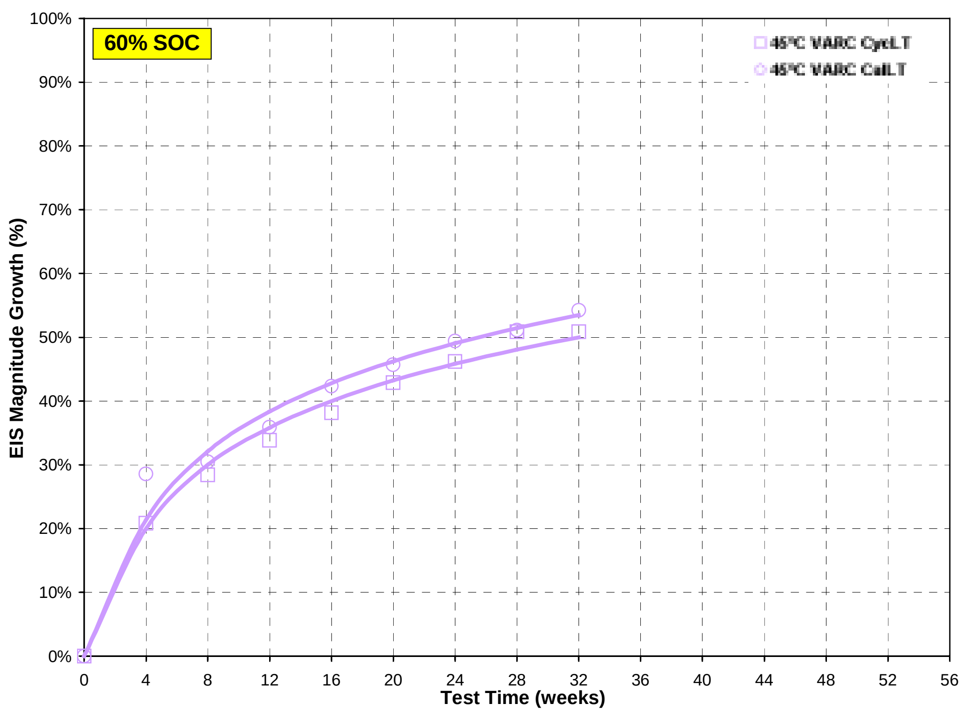

Figure 61. Average EIS magnitude growth at the semicircle trough as a function of the natural log of time for the 60% SOC calendar- and cycle-life Variant C cells.

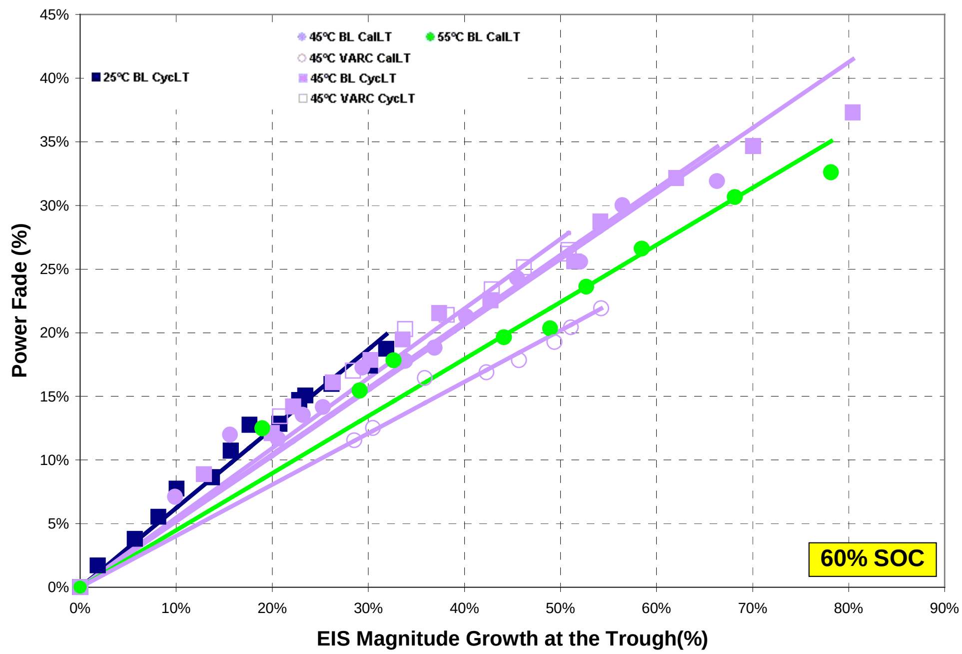

Figure 62. Power fade as a function of EIS magnitude growth at the semicircle trough for the Baseline and Variant C calendar- and cycle-life cells.

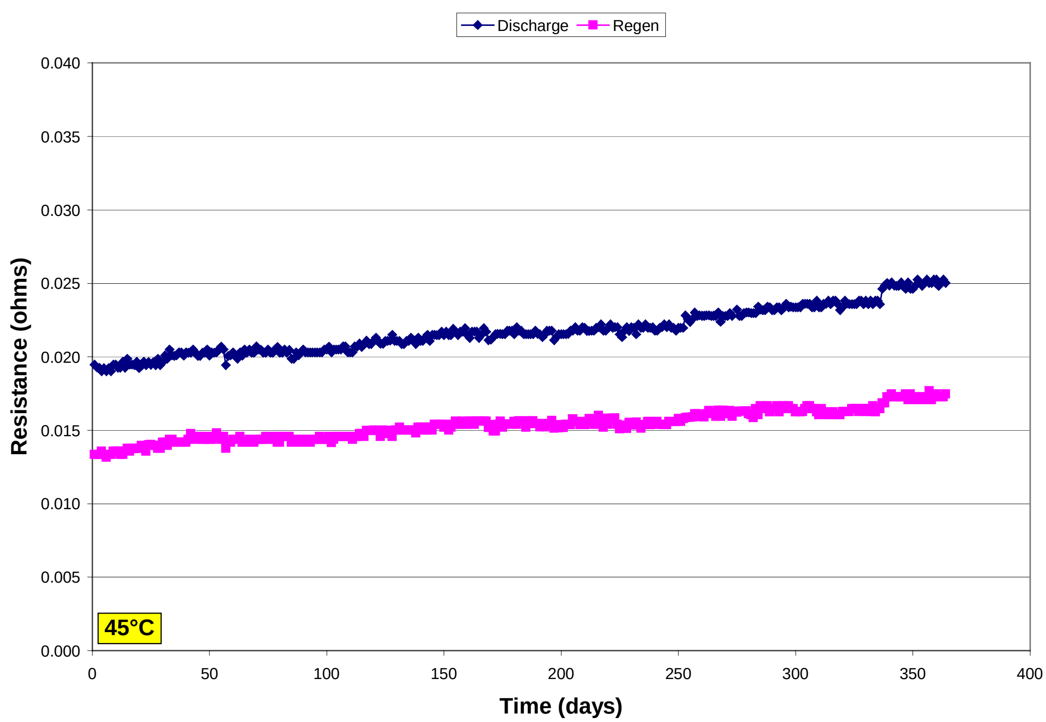

Figure 63. Discharge and regen pulse resistances for G2.60C45.A217.50.52.35.G.T (45°C calendar-life Baseline cell).

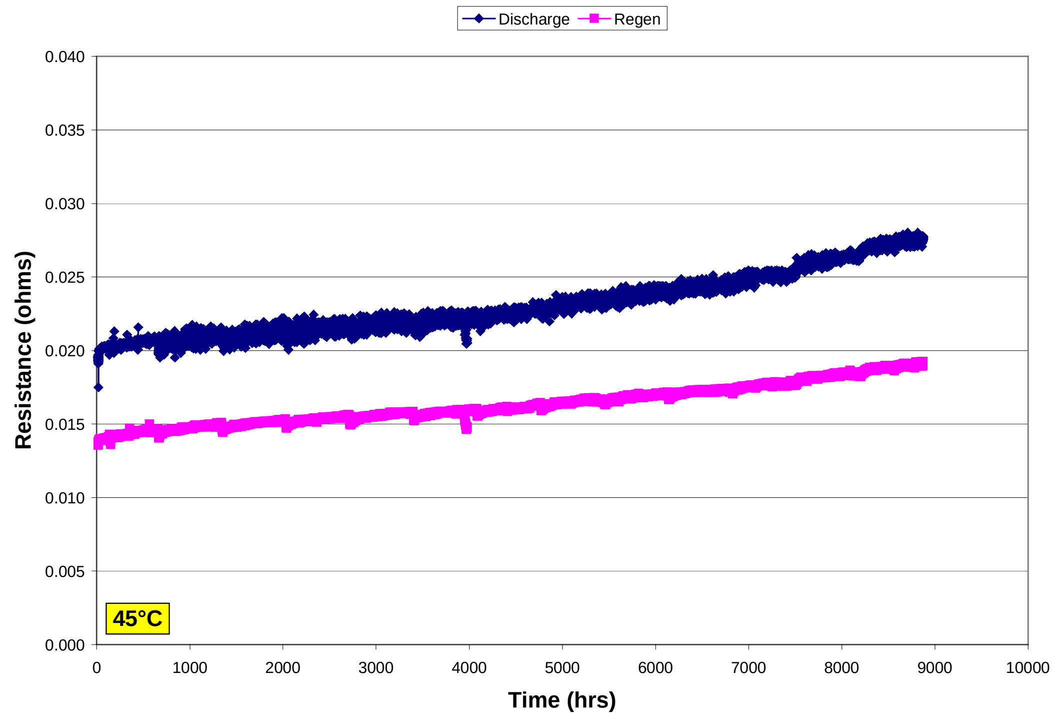

Figure 64. Discharge and regen pulse resistances for G2.60L45.I130.50.52.39.G.T (45°C cycle-life Baseline cell).

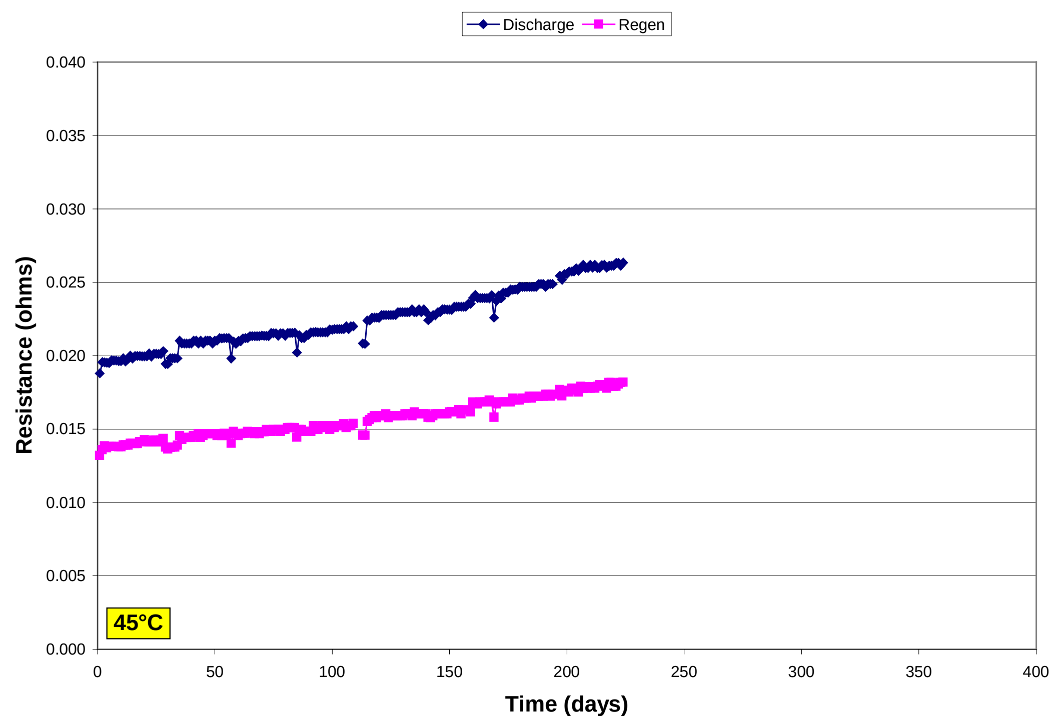

Figure 65. Discharge and regen pulse resistances for G2.60A45.S438.NA.36.43.G.T (45°C accelerated-life Baseline cell).

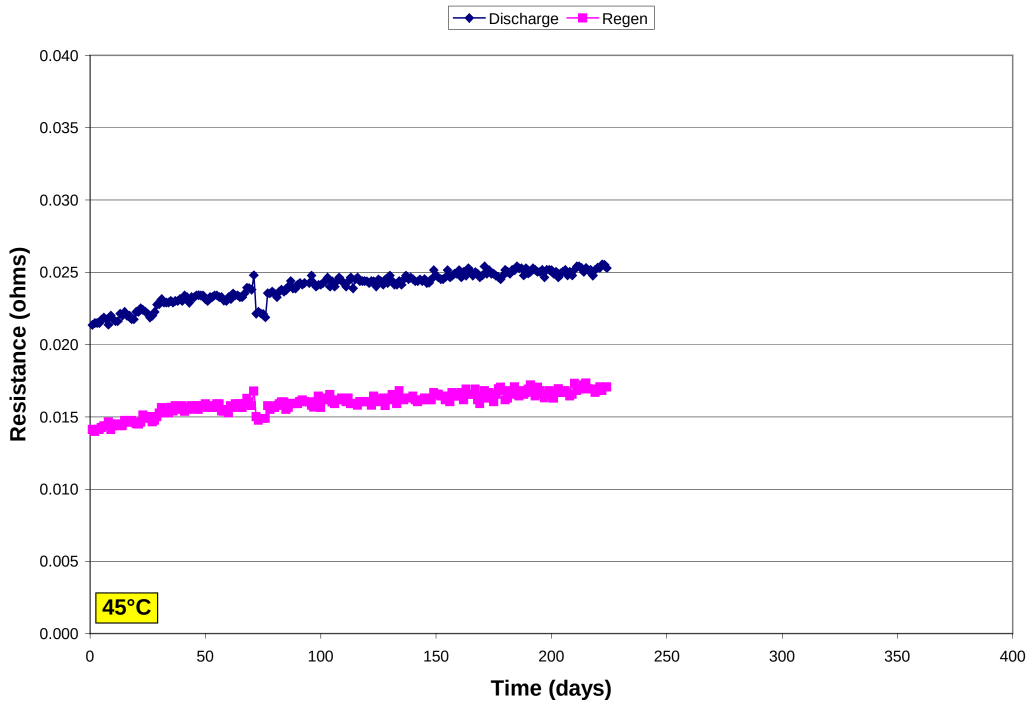

Figure 66. Discharge and regen pulse resistances for G2C.60C45.A226.25.32.22.G.T (45°C calendar-life Variant C cell).

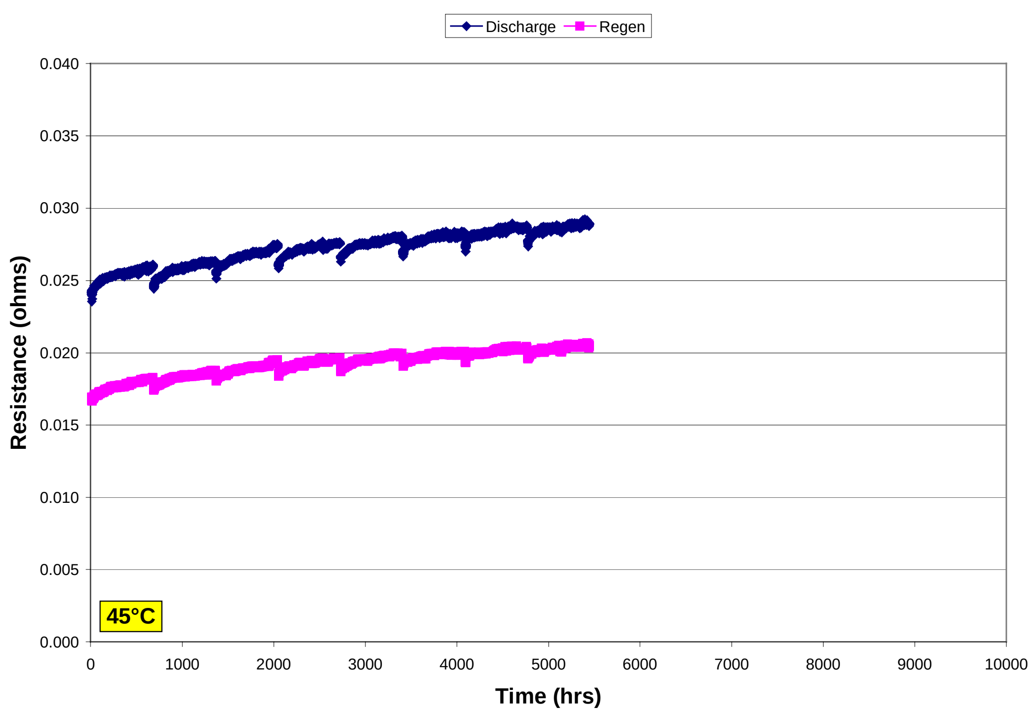

Figure 67. Discharge and regen pulse resistances for G2C.60L45.I162.30.32.26.G.T (45°C cycle-life Variant C cell).

4.5 Summary

4.5.1 Performance Summary

The average $C_1/1$ capacity fade, power fade, and EIS growth at the semicircle trough for the Baseline and Variant C cells for all cell groups aged at 60% SOC are summarized in Table 24. As expected, the 25°C cells show the least degradation, and the 55°C cells show the most degradation. Tables 25 and 26 show the $C_1/1$ capacity fade and power fade for the Baseline cells aged at 80 and 100% SOC, respectively. The $C_1/1$ capacity fade is highest at 100% SOC, except for the 55°C cells, which show the highest $C_1/1$ capacity fade at 80% SOC. The power fade is also highest at 100% SOC.

Table 27 compares the average $C_1/1$ capacity fade, power fade, and EIS growth at 32 weeks for the 45°C Baseline and Variant C cells. The Variant C $C_1/1$ capacity shows significantly less fade than the Baseline cells. The power fade and EIS growth were initially very high compared to the Baseline cells. However, after 32 weeks, they are now comparable to the Baseline cells and are showing a slower degradation rate.

Table 24. Performance summary for the Baseline and Variant C cells aged at 60% SOC.

Temperature (°C)	Chemistry	Test	$C_1/1$ Capacity Fade	Power Fade	EIS Growth	Weeks Completed
25	Baseline	Cycle-Life	8.9%	18.7%	31.9%	52
	Baseline	Accelerated-Life	7.8%	23.2%	-	40
35	Baseline	Accelerated-Life	12.0%	34.8%	-	36
45	Baseline	Calendar-Life	13.8%	31.9%	66.3%	52
	Baseline	Cycle-Life	20.6%	37.3%	80.4%	52
	Baseline	Accelerated-Life	20.8%	42.6%	-	36
	Variant C	Calendar-Life	2.0%	21.9%	54.2%	32
	Variant C	Cycle-Life	3.9%	26.2%	50.9%	32
55	Baseline	Calendar-Life	18.5%	32.6%	78.2%	40
	Baseline	Accelerated-Life	29.8%	53.4%	-	32

Table 25. Performance summary for the Baseline cells aged at 80% SOC.

Temperature (°C)	Chemistry	Test	$C_1/1$ Capacity Fade	Power Fade	Weeks Completed
25	Baseline	Accelerated-Life	12.6%	28.1%	40
35	Baseline	Accelerated-Life	16.9%	41.7%	36
45	Baseline	Accelerated-Life	30.1%	48.1%	36
55	Baseline	Accelerated-Life	31.9%	54.8%	20

Table 26. Performance summary for the Baseline cells aged at 100% SOC.

Temperature (°C)	Chemistry	Test	$C_1/1$ Capacity Fade	Power Fade	Weeks Completed
25	Baseline	Accelerated-Life	17.1%	39.8%	40
35	Baseline	Accelerated-Life	25.5%	49.6%	36
45	Baseline	Accelerated-Life	35.9%	59.2%	36
55	Baseline	Accelerated-Life	28.4%	58.0%	20

Table 27. Performance summary at 32 weeks for the 60% SOC 45°C Baseline and Variant C cells.

Temperature (°C)	Chemistry	Test	$C_1/1$ Capacity Fade	Power Fade	EIS Growth	Weeks Completed
45	Baseline	Calendar-Life	7.6%	18.8%	36.9%	32
	Baseline	Cycle-Life	10.4%	22.5%	42.7%	32
	Baseline	Accelerated-Life	13.7%	36.1%	-	32
	Variant C	Calendar-Life	2.0%	21.9%	54.2%	32
	Variant C	Cycle-Life	3.9%	26.2%	50.9%	32

4.5.2 Gap Analysis

Table 28 compares the PNGV Power Assist goals (Reference 2) to the measured performance of calendar-life Baseline cells G2.60C55.A214.33.40.34.G.L (a representative 55°C cell) and G2.60C45.A217.50.52.35.G.T (a representative 45°C Baseline cell) at 40 and 52 weeks, respectively, and calendar-life Variant C cell G2C.60C45.A226.25.32.22.G.T (a representative 45°C cell) at 32 weeks. Table 29 shows the gap analysis of cycle-life Baseline cells G2.60L25.I114.25.52.19.G.T (a representative 25°C cell) and G2.60L45.I130.50.52.39.G.T (a representative 45°C cell) at 52 weeks, and cycle-life Variant C cell G2C.60L45.I162.30.32.26.G.T (a representative 45°C cell) at 32 weeks. Table 30 shows the gap analysis of G2.60A25.S318.NA.40.23.G.T, G2.60A35.S329.NA.36.34.G.T, G2.60A45.S438.NA.36.43.G.T, and G2.60A55.S357.NA.32.52.G.F (representative 60% SOC accelerated-life cells tested at 25, 35, 45, and 55°C, respectively). Table 31 shows the gap analysis of G2.80A25.S346.NA.40.28.G.T, G2.80A35.S351.NA.36.43.G.T, G2.80A45.S432.NA.36.48.G.F, and G2.80A55.S321.NA.20.57.G.F (representative 80% SOC accelerated-life cells tested at 25, 35, 45, and 55°C, respectively). Table 32 shows the gap analysis of G2.100A25.S323.NA.40.40.G.T, G2.100A35.S428.NA.36.53.G.F, G2.100A45.S427.NA.36.60.G.F, and G2.100A55.S319.NA.20.54.G.F (representative 100% SOC accelerated-life cells tested at 25, 35, 45, and 55°C, respectively).

The green background indicates that the PNGV goal was met, whereas the red background indicates failure to meet the goal. The 18-s discharge pulse power is equivalent to the power at 300 W·h (as calculated from the available energy curves, Figures 32 through 34). The corresponding 2-s regen pulse power is the discharge power scaled by 1.2, as described in Reference 2. The available energy is calculated at a power of 25 kW (Figures 32 through 34). The standard PNGV efficiency, cold cranking, and self-discharge tests are not a part of the ATD Gen 2 cell conditioning for diagnostics. The efficiency shown in Table 29 is only calculated from the cycle-life test. The maximum system weight is found by multiplying the cell weights by the BSF (553 for the Baseline cells and 651 for the Variant C cells). The system volume is found by measuring the cell height (h) and maximum cell radius (r) and calculating $\pi r^2 h$ multiplied by the BSF. To stay within the maximum operating voltage goal, the 553 Baseline cells would need to be divided into seven parallel strings. The maximum operating voltage is then found by multiplying the HPPC pulse power maximum voltage (4.1 V) by 79 (i.e., 553 / 7). Likewise, the Variant C cells require seven parallel strings (i.e., 93 cells per string) to meet the maximum operating voltage goal. The minimum operating voltage is found by multiplying the HPPC pulse power minimum voltage (3.0 V) by the BSF divided by seven parallel strings. The maximum DC-link current is the discharge pulse power goal (25 kW) divided by the minimum operating voltage.

Table 28. ATD Gen 2 gap analysis chart for representative calendar-life cells.

Power Assist	EOT Target	Baseline Cells				Variant C Cell	
		55°C G2.60C55.A214.33.40.34.G.L		45°C G2.60C45.A217.50.52.35.G.T		45°C G2C.60C45.A226.25.32.22.G.T	
		Char.	40-Weeks	Char.	52-Weeks	Char.	32-Weeks
18s Discharge Pulse Power (kW)	25	31.5	20.7	35.8	23.5	35.6	27.5
2s Regenerative Pulse Power (kW)	30	37.7	24.8	43.0	28.2	42.8	33.0
Available Energy (kWh)	0.3	0.776	0	0.983	0	0.936	0.528
Efficiency (%)	>90	NA	NA	NA	NA	NA	NA
Cycle Life (25Wh profile)	300k	NA	NA	NA	NA	NA	NA
Cold Cranking Power @ -30C (kW)	5	NA	NA	NA	NA	NA	NA
Calendar Life (Yrs)	15	NA	NA	NA	NA	NA	NA
Maximum System Weight (kg)	40	0.04/21.8		0.04/21.7		0.04/24.8	
Maximum System Volume (Liters)	32	TBD		TBD		TBD	
Selling Price ($/system @ 100k/yr)	300	NA	NA	NA	NA	NA	NA
Maximum Operating Voltage (Vdc)	440	323.9		323.9		381.3	
Minimum Operating Voltage (Vdc)	0.55 x V_{max}	237		237		279.0	
Maximum DC-Link Current (A)	217	105.5		105.5		89.6	
Self Discharge (Wh/day)	50	NA	NA	NA	NA	NA	NA
Thermal Management (Avg. Wh/Day)		NA	NA	NA	NA	NA	NA
Operating Temperature Range (°C)	-30 to +52	NA	NA	NA	NA	NA	NA
Survival Temperature Range (°C)	-46 to +66	NA	NA	NA	NA	NA	NA
Hardware Level		Cell	Cell	Cell	Cell	Cell	Cell
Design Basis		Pack	Pack	Pack	Pack	Pack	Pack
BSF / Parallel Strings		553	7	553	7	651	7

Table 29. ATD Gen 2 gap analysis chart for representative cycle-life cells.

Power Assist	EOT Target	Baseline Cells				Variant C Cell	
		25°C G2.60L25.I114.25.52.19.G.T		45°C G2.60L45.I130.50.52.39.G.T		45°C G2C.60L45.I162.30.32.26.G.T	
		Char.	52-Weeks	Char.	52-Weeks	Char.	32-Weeks
18s Discharge Pulse Power (kW)	25	32.7	26.4	33.5	20.5	32.1	23.9
2s Regenerative Pulse Power (kW)	30	39.3	31.7	40.2	24.6	38.6	28.7
Available Energy (kWh)	0.3	0.820	0.425	0.867	0	0.802	0.170
Efficiency (%)	>90	94.2%	94.2%	96.0%	94.9%	95.9%	95.3%
Cycle Life (25Wh profile)	300k	0	436.8 k	0	436.8 k	0	268.8 k
Cold Cranking Power @ -30C (kW)	5	NA	NA	NA	NA	NA	NA
Calendar Life (Yrs)	15	NA	NA	NA	NA	NA	NA
Maximum System Weight (kg)	40	0.04/21.4		0.04/21.6		0.04/25.1	
Maximum System Volume (Liters)	32	9.67		9.70		11.21	
Selling Price ($/system @ 100k/yr)	300	NA	NA	NA	NA	NA	NA
Maximum Operating Voltage (Vdc)	440	323.9		323.9		381.3	
Minimum Operating Voltage (Vdc)	0.55 x V_{max}	237		237		279.0	
Maximum DC-Link Current (A)	217	105.5		105.5		89.6	
Self Discharge (Wh/day)	50	NA	NA	NA	NA	NA	NA
Thermal Management (Avg. Wh/Day)		NA	NA	NA	NA	NA	NA
Operating Temperature Range (°C)	-30 to +52	NA	NA	NA	NA	NA	NA
Survival Temperature Range (°C)	-46 to +66	NA	NA	NA	NA	NA	NA
			P72		P72		P72
Hardware Level		Cell	Cell	Cell	Cell	Cell	Cell
Design Basis		Pack	Pack	Pack	Pack	Pack	Pack
BSF / Parallel Strings		553	7	553	7	651	7

Table 30. ATD Gen 2 gap analysis chart for representative accelerated-life cells tested at 60% SOC

Power Assist	EOT Target	Baseline Cells							
		25°C		35°C		45°C		55°C	
		G2.60A25.S318.NA.40.23.G.T		G2.60A35.S329.NA.36.34.G.T		G2.60A45.S438.NA.36.43.G.T		G2.60A55.S357.NA.32.52.G.F	
		Char.	40-Weeks	Char.	36-Weeks	Char.	36-Weeks	Char.	32-Weeks
18s Discharge Pulse Power (kW)	25	33.5	26.8	32.1	22.2	32.8	18.8	33.5	15.6
2s Regenerative Pulse Power (kW)	30	40.2	32.2	38.5	26.6	39.4	22.6	40.2	18.7
Available Energy (kWh)	0.3	0.845	0.435	0.786	0	0.818	0	0.857	0
Efficiency (%)	>90	NA	NA	NA	NA	NA	NA	NA	NA
Cycle Life (25Wh profile)	300k	NA	NA	NA	NA	NA	NA	NA	NA
Cold Cranking Power @ -30C (kW)	5	NA	NA	NA	NA	NA	NA	NA	NA
Calendar Life (Yrs)	15	NA	NA	NA	NA	NA	NA	NA	NA
Maximum System Weight (kg)	40	0.04/21.2		0.04/21.2		0.04/21.2		0.04/21.3	
Maximum System Volume (Liters)	32	TBD		TBD		TBD		TBD	
Selling Price ($/system @ 100k/yr)	300	NA	NA	NA	NA	NA	NA	NA	NA
Maximum Operating Voltage (Vdc)	440	323.9		323.9		323.9		323.9	
Minimum Operating Voltage (Vdc)	0.55 x V_{max}	237		237		237		237	
Maximum DC-Link Current (A)	217	105.5		105.5		105.5		105.5	
Self Discharge (Wh/day)	50	NA	NA	NA	NA	NA	NA	NA	NA
Thermal Management (Avg. Wh/Day)		NA	NA	NA	NA	NA	NA	NA	NA
Operating Temperature Range (°C)	-30 to +52	NA	NA	NA	NA	NA	NA	NA	NA
Survival Temperature Range (°C)	-46 to +66	NA	NA	NA	NA	NA	NA	NA	NA
Hardware Level		Cell	Cell	Cell	Cell	Cell	Cell	Cell	Cell
Design Basis		Pack	Pack	Pack	Pack	Pack	Pack	Pack	Pack
BSF / Parallel Strings		553	7	553	7	553	7	553	7

Table 31. ATD Gen 2 gap analysis chart for representative accelerated-life cells tested at 80% SOC

Power Assist	EOT Target	Baseline Cells							
		25°C		35°C		45°C		55°C	
		G2.80A25.S346.NA.40.28.G.T		G2.80A35.S351.NA.36.43.G.T		G2.80A45.S432.NA.36.48.G.F		G2.80A55.S321.NA.20.57.G.F	
		Char.	40-Weeks	Char.	36-Weeks	Char.	36-Weeks	Char.	20-Weeks
18s Discharge Pulse Power (kW)	25	33.8	25.6	33.8	20.3	32.5	16.8	35.6	15.4
2s Regenerative Pulse Power (kW)	30	40.6	30.7	40.6	24.4	39.0	20.2	42.7	18.5
Available Energy (kWh)	0.3	0.852	0.354	0.839	0	0.794	0	0.918	0
Efficiency (%)	>90	NA	NA	NA	NA	NA	NA	NA	NA
Cycle Life (25Wh profile)	300k	NA	NA	NA	NA	NA	NA	NA	NA
Cold Cranking Power @ -30C (kW)	5	NA	NA	NA	NA	NA	NA	NA	NA
Calendar Life (Yrs)	15	NA	NA	NA	NA	NA	NA	NA	NA
Maximum System Weight (kg)	40	0.04/21.3		0.04/21.2		0.04/21.1		0.04/21.1	
Maximum System Volume (Liters)	32	TBD		TBD		TBD		TBD	
Selling Price ($/system @ 100k/yr)	300	NA	NA	NA	NA	NA	NA	NA	NA
Maximum Operating Voltage (Vdc)	440	323.9		323.9		323.9		323.9	
Minimum Operating Voltage (Vdc)	0.55 x V_{max}	237		237		237		237	
Maximum DC-Link Current (A)	217	105.5		105.5		105.5		105.5	
Self Discharge (Wh/day)	50	NA	NA	NA	NA	NA	NA	NA	NA
Thermal Management (Avg. Wh/Day)		NA	NA	NA	NA	NA	NA	NA	NA
Operating Temperature Range (°C)	-30 to +52	NA	NA	NA	NA	NA	NA	NA	NA
Survival Temperature Range (°C)	-46 to +66	NA	NA	NA	NA	NA	NA	NA	NA
Hardware Level		Cell	Cell	Cell	Cell	Cell	Cell	Cell	Cell
Design Basis		Pack	Pack	Pack	Pack	Pack	Pack	Pack	Pack
BSF / Parallel Strings		553	7	553	7	553	7	553	7

Table 32. ATD Gen 2 gap analysis chart for representative accelerated-life cells tested at 100% SOC

Power Assist	EOT Target	Baseline Cells 25°C G2.100A25.S323.NA.40.40.G.T Char.	25°C 40-Weeks	35°C G2.100A35.S428.NA.36.53.G.F Char.	35°C 36-Weeks	45°C G2.100A45.S427.NA.36.60.G.F Char.	45°C 36-Weeks	55°C G2.100A55.S319.NA.20.54.G.F Char.	55°C 20-Weeks
18s Discharge Pulse Power (kW)	25	35.1	22.2	32.7	15.5	33.4	13.0	34.8	15.9
2s Regenerative Pulse Power (kW)	30	42.1	26.6	39.2	18.6	40.1	15.6	41.8	19.1
Available Energy (kWh)	0.3	0.903	0	0.813	0	0.817	0	0.890	0
Efficiency (%)	>90	NA	NA	NA	NA	NA	NA	NA	NA
Cycle Life (25Wh profile)	300k	NA	NA	NA	NA	NA	NA	NA	NA
Cold Cranking Power @ -30C (kW)	5	NA	NA	NA	NA	NA	NA	NA	NA
Calendar Life (Yrs)	15	NA	NA	NA	NA	NA	NA	NA	NA
Maximum System Weight (kg)	40	0.04/21.2		0.04/21.1		0.04/21.2		0.04/21.3	
Maximum System Volume (Liters)	32	TBD		TBD		TBD		TBD	
Selling Price ($/system @ 100k/yr)	300	NA	NA	NA	NA	NA	NA	NA	NA
Maximum Operating Voltage (Vdc)	440	323.9		323.9		323.9		323.9	
Minimum Operating Voltage (Vdc)	0.55 x V_{max}	237		237		237		237	
Maximum DC-Link Current (A)	217	105.5		105.5		105.5		105.5	
Self Discharge (Wh/day)	50	NA	NA	NA	NA	NA	NA	NA	NA
Thermal Management (Avg. Wh/Day)		NA	NA	NA	NA	NA	NA	NA	NA
Operating Temperature Range (°C)	-30 to +52	NA	NA	NA	NA	NA	NA	NA	NA
Survival Temperature Range (°C)	-46 to +66	NA	NA	NA	NA	NA	NA	NA	NA
Hardware Level		Cell	Cell	Cell	Cell	Cell	Cell	Cell	Cell
Design Basis		Pack	Pack	Pack	Pack	Pack	Pack	Pack	Pack
BSF / Parallel Strings		553	7	553	7	553	7	553	7

4.6 Continuing Work

ATD Gen 2 testing will continue until the specified EOT criteria (Section 3.4) have been met. Tables 33 through 35 show the actual number of days and average cumulative power fade for the cell groups already removed from test as well as the projected total number of days (or cycles) and cumulative power fade at EOT for the remaining 60, 80, and 100% SOC cell groups, respectively. The 55°C Baseline cells for all cell groups at all SOC conditions have already been removed from test. The 45°C Baseline cell groups calendar-life testing at 80 and 100% SOC have also been removed from test. All other cell groups are continuing to test until the average power fade meets or exceeds to target cumulative power fade.

Table 33. Projected and actual EOT for the 60% SOC cell groups.

Temperature (°C)	Chemistry	Test	EOT Projection Date	Weeks Completed	Days / cycles	Cumulative Power Fade
25	Baseline	Cycle-Life	July 2003	92	772.8k	~36%
	Baseline	Accelerated-Life	August 2003	80	560 Days	~50%
35	Baseline	Accelerated-Life	February 2003	60	420 Days	~50%
45	Baseline	Calendar-Life	April 2003	80	560 Days	~50%
	Baseline	Cycle-Life	January 2003	72	604.8k	~50%
	Baseline	Accelerated-Life	September 2002	44	308 Days	~50%
	Variant C	Calendar-Life	February 2004	116	812 Days	~50%
	Variant C	Cycle-Life	October 2003	104	873.6k	~50%
55	Baseline	Calendar-Life	April 2002	40	280 Days	32.6%
	Baseline	Accelerated-Life	June 2002	32	224 Days	53.4%

Table 34. Projected and actual EOT for the 80% SOC cell groups.

Temperature (°C)	Chemistry	Test	EOT Projection Date	Weeks Completed	Days	Cumulative Power Fade
25	Baseline	Accelerated-Life	March 2003	64	448 Days	~50%
35	Baseline	Accelerated-Life	October 2002	48	336 Days	~50%
45	Baseline	Accelerated-Life	July 2002	36	252 Days	48.1%
55	Baseline	Accelerated-Life	January 2002	20	140 Days	54.8%

Table 35. Projected and actual EOT for the 100% SOC cell groups.

Temperature (°C)	Chemistry	Test	EOT Projection Date	Weeks Completed	Days / cycles	Cumulative Power Fade
25°C	Baseline	Accelerated-Life	December 2002	52	364 Days	~50%
35°C	Baseline	Accelerated-Life	August 2002	40	280 Days	~50%
45°C	Baseline	Accelerated-Life	July 2002	36	252 Days	59.2%
55°C	Baseline	Accelerated-Life	January 2002	20	140 Days	58.0%

5. CONCLUSIONS

Concurrent testing and analysis of the ATD Gen 2 Baseline and Variant C cells is on track, and the cells are performing well. The 18650-size cells, manufactured by Quallion consist of a baseline chemistry and variant chemistry (Variant C). These cells were distributed over a matrix of three life-testing protocols (calendar-, cycle-, and accelerated-life), four temperatures (25, 35, 45, and 55°C), and three SOCs (60, 80, and 100% SOC). Calendar- and cycle-life testing is only performed at 60% SOC. All testing is performed in accordance with the *PNGV Battery Test Manual*, Revision 3, and the ATD Gen 2 test plans.

The 25°C cycle- and accelerated-life Baseline cells have completed 52 and 40 weeks of aging, respectively. The 35°C accelerated-life Baseline cells have completed 36 weeks of aging. The 45°C calendar-, cycle-, and accelerated-life cells have completed 52, 52, and 36 weeks of aging at 60% SOC, respectively. All 45°C accelerated-life cells being tested at 80 and 100% SOC were removed from test after 36 weeks. The 45°C calendar- and cycle-life Variant C cells have both completed 32 weeks of aging. All 55°C cells have been removed from test; the calendar-life Baseline cells reached end of test after 40 weeks of aging and the accelerated-life Baseline cells aged at 60, 80, and 100% SOC reached end of test after 32, 20, and 20 weeks of aging, respectively.

From the RPTs conducted every 4 weeks during life testing, the $C_1/1$ capacity fade, $C_1/25$ capacity fade, power fade at 300 Wh, and EIS growth at the semicircle trough are calculated and used as measures of cell degradation. In general, the Baseline cell degradation increases with increasing temperature and SOC. The degradation is generally lowest for the calendar-life cells, in the middle for the cycle-life cells, and highest for the accelerated-life cells at a given test temperature and SOC. The Baseline cell degradation generally shows an initial square root of time dependence followed by a linear time dependence. A square root of time dependence may be attributable to a thermal diffusion process for the formation of an SEI layer. A linear-time dependence may be attributable to the steady-sate formation of the SEI layer. Once the second mechanism dominates, the Baseline cell rate of degradation generally increases.

The 60% SOC $C_1/25$ capacity fade does not follow the trends identified above and only shows a square root of time dependence, with no apparent change in mechanism. This is primarily due to the slower diffusion rates during the $C_1/25$ test. However, mechanistic changes appear at higher SOCs. Through 52 weeks of testing, the 25°C cycle-life Baseline cells also show no apparent mechanistic change. The $C_1/1$ and $C_1/25$ capacity fades show only a square root of time dependence, whereas the power fade and EIS growth show only a linear time dependence. Since this is the least stressful test in the matrix, however, it is possible that a mechanistic change will occur later in life. More data are required to understand the linear-time dependence seen in the power fade and EIS growth. It may simply be a slowly developing square root of time dependence.

The 45°C Variant C calendar- and cycle-life cells follow the same general trends as the Baseline cells. These cell groups show an initial square root of time dependence followed by a linear time dependence, and the calendar-life cell degradation is generally lower than the cycle-life cells. Unlike the Baseline cells, cell degradation generally decreases once the second mechanism dominates. The $C_1/1$ and $C_1/25$ capacity fades are significantly less than the respective Baseline cells and show little or no fade in the linear time dependence region. The power fade and EIS growth are initially higher than the respective Baseline cells but have since slowed down. The different behavior of the Variant C cells may suggest an alternate time dependency. These cells were also modeled with a natural log of time dependency, which may relate to the transport of ions due to electric fields present at the SEI layer. Although the coefficient of determination (i.e., R^2) was generally lower with a natural log of time dependence, it generally did not show any mechanistic changes through 32 weeks of testing. More data are required to determine the time dependency that best supports the behavior of the Variant C cell degradation.

All ATD Gen 2 testing will continue until the specified EOT criteria have been met. Six cycle-life and seven accelerated-life Baseline cells remain on test at 25°C. The cycle-life cells will reach EOT when the power fade is 30% plus one fade increment (i.e., approximately 36%). The accelerated-life cells will continue until the power fade reaches 50%. All remaining 35 and 45°C cell groups will continue until the power fade reaches 50% in accordance with the EOT criteria (i.e., cells removed from test at regular fade increments). Eight accelerated-life Baseline cells remain on test at 35°C and two calendar-life, two cycle-life, and three accelerated-life Baseline cells remain on test at 45°C. Also at 45°C, five calendar-life and four cycle-life Variant C cells remain on test. All 55°C cell groups have already been removed from test and sent to diagnostic laboratories.

6. REFERENCES

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3. Gary Henriksen, "Gen 1 & Gen 2 Cells," ATD Merit Review presentation, Argonne, IL, July 2002.

4. Kofstad, P., *High-Temperature Oxidation of Metals*, John Wiley & Sons, New York, 1966.

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Appendix 1

Individual Cell Results

A1. INDIVIDUAL CELL RESULTS

This appendix details $C_1/1$ capacity fade, power fade, and EIS magnitude growth at the semicircle trough results for each ATD Gen 2 Baseline and Variant C cell. The cell label and percent-fade from beginning of life either has a blue or green background. A blue background indicates that the cell is still being tested, a green background indicates that the cell has already been removed from test. A gray background indicates that no data are expected. The yellow background is for averages (upper row) and standard deviations (lower row). The averages and standard deviations are only calculated using the cells with a blue background in the fade column. The first column describes the test group (i.e., the SOC, life-test profile, and test temperature). The second column shows the laboratory-specific cell number and the third column shows the ATD label. See Appendix 2 for information on how the ATD label is structured. The remaining columns provide the cell-specific data at each four-week increment starting from BOL (i.e., characterization) through 52 weeks. The last column shows the percent-fade in cell degradation, normalized to the characterization RPT.

A1.1 Calendar-Life $C_1/1$ Capacity Fade

Table A1.1. $C_1/1$ capacity fade for the 45°C calendar-life Baseline cells.

Calendar-Life Cells			**$C_1/1$ Capacity**														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC																	
(SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
		Average	0.981	0.968	0.959	0.950	0.945	0.937	0.928	0.920	0.907	0.901	0.889	0.876	0.859	0.845	13.83%
		Standard Deviation	0.010	0.013	0.015	0.017	0.019	0.020	0.022	0.008	0.007	0.010	0.012	0.015	0.017	0.020	1.14%
60C45	216	G2.60C45.A216.50.52.29.G.T	0.988	0.977	0.970	0.962	0.958	0.951	0.944	0.926	0.912	0.908	0.898	0.887	0.871	0.859	13.02%
60C45	217	G2.60C45.A217.50.52.35.G.T	0.974	0.959	0.949	0.938	0.931	0.923	0.913	0.914	0.901	0.894	0.880	0.865	0.847	0.831	14.63%

Table A1.2. $C_1/1$ capacity fade for the 55°C calendar-life Baseline cells.

Calendar-Life Cells			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
		Average	0.987	0.950	0.941	0.916	0.900	0.886	0.873	0.857	0.843	0.823	0.808				18.48%
		Standard Deviation	0.011	0.006	0.008	0.007	0.007	0.008	0.006	0.007	0.009	0.013	0.008				0.95%
60C55	201	G2.60C55.A201.00.00.NA.G.A	0.992														0%
60C55	202	G2.60C55.A202.15.04.13.G.L	0.972	0.944													2.95%
60C55	203	G2.60C55.A203.15.04.15.G.A	0.992	0.956													3.71%
60C55	204	G2.60C55.A204.16.08.13.G.A	0.992	0.947	0.925												6.77%
60C55	205	G2.60C55.A205.16.08.13.G.L	0.991	0.952	0.932												5.95%
60C55	206	G2.60C55.A206.19.16.18.G.L	0.970	0.956	0.944	0.913	0.897										7.56%
60C55	207	G2.60C55.A207.19.16.21.G.A	0.989	0.954	0.951	0.916	0.901										8.87%
60C55	208	G2.60C45.A208.00.01.NA.S.A	1.010														0%
60C55	209	G2.60C55.A209.27.32.27.G.A	0.982	0.950	0.946	0.914	0.899	0.887	0.872	0.859	0.845						14.01%
60C55	210	G2.60C55.A210.30.40.32.G.A	0.994	0.948	0.948	0.918	0.904	0.890	0.875	0.860	0.846	0.830	0.812				18.29%
60C55	211	G2.60C55.A211.30.40.31.G.L	0.986	0.957	0.942	0.924	0.910	0.895	0.879	0.865	0.850	0.833	0.813				17.63%
60C55	212	G2.60C55.A212.24.28.24.G.L	0.996	0.945	0.948	0.913	0.899	0.884	0.869	0.853							14.32%
60C55	213	G2.60C55.A213.24.20.24.G.A	0.967	0.936	0.943	0.903	0.889	0.874									9.56%
60C55	214	G2.60C55.A214.33.40.34.G.L	0.992	0.956	0.942	0.927	0.909	0.894	0.880	0.863	0.846	0.824	0.798				19.51%
60C55	215	G2.60C55.A215.33.36.35.G.A	0.975	0.948	0.931	0.914	0.895	0.879	0.863	0.845	0.827	0.805					17.49%

Table A1.3. $C_1/1$ capacity fade for the 45°C calendar-life Variant C cells.

Calendar-Life Cells			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
		Average	0.830	0.774	0.817	0.812	0.811	0.811	0.813	0.813	0.814						2.03%
		Standard Deviation	0.011	0.072	0.010	0.010	0.012	0.014	0.013	0.013	0.013						0.47%
60C45	218	G2C.60C45.A218.06.04.27.G.A	0.820	0.672													18.08%
60C45	219	G2C.60C25.A219.00.CC.00.T.A	0.847														0%
60C45	220	G2C.60C45.A220.30.32.21.G.T	0.814	0.790	0.798	0.795	0.789	0.790	0.790	0.791	0.791						2.75%
60C45	221	G2C.60C45.A221.25.32.22.G.T	0.841	0.820	0.828	0.822	0.822	0.822	0.822	0.823	0.824						2.02%
60C45	222	G2C.60C45.A222.06.04.17.G.L	0.820	0.628													23.43%
60C45	223	G2C.60C45.A223.20.16.20.G.A	0.835	0.818	0.820	0.817	0.820										2.12%
60C45	224	G2C.60C45.A224.25.32.22.G.T	0.829	0.809	0.817	0.812	0.807	0.807	0.813	0.814	0.815						1.60%
60C45	225	G2C.60C45.A225.25.32.24.G.T	0.842	0.819	0.828	0.823	0.822	0.822	0.822	0.823	0.824						2.14%
60C45	226	G2C.60C45.A226.25.32.22.G.T	0.831	0.810	0.817	0.812	0.815	0.816	0.816	0.816	0.817						1.63%
60C45	227	G2C.60C45.A227.20.16.21.G.L	0.821	0.799	0.809	0.804	0.803										2.77%

A1.2 Calendar-Life Power Fade

Table A1.4. Power fade for the 45°C calendar-life Baseline cells.

Calendar-Life Cells			**Power at 300 Wh**														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(%)
		Average	35.39	32.87	31.15	31.26	30.59	30.37	29.28	29.08	28.72	27.85	26.78	26.33	24.75	24.09	31.90%
		Standard Deviation	0.648	0.245	0.258	0.836	0.287	0.255	0.042	0.361	0.370	0.634	0.457	0.420	0.590	0.854	3.66%
60C45	216	G2.60C45.A216.50.52.29.G.T	34.93	32.70	30.96	30.67	30.79	30.55	29.31	29.34	28.98	28.30	27.11	26.63	25.17	24.69	29.31%
60C45	217	G2.60C45.A217.50.52.35.G.T	35.84	33.04	31.33	31.85	30.38	30.19	29.25	28.83	28.46	27.41	26.46	26.03	24.34	23.48	34.49%

Table A1.5. Power fade for the 55°C calendar-life Baseline cells.

Calendar-Life Cells			**Power at 300 Wh**														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(%)
		Average	33.66	31.47	28.92	27.78	27.00	25.73	25.27	24.24	23.46	21.63	20.82				32.61%
		Standard Deviation	2.296	1.339	1.501	1.820	1.689	0.917	1.190	1.029	1.208	0.559	0.228				1.43%
60C55	201	G2.60C55.A201.00.00.NA.G.A	35.37														0%
60C55	202	G2.60C55.A202.15.04.13.G.L	36.54	31.65													13.38%
60C55	203	G2.60C55.A203.15.04.15.G.A	36.35	30.74													15.43%
60C55	204	G2.60C55.A204.16.08.13.G.A	33.26	30.64	28.81												13.37%
60C55	205	G2.60C55.A205.16.08.13.G.L	34.67	32.09	29.99												13.48%
60C55	206	G2.60C55.A206.19.16.18.G.L	34.23	31.88	29.11	28.60	27.95										18.35%
60C55	207	G2.60C55.A207.19.16.21.G.A	37.47	34.34	31.47	30.65	29.60										21.00%
60C55	208	G2.60C45.A208.00.01.NA.S.A	32.62														0%
60C55	209	G2.60C55.A209.27.32.27.G.A	35.13	32.11	29.73	29.48	28.27	27.18	27.05	26.14	25.51						27.36%
60C55	210	G2.60C55.A210.30.40.32.G.A	31.15	30.24	27.37	26.28	25.53	25.44	24.84	24.14	22.93	21.86	21.08				32.31%
60C55	211	G2.60C55.A211.30.40.31.G.L	30.09	30.10	27.38	26.14	25.44	25.12	24.85	23.81	23.27	21.78	20.65				31.36%
60C55	212	G2.60C55.A212.24.28.24.G.L	30.52	28.98	26.29	25.09	24.30	24.56	23.65	23.11							24.29%
60C55	213	G2.60C55.A213.24.20.24.G.A	33.92	31.67	28.19	26.77	26.70	25.73									24.14%
60C55	214	G2.60C55.A214.33.40.34.G.L	31.49	32.42	30.13	28.99	28.26	26.72	26.20	24.40	23.25	22.07	20.73				34.16%
60C55	215	G2.60C55.A215.33.36.35.G.A	32.13	32.21	29.62	28.05	26.94	25.34	25.03	23.82	22.34	20.81					35.22%

Table A1.6. Power fade for the 45°C calendar-life Variant C cells.

Calendar-Life Cells			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(%)
		Average	34.11	30.09	30.40	29.04	28.89	28.09	27.60	27.20	26.70						21.91%
		Standard Deviation	2.290	3.496	0.908	0.626	1.144	0.568	0.547	0.513	0.593						0.62%
60C45	218	G2C.60C45.A218.06.04.27.G.A	34.25	24.84													27.47%
60C45	219	G2C.60C25.A219.00.CC.00.T.A	35.12														0%
60C45	220	G2C.60C45.A220.30.32.21.G.T	32.84	32.02	29.63	28.30	27.56	27.19	26.83	26.54	25.90						21.12%
60C45	221	G2C.60C45.A221.25.32.22.G.T	34.00	31.27	29.09	28.55	27.53	28.61	27.34	26.89	26.40						22.35%
60C45	222	G2C.60C45.A222.06.04.17.G.L	28.29	23.44													17.16%
60C45	223	G2C.60C45.A223.20.16.20.G.A	36.58	30.39	30.80	29.45	29.26										20.00%
60C45	224	G2C.60C45.A224.25.32.22.G.T	34.34	31.63	31.72	28.58	30.70	28.13	27.74	27.38	26.90						21.65%
60C45	225	G2C.60C45.A225.25.32.24.G.T	34.62	31.60	30.34	29.32	29.57	27.95	27.81	27.31	26.77						22.68%
60C45	226	G2C.60C45.A226.25.32.22.G.T	35.14	32.02	31.18	30.09	29.20	28.54	28.28	27.89	27.50						21.74%
60C45	227	G2C.60C45.A227.20.16.21.G.L	35.91	33.61	30.05	29.01	28.38										20.98%

A1.3 Calendar-Life EIS Growth

Table A1.7. EIS growth for the 45°C calendar-life Baseline cells.

Calendar-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(%)
		Average	15.34	16.85	17.73	18.49	18.89	19.21	19.83	20.52	20.98	21.49	22.29	23.30	23.97	25.47	66.29%
		Standard Deviation	0.553	0.104	0.388	0.212	0.219	0.325	0.478	0.380	0.631	0.493	0.729	0.915	1.163	1.407	15.16%
60C45	216	G2.60C45.A216.50.52.29.G.T	15.73	16.92	18.01	18.34	19.05	19.44	19.50	20.25	20.53	21.14	21.78	22.65	23.15	24.48	55.58%
60C45	217	G2.60C45.A217.50.52.35.G.T	14.95	16.78	17.46	18.64	18.74	18.98	20.17	20.79	21.43	21.83	22.81	23.95	24.79	26.47	77.01%

Table A1.8. EIS growth for the 55°C calendar-life Baseline cells.

Calendar-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(%)
		Average	15.92	18.31	19.80	21.01	21.58	23.83	25.03	25.66	26.61	28.87	30.57				78.16%
		Standard Deviation	1.046	0.694	0.730	0.935	1.030	1.352	1.426	0.783	1.280	0.748	0.486				3.51%
60C55	201	G2.60C55.A201.00.00.NA.G.A	14.69														0%
60C55	202	G2.60C55.A202.15.04.13.G.L	14.64														0%
60C55	203	G2.60C55.A203.15.04.15.G.A	14.56	18.95													30.18%
60C55	204	G2.60C55.A204.16.08.13.G.A	16.07		20.14												25.38%
60C55	205	G2.60C55.A205.16.08.13.G.L	15.57		18.92												21.54%
60C55	206	G2.60C55.A206.19.16.18.G.L	15.52			21.29	21.93										41.24%
60C55	207	G2.60C55.A207.19.16.21.G.A	14.71			19.62	20.13										36.85%
60C55	208	G2.60C45.A208.00.01.NA.S.A	16.15														0%
60C55	209	G2.60C55.A209.27.32.27.G.A	15.32					22.08	23.02	24.15	24.53						60.16%
60C55	210	G2.60C55.A210.30.40.32.G.A	16.85					25.23	25.06	25.90	27.02	28.47	30.38				80.33%
60C55	211	G2.60C55.A211.30.40.31.G.L	16.78					24.45	25.81	25.87	26.87	28.42	30.21				80.04%
60C55	212	G2.60C55.A212.24.28.24.G.L	16.94						26.18	26.43							56.04%
60C55	213	G2.60C55.A213.24.20.24.G.A	15.86														0%
60C55	214	G2.60C55.A214.33.40.34.G.L	17.88	17.57	19.53	21.55	21.71		23.60	25.68	26.63	28.60	31.13				74.11%
60C55	215	G2.60C55.A215.33.36.35.G.A	17.20	18.42	20.60	21.57	22.54	23.55	26.50	25.95	28.02	29.99					74.29%

Table A1.9. EIS growth for the 45°C calendar-life Variant C cells.

Calendar-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(%)
		Average	17.04	21.85	22.22	23.01	24.10	24.65	25.28	25.57	26.10						54.25%
		Standard Deviation	0.567	2.490	0.831	0.606	0.802	0.742	0.649	0.741	0.760						1.99%
60C45	218	G2C.60C45.A218.06.04.27.G.A	16.53	26.25													58.85%
60C45	219	G2C.60C25.A219.00.CC.00.T.A	17.49														0%
60C45	220	G2C.60C45.A220.30.32.21.G.T	17.56	22.05	22.72	23.78	25.25	25.24	25.96	26.43	27.05						54.08%
60C45	221	G2C.60C45.A221.25.32.22.G.T	17.14	21.06	23.37	23.43	24.76	25.38	25.57	26.10	26.56						54.92%
60C45	222	G2C.60C45.A222.06.04.17.G.L	17.88	25.90													44.84%
60C45	223	G2C.60C45.A223.20.16.20.G.A	16.58	20.20	20.88	22.15	23.15										39.69%
60C45	224	G2C.60C45.A224.25.32.22.G.T	17.19	20.53	22.20	23.21	24.41	24.71	25.31	25.26	25.95						50.90%
60C45	225	G2C.60C45.A225.25.32.24.G.T	16.70	20.58	21.91	23.08	23.97	24.43	25.34	25.53	25.94						55.31%
60C45	226	G2C.60C45.A226.25.32.22.G.T	16.04	19.53		22.22	23.05	23.52	24.22	24.53	25.03						56.01%
60C45	227	G2C.60C45.A227.20.16.21.G.L	17.33	20.56	22.23	23.19	24.10										39.02%

A1.4 Cycle-Life $C_1/1$ Capacity Fade

Table A1.10. $C_1/1$ capacity fade for the 25°C cycle-life Baseline cells.

Cycle-Life Cells			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.981	0.954	0.944	0.939	0.932	0.926	0.924	0.921	0.914	0.909	0.906	0.900	0.894	0.889	8.91%
			0.013	0.012	0.008	0.008	0.008	0.008	0.010	0.010	0.009	0.010	0.011	0.011	0.011	0.011	0.74%
60L25	101	G2.60L25.I101.00.NA.NA.T.A	0.987														0%
60L25	102	G2.60L25.I102.02.04.02.G.A	1.009	0.979													2.91%
60L25	103	G2.60L25.I103.02.04.02.G.L	0.997	0.968													2.90%
60L25	104	G2.60L25.I104.14.36.15.G.A	0.979	0.952	0.944	0.943	0.931	0.925	0.921	0.917	0.912	0.904					7.64%
60L25	105	G2.60L25.I105.20.52.20.G.L	0.979	0.947	0.940	0.937	0.927	0.922	0.918	0.915	0.908	0.903	0.898	0.891	0.885	0.879	10.20%
60L25	106	G2.60L25.I106.09.20.09.G.A	0.978	0.950	0.943	0.935	0.929	0.925									5.43%
60L25	107	G2.60L25.I107.09.20.09.G.L	0.982	0.952	0.944	0.937	0.928	0.924									5.89%
60L25	108	G2.60L25.I108.25.52.17.G.T	0.974	0.947	0.941	0.939	0.930	0.925	0.923	0.920	0.914	0.907	0.905	0.903	0.896	0.891	8.48%
60L25	109	G2.60L25.I109.25.52.18.G.T	0.992	0.965	0.958	0.954	0.946	0.942	0.940	0.939	0.932	0.927	0.923	0.919	0.912	0.907	8.56%
60L25	110	G2.60L25.I110.14.36.16.G.L	0.982	0.955	0.946	0.939	0.931	0.925	0.923	0.920	0.911	0.906					7.69%
60L25	111	G2.60L25.I111.25.52.18.G.T	0.990	0.967	0.959	0.952	0.946	0.942	0.940	0.939	0.930	0.926	0.920	0.912	0.907	0.903	8.78%
60L25	112	G2.60L25.I112.20.52.20.G.A	0.983	0.957	0.949	0.941	0.934	0.929	0.926	0.924	0.915	0.911	0.905	0.898	0.892	0.886	9.83%
60L25	113	G2.60L25.I113.25.52.19.G.T	0.961	0.939	0.933	0.927	0.922	0.917	0.914	0.911	0.906	0.901	0.897	0.890	0.884	0.880	8.51%
60L25	114	G2.60L25.I114.25.52.19.G.T	0.970	0.943	0.943	0.937	0.932	0.924	0.919	0.917	0.911	0.907	0.901	0.894	0.889	0.883	8.90%
60L25	115	G2.60L25.I115.25.52.18.G.T	0.955	0.935	0.934	0.931	0.923	0.916	0.913	0.909	0.904	0.897	0.895	0.891	0.884	0.879	7.99%
60L25	176	G2.60L25.I176.00.CC.00.G.B	0.984														0%

Table A1.11. $C_1/1$ capacity fade for the 45°C cycle-life Baseline cells.

Cycle-Life Cells			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.977	0.941	0.929	0.921	0.908	0.900	0.894	0.887	0.874	0.861	0.842	0.825	0.808	0.781	20.59%
			0.006	0.007	0.008	0.008	0.008	0.008	0.009	0.009	0.009	0.010	0.011	0.013	0.008	0.008	0.88%
60L45	116	G2.60L45.I116.00.CC.00.G.L	0.968														0%
60L45	117	G2.60L45.I117.09.04.09.G.A	0.977	0.933													4.51%
60L45	118	G2.60L45.I118.10.04.10.G.L	0.974	0.943													3.17%
60L45	119	G2.60L45.I119.30.44.32.G.A	0.967	0.933	0.919	0.914	0.903	0.892	0.884	0.878	0.865	0.853	0.832	0.808			16.44%
60L45	120	G2.60L45.I120.26.40.29.G.L	0.966	0.929	0.916	0.912	0.901	0.890	0.884	0.878	0.866	0.854	0.834				13.69%
60L45	121	G2.60L45.I121.26.40.29.G.A	0.971	0.939	0.925	0.915	0.898	0.889	0.887	0.876	0.866	0.849	0.831				14.47%
60L45	122	G2.60L45.I122.19.20.20.G.L	0.983	0.946	0.933	0.923	0.915	0.908									7.69%
60L45	123	G2.60L45.I123.16.16.16.G.A	0.986	0.947	0.934	0.924	0.911										7.55%
60L45	124	G2.60L45.I124.23.32.23.G.L	0.972	0.932	0.919	0.909	0.900	0.892	0.885	0.880	0.867						10.88%
60L45	125	G2.60L45.I125.23.32.23.G.A	0.981	0.946	0.933	0.923	0.913	0.906	0.900	0.897	0.883						9.99%
60L45	126	G2.60L45.I126.30.44.32.G.B	0.977	0.941	0.928	0.919	0.910	0.903	0.895	0.891	0.878	0.869	0.849	0.826			15.39%
60L45	127	G2.60L45.I127.50.52.36.G.T	0.982	0.953	0.941	0.932	0.917	0.909	0.908	0.899	0.888	0.873	0.857	0.840	0.814	0.786	19.97%
60L45	128	G2.60L45.I128.16.16.17.G.L	0.973	0.939	0.926	0.918	0.895										8.04%
60L45	129	G2.60L45.I129.19.24.20.G.A	0.982	0.941	0.937	0.928	0.916	0.905	0.899								8.46%
60L45	130	G2.60L45.I130.50.52.39.G.T	0.984	0.945	0.939	0.932	0.918	0.907	0.902	0.893	0.880	0.867	0.849	0.827	0.802	0.775	21.21%

Table A1.12. $C_1/1$ capacity fade for the 45°C cycle-life Variant C cells.

Cycle-Life Cells			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
			0.827	0.812	0.809	0.801	0.798	0.797	0.796	0.798	0.796						3.85%
			0.016	0.017	0.018	0.018	0.020	0.021	0.021	0.018	0.019						0.51%
60L45	161	G2C.60L45.I161.00.CC.00.G.L	0.811														0%
60L45	162	G2C.60L45.I162.30.32.26.G.T	0.840	0.826	0.824	0.816	0.813	0.815	0.816	0.814	0.812						3.38%
60L45	163	G2C.60L45.I163.27.28.27.G.B	0.809	0.790	0.790	0.786	0.785	0.782	0.779	0.778							3.88%
60L45	164	G2C.60L45.I164.18.08.18.G.A	0.829	0.815	0.812												2.13%
60L45	165	G2C.60L45.I165.27.28.27.G.F	0.842	0.822	0.820	0.816	0.814	0.812	0.810	0.809							3.90%
60L45	166	G2C.60L45.I166.30.32.27.G.T	0.809	0.791	0.788	0.782	0.779	0.778	0.778	0.776	0.773						4.46%
60L45	167	G2C.60L45.I167.21.12.21.G.A	0.836	0.822	0.815	0.805											3.75%
60L45	168	G2C.60L45.I168.24.24.26.G.B	0.794	0.777	0.774	0.769	0.766	0.764	0.762								4.08%
60L45	169	G2C.60L45.I169.21.12.21.G.L	0.824	0.808	0.805	0.798											3.20%
60L45	170	G2C.60L45.I170.15.04.15.G.A	0.822	0.808													1.75%
60L45	171	G2C.60L45.I171.30.32.27.G.T	0.847	0.832	0.829	0.823	0.820	0.820	0.819	0.818	0.813						4.07%
60L45	172	G2C.60L45.I172.30.32.25.G.T	0.817	0.804	0.801	0.794	0.792	0.793	0.794	0.793	0.788						3.50%
60L45	173	G2C.60L45.I173.00.NA.NA.L.Q															0%
60L45	174	G2C.60L45.I174.18.08.18.G.L	0.842	0.828	0.824												2.17%
60L45	175	G2C.60L45.I175.24.24.25.G.F	0.843	0.830	0.826	0.818	0.814	0.813	0.811								3.77%

A1.5 Cycle-Life Power Fade

Table A1.13. Power fade for the 25°C cycle-life Baseline cells.

Cycle-Life Cells			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(%)
			32.51	31.98	31.24	30.68	29.96	29.68	28.92	28.26	28.31	27.64	27.44	27.15	26.68	26.25	18.73%
			0.724	0.692	0.659	0.699	0.705	0.701	0.677	0.658	0.638	0.631	0.703	0.722	0.691	0.617	0.99%
60L25	101	G2.60L25.I101.00.NA.NA.T.A															0%
60L25	102	G2.60L25.I102.02.04.02.G.A	32.71	32.12													1.82%
60L25	103	G2.60L25.I103.02.04.02.G.L	33.10	32.45													1.95%
60L25	104	G2.60L25.I104.14.36.15.G.A	32.75	32.17	31.38	30.97	30.07	29.84	29.21	28.25	28.38	27.68					15.49%
60L25	105	G2.60L25.I105.20.52.20.G.L	32.71	32.15	31.33	30.87	30.24	29.94	29.15	28.61	28.48	27.82	27.66	27.23	26.71	26.24	19.77%
60L25	106	G2.60L25.I106.09.20.09.G.A	32.54	31.76	31.06	30.44	29.90	29.45									9.48%
60L25	107	G2.60L25.I107.09.20.09.G.L	33.22	32.55	31.85	31.22	30.38	30.11									9.38%
60L25	108	G2.60L25.I108.25.52.17.G.T	32.00	31.62	31.02	30.58	29.72	29.47	28.79	27.85	28.09	27.36	27.33	27.27	26.90	26.48	17.25%
60L25	109	G2.60L25.I109.25.52.18.G.T	30.34	30.03	29.66	29.04	28.16	27.84	27.34	26.78	26.83	26.16	25.99	25.63	25.30	25.00	17.59%
60L25	110	G2.60L25.I110.14.36.16.G.L	32.80	32.14	31.46	30.58	30.04	29.73	28.88	28.36	28.37	27.70					15.56%
60L25	111	G2.60L25.I111.25.52.18.G.T	31.96	31.30	30.52	29.94	29.38	29.17	28.47	28.00	28.05	27.36	27.10	26.92	26.44	26.06	18.47%
60L25	112	G2.60L25.I112.20.52.20.G.A	32.65	32.12	31.29	30.64	29.88	29.75	29.00	28.14	28.29	27.60	27.38	26.97	26.49	26.11	20.04%
60L25	113	G2.60L25.I113.25.52.19.G.T	32.72	32.28	31.55	31.04	30.21	30.03	29.15	28.75	28.59	28.03	27.82	27.50	26.91	26.49	19.04%
60L25	114	G2.60L25.I114.25.52.19.G.T	32.72	32.11	31.53	31.04	30.55	30.06	29.29	28.67	28.75	28.16	27.88	27.55	26.98	26.41	19.31%
60L25	115	G2.60L25.I115.25.52.18.G.T	33.34	32.97	32.26	31.85	31.03	30.74	29.95	29.22	29.33	28.51	28.36	28.12	27.75	27.21	18.38%
60L25	176	G2.60L25.I176.00.CC.00.G.B	32.08														0%

Table A1.14. Power fade for the 45°C cycle-life Baseline cells.

Cycle-Life Cells			Power at 300 Wh														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (kW)	4 wk (kW)	8 wk (kW)	12 wk (kW)	16 wk (kW)	20 wk (kW)	24 wk (kW)	28 wk (kW)	32 wk (kW)	36 wk (kW)	40 wk (kW)	44 wk (kW)	48 wk (kW)	52 wk (kW)	fade (%)
			32.42	29.54	28.40	27.72	27.11	26.60	26.12	25.46	25.13	24.26	23.24	22.08	21.49	20.63	37.29%
			0.665	0.604	0.607	0.576	0.517	0.577	0.509	0.454	0.467	0.423	0.453	0.488	0.148	0.232	2.22%
60L45	116	G2.60L45.I116.00.CC.00.G.L	33.73														0%
60L45	117	G2.60L45.I117.09.04.09.G.A	33.58	30.40													9.48%
60L45	118	G2.60L45.I118.10.04.10.G.L	32.64	29.52													9.56%
60L45	119	G2.60L45.I119.30.44.32.G.A	31.50	28.59	27.57	26.98	26.53	26.00	25.35	24.79	24.58	23.64	22.43	21.35			32.21%
60L45	120	G2.60L45.I120.26.40.29.G.L	33.01	30.05	28.82	28.18	27.71	27.12	26.55	25.89	25.72	24.72	23.50				28.83%
60L45	121	G2.60L45.I121.26.40.29.G.A	32.51	29.98	28.88	27.99	27.26	26.72	26.31	25.40	25.38	24.00	23.00				29.25%
60L45	122	G2.60L45.I122.19.20.20.G.L	31.91	28.96	27.97	27.34	26.95	25.58									19.82%
60L45	123	G2.60L45.I123.16.16.16.G.A	31.39	28.68	27.59	26.84	26.28										16.27%
60L45	124	G2.60L45.I124.23.32.23.G.L	32.02	29.21	28.02	27.38	26.94	26.44	25.77	25.18	24.68						22.91%
60L45	125	G2.60L45.I125.23.32.23.G.A	31.85	29.08	27.89	27.24	26.68	26.20	25.58	25.03	24.55						22.90%
60L45	126	G2.60L45.I126.30.44.32.G.B	32.84	29.91	28.86	28.11	27.62	27.08	26.41	25.79	25.32	24.53	23.50	22.28			32.16%
60L45	127	G2.60L45.I127.50.52.36.G.T	32.35	29.76	28.78	27.92	27.17	26.68	26.29	25.44	25.20	24.08	23.38	22.28	21.60	20.79	35.73%
60L45	128	G2.60L45.I128.16.16.17.G.L	32.56	29.65	28.49	28.22	26.90										17.38%
60L45	129	G2.60L45.I129.19.24.20.G.A	32.28	29.28	28.31	27.70	27.15	26.58	25.86								19.91%
60L45	130	G2.60L45.I130.50.52.39.G.T	33.47	30.54	29.57	28.78	28.10	27.55	26.93	26.12	25.62	24.61	23.64	22.41	21.39	20.46	38.86%

Table A1.15. Power fade for the 45°C cycle-life Variant C cells.

Cycle-Life Cells			Power at 300 Wh														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (kW)	4 wk (kW)	8 wk (kW)	12 wk (kW)	16 wk (kW)	20 wk (kW)	24 wk (kW)	28 wk (kW)	32 wk (kW)	36 wk (kW)	40 wk (kW)	44 wk (kW)	48 wk (kW)	52 wk (kW)	fade (%)
			32.60	28.23	27.09	26.27	25.77	25.11	24.55	23.92	24.00						26.19%
			1.093	1.075	1.032	0.672	0.711	0.676	0.624	0.544	0.408						0.86%
60L45	161	G2C.60L45.I161.00.CC.00.G.L	32.21														0%
60L45	162	G2C.60L45.I162.30.32.26.G.T	32.15	28.02	26.99	25.76	25.40	24.83	24.29	23.84	23.89						25.68%
60L45	163	G2C.60L45.I163.27.28.27.G.B	31.74	27.28	26.31	25.40	25.00	24.29	23.71	23.11							27.19%
60L45	164	G2C.60L45.I164.18.08.18.G.A	30.73	26.39	25.29												17.71%
60L45	165	G2C.60L45.I165.27.28.27.G.F	33.48	28.84	27.70	26.67	26.33	25.59	25.01	24.46							26.94%
60L45	166	G2C.60L45.I166.30.32.27.G.T	33.40	28.99	27.76	26.59	26.18	25.54	24.97	24.42	24.43						26.84%
60L45	167	G2C.60L45.I167.21.12.21.G.A	33.94	29.78	28.35	26.88											20.79%
60L45	168	G2C.60L45.I168.24.24.26.G.B	32.69	28.23	26.93	25.95	25.43	24.74	24.19								26.01%
60L45	169	G2C.60L45.I169.21.12.21.G.L	33.32	28.74	27.49	26.37											20.85%
60L45	170	G2C.60L45.I170.15.04.15.G.A	32.12	27.44													14.58%
60L45	171	G2C.60L45.I171.30.32.27.G.T	33.14	28.73	27.45	26.34	25.93	25.30	24.74	24.23	24.19						27.01%
60L45	172	G2C.60L45.I172.30.32.25.G.T	31.42	27.57	26.31	25.31	24.93	24.36	23.92	23.49	23.49						25.26%
60L45	173	G2C.60L45.I173.00.NA.NA.L.Q															0%
60L45	174	G2C.60L45.I174.18.08.18.G.L	31.40	26.98	25.76												17.95%
60L45	175	G2C.60L45.I175.24.24.25.G.F	34.28	29.97	28.75	27.44	26.98	26.25	25.55								25.47%

A1.6 Cycle-Life EIS Growth

Table A1.16. EIS growth for the 25°C cycle-life Baseline cells.

Cycle-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (mΩ)	4 wk (mΩ)	8 wk (mΩ)	12 wk (mΩ)	16 wk (mΩ)	20 wk (mΩ)	24 wk (mΩ)	28 wk (mΩ)	32 wk (mΩ)	36 wk (mΩ)	40 wk (mΩ)	44 wk (mΩ)	48 wk (mΩ)	52 wk (mΩ)	fade (%)
			16.97	17.17	17.70	18.04	18.66	19.28	19.66	19.99	20.52	20.87	21.07	21.53	22.22	22.50	31.88%
			0.439	0.379	0.353	0.354	0.526	0.540	0.508	0.531	0.539	0.528	0.583	0.618	0.594	0.559	1.70%
60L25	101	G2.60L25.I101.00.NA.NA.T.A															0%
60L25	102	G2.60L25.I102.02.04.02.G.A	17.21	17.48													1.57%
60L25	103	G2.60L25.I103.02.04.02.G.L	16.85	17.29													2.59%
60L25	104	G2.60L25.I104.14.36.15.G.A	16.78		18.05		18.73	19.20	19.83	20.02	20.70	20.94					24.78%
60L25	105	G2.60L25.I105.20.52.20.G.L	16.85		17.77		18.40	18.98	19.25	19.73	20.39	20.50	20.98	21.36	22.08	22.44	33.20%
60L25	106	G2.60L25.I106.09.20.09.G.A	16.92				18.74	19.42									14.76%
60L25	107	G2.60L25.I107.09.20.09.G.L	16.56				18.43	19.16									15.70%
60L25	108	G2.60L25.I108.25.52.17.G.T	16.84				18.49	19.25	19.58	19.83	20.51	20.77	20.82	21.43	22.11	22.41	33.09%
60L25	109	G2.60L25.I109.25.52.18.G.T	18.23				19.94	20.58	20.66	21.20	21.75	22.06	22.11	22.72	23.38	23.57	29.26%
60L25	110	G2.60L25.I110.14.36.16.G.L	16.63				18.36	19.01	19.36	19.73	20.26	20.64					24.16%
60L25	111	G2.60L25.I111.25.52.18.G.T	17.36				18.97	19.71	19.98	20.24	20.79	21.05	21.33	21.75	22.37	22.52	29.71%
60L25	112	G2.60L25.I112.20.52.20.G.A	17.23				19.19	19.69	20.17	20.37	20.77	21.35	21.59	21.97	22.67	23.01	33.58%
60L25	113	G2.60L25.I113.25.52.19.G.T	16.67				18.31	18.97	19.34	19.79	20.06	20.54	20.61	21.08	21.70	21.98	31.85%
60L25	114	G2.60L25.I114.25.52.19.G.T	16.99	17.29	17.78	18.29	18.44	18.97	19.50	19.78	20.14	20.66	20.80	21.27	21.93	22.27	31.06%
60L25	115	G2.60L25.I115.25.52.18.G.T	16.38	16.61	17.21	17.79	17.88	18.40	18.92	19.20	19.81	20.18	20.29	20.69	21.50	21.83	33.26%
60L25	176	G2.60L25.I176.00.CC.00.G.B	17.08														0%

Table A1.17. EIS growth for the 45°C cycle-life Baseline cells.

Cycle-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (mΩ)	4 wk (mΩ)	8 wk (mΩ)	12 wk (mΩ)	16 wk (mΩ)	20 wk (mΩ)	24 wk (mΩ)	28 wk (mΩ)	32 wk (mΩ)	36 wk (mΩ)	40 wk (mΩ)	44 wk (mΩ)	48 wk (mΩ)	52 wk (mΩ)	fade (%)
			17.07	18.92	20.39	20.77	21.67	22.28	22.81	23.42	24.33	25.66	26.13	27.63	28.85	30.61	80.43%
			0.452	0.507	0.664	0.668	0.590	0.661	0.504	0.502	0.506	0.565	0.623	0.642	0.180	0.142	4.90%
60L45	116	G2.60L45.I116.00.CC.00.G.L	16.25														0%
60L45	117	G2.60L45.I117.09.04.09.G.A	16.30	18.58													14.00%
60L45	118	G2.60L45.I118.10.04.10.G.L	16.86	19.29													14.44%
60L45	119	G2.60L45.I119.30.44.32.G.A	17.54		21.17	21.60	22.32	22.78	23.66	24.18	25.12	26.42	27.16	28.57			62.91%
60L45	120	G2.60L45.I120.26.40.29.G.L	16.57		19.98	20.36	20.99	21.56	22.26	22.78	23.67	25.17	25.76				55.50%
60L45	121	G2.60L45.I121.26.40.29.G.A	16.92				21.58	22.15	22.79	23.30	24.39	25.97	26.57				57.06%
60L45	122	G2.60L45.I122.19.20.20.G.L	17.35				22.05	23.67									36.39%
60L45	123	G2.60L45.I123.16.16.16.G.A	17.87				22.63										26.61%
60L45	124	G2.60L45.I124.23.32.23.G.L	17.09				21.76	22.48	23.06	23.90	24.61						43.97%
60L45	125	G2.60L45.I125.23.32.23.G.A	17.62				22.08	22.55	23.19	23.81	24.84						41.00%
60L45	126	G2.60L45.I126.30.44.32.G.B	16.73				20.98	21.75	22.41	22.98	23.98	25.25	25.77	27.23			62.74%
60L45	127	G2.60L45.I127.50.52.36.G.T	17.36				21.57	22.14	22.88	23.44	24.26	26.09	26.01	27.55	28.98	30.71	76.96%
60L45	128	G2.60L45.I128.16.16.17.G.L	16.93				21.74										28.44%
60L45	129	G2.60L45.I129.19.24.20.G.A	17.30	19.42	20.71	21.01	21.76	22.30	23.02								33.06%
60L45	130	G2.60L45.I130.50.52.39.G.T	16.59	18.41	19.72	20.12	20.58	21.38	22.04	22.98	23.82	25.09	25.50	27.19	28.73	30.51	83.89%

Table A1.18. EIS growth for the 45°C cycle-life Variant C cells.

Cycle-Life Cells			EIS Magnitude Growth at the Semicircle Trough														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(mΩ)	(%)
			20.46	24.22	25.69	26.28	27.26	28.18	28.84	30.14	30.55						50.86%
			1.916	1.464	1.543	0.991	1.139	1.011	1.022	0.954	0.975						4.00%
60L45	161	G2C.60L45.I161.00.CC.00.G.L	20.25														0%
60L45	162	G2C.60L45.I162.30.32.26.G.T	20.48	24.23	25.90	26.90	28.07	28.69	29.56	30.55	30.77						50.29%
60L45	163	G2C.60L45.I163.27.28.27.G.B	19.94	24.32	25.72	27.09	27.78	28.76	29.38	30.43							52.66%
60L45	164	G2C.60L45.I164.18.08.18.G.A	21.91	26.75	28.36												29.48%
60L45	165	G2C.60L45.I165.27.28.27.G.F	18.96	23.08	24.58	25.42	26.41	27.37	28.00	29.00							52.99%
60L45	166	G2C.60L45.I166.30.32.27.G.T	19.07	22.98	24.51	25.55	26.50	27.31	28.02	29.24	29.49						54.65%
60L45	167	G2C.60L45.I167.21.12.21.G.A	19.00	22.45	24.01	25.39											33.63%
60L45	168	G2C.60L45.I168.24.24.26.G.B	19.56	23.89	25.35	26.39	27.32	28.38	28.73								46.89%
60L45	169	G2C.60L45.I169.21.12.21.G.L	19.53	23.69	25.00	26.36											34.97%
60L45	170	G2C.60L45.I170.15.04.15.G.A	20.53	25.35													23.50%
60L45	171	G2C.60L45.I171.30.32.27.G.T	19.70	23.71	25.36	26.38	27.13	28.36	28.97	29.97	30.14						52.99%
60L45	172	G2C.60L45.I172.30.32.25.G.T	21.84	25.36	27.16	28.31	29.27	29.88	30.60	31.61	31.78						45.49%
60L45	173	G2C.60L45.I173.00.NA.NA.L.Q	25.84														0%
60L45	174	G2C.60L45.I174.18.08.18.G.L	21.73	26.75	28.42												30.76%
60L45	175	G2C.60L45.I175.24.24.25.G.F	18.38	22.30	23.90	25.02	25.59	26.69	27.42								49.17%

A1.7 Accelerated-Life $C_1/1$ Capacity Fade

Table A1.19. $C_1/1$ capacity fade for the 25°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.927	0.918	0.912	0.916	0.909	0.899	0.902	0.887	0.878	0.867	0.854				7.82%
			0.006	0.008	0.008	0.008	0.004	0.006	0.005	0.006	0.004	0.005	0.004				0.37%
60A25	318	G2.60A25.S318.NA.40.23.G.T	0.921	0.908	0.903	0.906	0.904	0.892	0.898	0.883	0.875	0.864	0.851				7.56%
60A25	341	G2.60A25.S341.NA.20.11.V.F	0.930	0.921	0.916	0.920	0.911	0.899									3.25%
60A25	356	G2.60A25.S356.NA.40.24.G.T	0.931	0.923	0.917	0.921	0.912	0.905	0.905	0.891	0.881	0.870	0.856				8.08%

Table A1.20. $C_1/1$ capacity fade for the 25°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.930	0.909	0.896	0.897	0.888	0.882	0.886	0.871	0.856	0.842	0.821				12.63%
			0.019	0.018	0.016	0.016	0.016	0.014	0.013	0.010	0.008	0.003	0.000				1.13%
80A25	346	G2.80A25.S346.NA.40.28.G.T	0.930	0.907	0.895	0.895	0.884	0.881	0.877	0.864	0.850	0.840	0.820				11.84%
80A25	433	G2.80A25.S433.NA.40.28.G.T	0.948	0.928	0.912	0.914	0.905	0.897	0.895	0.878	0.861	0.844	0.821				13.43%
80A25	447	G2.80A25.S447.NA.16.12.D.F	0.910	0.892	0.880	0.882	0.875	0.869									4.56%

Table A1.21. $C_1/1$ capacity fade for the 25°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.935	0.911	0.897	0.899	0.886	0.873	0.868	0.843	0.831	0.803	0.776				17.12%
			0.011	0.005	0.005	0.006	0.009	0.007	0.018	0.015	0.009	0.008	0.007				0.04%
100A25	323	G2.100A25.S323.NA.40.40.G.T	0.931	0.904	0.889	0.890	0.881	0.870	0.869	0.845	0.824	0.797	0.771				17.15%
100A25	342	G2.100A25.S342.NA.08.09.D.F	0.944	0.912	0.900	0.902											4.63%
100A25	424	G2.100A25.S424.NA.40.39.G.T	0.942	0.915	0.901	0.902	0.896	0.881	0.884	0.857	0.837	0.809	0.781				17.09%
100A25	434	G2.100A25.S434.NA.28.30.G.T	0.921	0.911	0.896	0.901	0.881	0.869	0.849	0.827							10.22%

Table A1.22. C_1/1 capacity fade for the 35°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			C_1/1 Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.934	0.921	0.896	0.889	0.881	0.870	0.864	0.855	0.846	0.822					12.00%
			0.010	0.010	0.012	0.011	0.012	0.012	0.012	0.012	0.012	0.014					0.79%
60A35	329	G2.60A35.S329.NA.36.34.G.T	0.942	0.930	0.906	0.899	0.891	0.880	0.874	0.865	0.856	0.837					11.15%
60A35	361	G2.60A35.S361.NA.36.36.G.T	0.922	0.910	0.883	0.877	0.868	0.857	0.851	0.842	0.832	0.810					12.15%
60A35	442	G2.60A35.S442.NA.36.34.G.T	0.937	0.924	0.899	0.892	0.884	0.873	0.868	0.859	0.850	0.818					12.70%

Table A1.23. C_1/1 capacity fade for the 35°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			C_1/1 Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.928	0.915	0.909	0.880	0.891	0.875	0.863	0.839	0.823	0.769					16.88%
			0.007	0.006	0.003	0.007	0.002	0.003	0.001	0.002	0.001	0.004					0.55%
80A35	348	G2.80A35.S348.NA.36.43.G.T	0.933	0.919	0.911	0.885	0.892	0.877	0.864	0.840	0.824	0.771					17.36%
80A35	351	G2.80A35.S351.NA.36.43.G.T	0.923	0.910	0.907	0.875	0.889	0.873	0.862	0.837	0.822	0.766					17.01%
80A35	437	G2.80A35.S437.NA.36.40.G.T	0.854	0.840	0.811	0.803	0.795	0.782	0.772	0.762	0.748	0.715					16.28%

Table A1.24. C_1/1 capacity fade for the 35°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			C_1/1 Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.932	0.898	0.895	0.867	0.869	0.847	0.826	0.790	0.759	0.698					25.50%
			0.011	0.013	0.010	0.012	0.011	0.011	0.014	0.017	0.028	0.033					2.54%
100A35	428	G2.100A35.S428.NA.36.53.G.F	0.927	0.894	0.891	0.862	0.862	0.839	0.812	0.771	0.739	0.674					27.29%
100A35	435	G2.100A35.S435.NA.24.32.D.F	0.924	0.888	0.887	0.858	0.863	0.843	0.826	0.793							14.18%
100A35	444	G2.100A35.S444.NA.36.47.G.F	0.945	0.913	0.906	0.880	0.882	0.860	0.840	0.805	0.778	0.721					23.70%

Table A1.25. $C_1/1$ capacity fade for the 45°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
			0.946	0.931	0.923	0.915	0.904	0.890	0.875	0.850	0.817	0.750					20.78%
			0.017	0.017	0.017	0.017	0.018	0.017	0.017	0.016	0.017	0.020					2.03%
60A45	343	G2.60A45.S343.NA.36.43.G.T	0.965	0.950	0.941	0.933	0.922	0.907	0.890	0.862	0.825	0.751					22.18%
60A45	421	G2.60A45.S421.NA.36.42.G.T	0.943	0.928	0.921	0.912	0.902	0.890	0.877	0.856	0.828	0.769					18.45%
60A45	438	G2.60A45.S438.NA.36.43.G.T	0.931	0.916	0.908	0.899	0.887	0.873	0.857	0.831	0.797	0.729					21.70%

Table A1.26. $C_1/1$ capacity fade for the 45°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
			0.928	0.904	0.885	0.867	0.856	0.826	0.793	0.750	0.706	0.648					30.15%
			0.004	0.003	0.005	0.009	0.008	0.014	0.019	0.024	0.023	0.014					1.55%
80A45	325	G2.80A45.S325.NA.36.48.G.F	0.924	0.904	0.885	0.859	0.854	0.819	0.784	0.735	0.693	0.639					30.84%
80A45	333	G2.80A45.S333.NA.36.48.G.F	0.932	0.902	0.880	0.865	0.849	0.816	0.780	0.738	0.693	0.641					31.22%
80A45	432	G2.80A45.S432.NA.36.48.G.F	0.927	0.907	0.889	0.876	0.865	0.842	0.815	0.778	0.732	0.664					28.37%

Table A1.27. $C_1/1$ capacity fade for the 45°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			$C_1/1$ Capacity														
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ah)	4 wk (Ah)	8 wk (Ah)	12 wk (Ah)	16 wk (Ah)	20 wk (Ah)	24 wk (Ah)	28 wk (Ah)	32 wk (Ah)	36 wk (Ah)	40 wk (Ah)	44 wk (Ah)	48 wk (Ah)	52 wk (Ah)	fade (%)
			0.937	0.890	0.871	0.846	0.807	0.758	0.716	0.678	0.645	0.600					35.91%
			0.007	0.003	0.008	0.011	0.013	0.015	0.017	0.018	0.018	0.021					2.54%
100A45	328	G2.100A45.S328.NA.36.59.G.F	0.930	0.886	0.870	0.847	0.812	0.765	0.723	0.684	0.651	0.607					34.73%
100A45	344	G2.100A45.S344.NA.36.57.G.F	0.937	0.893	0.879	0.857	0.820	0.770	0.727	0.689	0.657	0.617					34.15%
100A45	350	G2.100A45.S350.NA.36.62.G.F	0.936	0.894	0.877	0.849	0.803	0.743	0.696	0.656	0.624	0.573					38.78%
100A45	427	G2.100A45.S427.NA.36.60.G.F	0.948	0.891	0.858	0.827	0.787	0.741	0.700	0.661	0.628	0.583					38.50%
100A45	441	G2.100A45.S441.NA.36.58.G.F	0.934	0.888	0.872	0.849	0.815	0.771	0.733	0.698	0.666	0.622					33.40%

Table A1.28. $C_1/1$ capacity fade for the 55°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.946	0.905	0.885	0.865	0.846	0.822	0.781	0.722	0.664						29.78%
			0.006	0.009	0.010	0.010	0.010	0.011	0.013	0.014	0.013						1.03%
60A55	337	G2.60A55.S337.NA.32.54.G.F	0.941	0.903	0.883	0.862	0.843	0.818	0.776	0.716	0.657						30.13%
60A55	349	G2.60A55.S349.NA.32.54.G.F	0.945	0.896	0.876	0.856	0.837	0.814	0.772	0.713	0.656						30.58%
60A55	357	G2.60A55.S357.NA.32.52.G.F	0.952	0.914	0.895	0.875	0.857	0.834	0.795	0.738	0.680						28.61%

Table A1.29. $C_1/1$ capacity fade for the 55°C accelerated-life Baseline cells at 80% SOC

Accelerated-Life Cells - 80% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.948	0.895	0.858	0.808	0.724	0.646									31.86%
			0.013	0.014	0.014	0.012	0.017	0.022									2.52%
80A55	321	G2.80A55.S321.NA.20.57.G.F	0.948	0.890	0.852	0.795	0.708	0.635									32.97%
80A55	336	G2.80A55.S336.NA.20.54.G.F	0.933	0.879	0.844	0.807	0.743	0.668									28.36%
80A55	436	G2.80A55.S436.NA.20.51.G.F	0.949	0.894	0.856	0.805	0.729	0.662									30.29%
80A55	443	G2.80A55.S443.NA.20.56.G.F	0.940	0.897	0.859	0.807	0.705	0.614									34.75%
80A55	446	G2.80A55.S446.NA.20.57.G.F	0.968	0.916	0.881	0.828	0.736	0.649									32.93%

Table A1.30. $C_1/1$ capacity fade for the 55°C accelerated-life Baseline cells at 100% SOC

Accelerated-Life Cells - 100% SOC			$C_1/1$ Capacity														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.948	0.875	0.832	0.773	0.720	0.679									28.45%
			0.006	0.007	0.010	0.016	0.019	0.021									1.86%
100A55	319	G2.100A55.S319.NA.20.54.G.F	0.956	0.884	0.848	0.799	0.750	0.712									25.49%
100A55	330	G2.100A55.S330.NA.20.58.G.F	0.947	0.870	0.828	0.772	0.718	0.676									28.56%
100A55	334	G2.100A55.S334.NA.20.58.G.F	0.948	0.875	0.829	0.771	0.721	0.681									28.14%
100A55	360	G2.100A55.S360.NA.20.60.G.F	0.952	0.879	0.833	0.770	0.712	0.668									29.89%
100A55	445	G2.100A55.S445.NA.20.60.G.F	0.939	0.867	0.821	0.756	0.699	0.656									30.16%

A1.8 Accelerated-Life Power Fade

Table A1.31. Power fade for the 25°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			34.16	33.64	33.18	32.45	32.14	30.83	30.10	29.01	28.06	27.03	25.91				23.22%
			0.762	0.926	0.770	0.655	0.941	0.327	0.482	0.423	0.185	0.298	0.095				0.55%
60A25	318	G2.60A25.S318.NA.40.23.G.T	33.49	32.80	32.56	31.83	31.26	30.45	29.76	28.71	27.93	26.82	25.84				22.83%
60A25	341	G2.60A25.S341.NA.20.11.V.F	34.99	34.63	34.04	33.14	33.13	31.06									11.24%
60A25	356	G2.60A25.S356.NA.40.24.G.T	34.01	33.49	32.95	32.37	32.03	30.98	30.44	29.31	28.19	27.25	25.98				23.61%

Table A1.32. Power fade for the 25°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			33.62	32.81	32.16	31.38	30.55	30.55	29.73	28.11	26.88	25.79	24.56				28.09%
			0.984	1.362	1.394	1.529	1.636	0.404	0.306	0.503	0.221	0.247	0.354				0.00%
80A25	346	G2.80A25.S346.NA.40.28.G.T	33.81	33.23	32.75	31.99	31.32	30.27	29.51	27.76	26.73	25.62	24.31				28.09%
80A25	433	G2.80A25.S433.NA.40.28.G.T	34.50	33.91	33.16	32.51	31.65	30.84	29.94	28.47	27.04	25.97	24.81				28.08%
80A25	447	G2.80A25.S447.NA.16.12.D.F	32.56	31.29	30.57	29.64	28.67										11.95%

Table A1.33. Power fade for the 25°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			34.905	33.081	31.824	30.900	29.604	28.170	26.799	24.994	23.943	22.571	21.284				39.81%
			0.713	0.704	0.856	1.059	1.465	1.551	1.451	1.241	0.558	0.606	0.574				0.88%
100A25	323	G2.100A25.S323.NA.40.40.G.T	35.05	33.20	32.05	31.10	29.84	28.61	27.09	25.28	23.55	22.14	20.88				40.44%
100A25	342	G2.100A25.S342.NA.08.09.D.F	34.95	32.92	31.82												8.96%
100A25	424	G2.100A25.S424.NA.40.39.G.T	35.67	33.95	32.74	31.84	30.94	29.45	28.08	26.07	24.34	23.00	21.69				39.19%
100A25	434	G2.100A25.S434.NA.28.30.G.T	33.95	32.25	30.68	29.75	28.04	26.45	25.22	23.64							30.37%

Table A1.34. Power fade for the 35°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			32.80	31.93	31.43	29.14	28.75	27.17	26.80	24.95	24.80	21.39					34.80%
			0.63	0.73	0.96	0.71	0.84	0.75	0.65	0.56	0.62	0.55					1.13%
60A35	329	G2.60A35.S329.NA.36.34.G.T	32.15	31.17	30.43	28.40	27.88	26.41	26.32	24.58	24.43	21.15					34.20%
60A35	361	G2.60A35.S361.NA.36.36.G.T	32.87	31.99	31.53	29.22	28.83	27.18	26.54	24.67	24.45	21.00					36.10%
60A35	442	G2.60A35.S442.NA.36.34.G.T	33.39	32.62	32.34	29.81	29.55	27.91	27.53	25.59	25.52	22.01					34.09%

Table A1.35. Power fade for the 35°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			33.46	31.88	31.65	28.98	28.55	26.46	25.70	23.54	23.05	19.18					41.75%
			0.534	0.970	1.334	1.185	1.107	0.881	0.862	0.794	0.619	0.247					1.63%
80A35	348	G2.80A35.S348.NA.36.43.G.T	33.08	31.19	30.70	28.15	27.77	25.84	25.09	22.98	22.61	19.00					42.56%
80A35	351	G2.80A35.S351.NA.36.43.G.T	33.83	32.56	32.59	29.82	29.33	27.08	26.31	24.11	23.49	19.35					42.81%
80A35	437	G2.80A35.S437.NA.36.40.G.T	32.59	31.39	30.77	28.60	28.06	26.27	25.74	23.82	23.53	19.60					39.87%

Table A1.36. Power fade for the 35°C accelerated-life Baseline cells at 100% SOC

Accelerated-Life Cells - 100% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			32.05	29.75	28.44	26.27	25.15	23.23	21.43	19.44	18.41	16.33					49.60%
			0.702	0.611	0.280	0.421	0.334	0.324	0.355	0.658	0.969	1.167					4.30%
100A35	428	G2.100A35.S428.NA.36.53.G.T	32.73	30.19	28.49	26.42	25.13	23.07	21.07	18.97	17.73	15.50					52.64%
100A35	435	G2.100A35.S435.NA.24.32.D.F	31.33	29.06	28.14	25.80	24.82	23.02	21.44								31.55%
100A35	444	G2.100A35.S444.NA.36.47.G.T	32.09	30.02	28.69	26.60	25.49	23.60	21.78	19.90	19.10	17.15					46.56%

Table A1.37. Power fade for the 45°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			32.92	30.68	30.04	28.53	26.98	25.52	24.45	22.33	21.03	18.88					42.64%
			1.453	1.440	1.061	1.111	0.964	0.850	0.669	0.542	0.443	0.751					0.26%
60A45	343	G2.60A45.S343.NA.36.43.G.T	34.43	32.20	31.20	29.67	28.03	26.47	25.22	22.96	21.53	19.65					42.93%
60A45	421	G2.60A45.S421.NA.36.42.G.T	31.54	29.33	29.12	27.45	26.14	24.82	24.02	22.02	20.87	18.15					42.45%
60A45	438	G2.60A45.S438.NA.36.43.G.T	32.80	30.53	29.79	28.47	26.77	25.28	24.12	22.02	20.69	18.85					42.53%

Table A1.38. Power fade for the 45°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			32.02	29.57	28.70	26.80	24.90	23.14	21.44	19.10	17.91	16.62					48.11%
			0.480	0.350	0.370	0.054	0.192	0.467	0.344	0.405	0.322	0.284					0.26%
80A45	325	G2.80A45.S325.NA.36.48.G.F	31.55	29.29	28.41	26.75	24.72	22.62	21.04	18.65	17.54	16.30					48.34%
80A45	333	G2.80A45.S333.NA.36.48.G.F	32.01	29.46	28.58	26.79	25.10	23.26	21.64	19.22	18.12	16.70					47.83%
80A45	432	G2.80A45.S432.NA.36.48.G.F	32.51	29.96	29.12	26.86	24.89	23.53	21.64	19.43	18.07	16.85					48.17%

Table A1.39. Power fade for the 45°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			32.27	28.19	26.09	22.72	19.61	17.73	16.12	14.64	13.88	13.17					59.19%
			0.909	0.557	0.681	0.578	0.503	0.654	0.507	0.653	0.561	0.494					1.77%
100A45	328	G2.100A45.S328.NA.36.59.G.F	31.03	27.28	25.28	22.32	19.44	17.60	15.83	14.40	13.75	12.78					58.83%
100A45	344	G2.100A45.S344.NA.36.57.G.F	31.83	28.20	26.72	23.36	20.03	18.30	16.60	15.25	14.37	13.60					57.28%
100A45	350	G2.100A45.S350.NA.36.62.G.F	32.88	28.79	26.77	23.09	19.75	17.63	15.97	14.66	13.96	12.50					61.99%
100A45	427	G2.100A45.S427.NA.36.60.G.F	33.37	28.34	25.52	21.94	18.81	16.75	15.51	13.67	13.00	13.50					59.54%
100A45	441	G2.100A45.S441.NA.36.58.G.F	32.26	28.36	26.16	22.88	20.00	18.37	16.68	15.22	14.34	13.45					58.30%

Table A1.40. Power fade for the 55°C accelerated-life Baseline cells at 60% SOC.

Accelerated-Life Cells - 60% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			33.89	29.37	28.11	26.55	25.01	22.79	20.09	18.02	15.78						53.42%
			0.322	0.191	0.109	0.055	0.156	0.161	0.359	0.321	0.252						1.11%
60A55	337	G2.60A55.S337.NA.32.54.G.F	33.95	29.16	27.99	26.52	24.85	22.67	19.87	17.78	15.55						54.20%
60A55	349	G2.60A55.S349.NA.32.54.G.F	34.18	29.54	28.21	26.61	25.03	22.72	19.89	17.89	15.75						53.92%
60A55	357	G2.60A55.S357.NA.32.52.G.F	33.55	29.40	28.13	26.52	25.17	22.97	20.50	18.38	16.05						52.15%

Table A1.41. Power fade for the 55°C accelerated-life Baseline cells at 80% SOC.

Accelerated-Life Cells - 80% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			34.96	29.39	26.70	22.26	18.13	15.76									54.85%
			1.254	1.000	0.762	0.665	0.632	0.322									2.36%
80A55	321	G2.80A55.S321.NA.20.57.G.F	35.64	29.39	26.33	22.10	17.95	15.39									56.82%
80A55	336	G2.80A55.S336.NA.20.54.G.F	34.29	28.78	26.51	22.41	18.36	15.89									53.67%
80A55	436	G2.80A55.S436.NA.20.51.G.F	33.22	28.23	26.01	22.36	18.61	16.19									51.25%
80A55	443	G2.80A55.S443.NA.20.56.G.F	35.17	29.64	26.65	21.30	17.12	15.50									55.92%
80A55	446	G2.80A55.S446.NA.20.57.G.F	36.48	30.88	27.99	23.15	18.63	15.84									56.57%

Table A1.42. Power fade for the 55°C accelerated-life Baseline cells at 100% SOC.

Accelerated-Life Cells - 100% SOC			Power at 300 Wh														
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	40 wk	44 wk	48 wk	52 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			35.53	27.99	22.39	19.19	16.61	14.91									58.00%
			0.486	0.185	0.439	0.655	0.631	0.647									2.18%
100A55	319	G2.100A55.S319.NA.20.54.G.F	34.80	27.83	23.02	20.19	17.57	15.90									54.32%
100A55	330	G2.100A55.S330.NA.20.58.G.F	35.79	27.96	22.60	19.31	16.59	14.92									58.32%
100A55	334	G2.100A55.S334.NA.20.58.G.F	36.05	28.28	22.35	19.25	16.79	15.09									58.13%
100A55	360	G2.100A55.S360.NA.20.60.G.F	35.70	28.03	22.08	18.64	16.05	14.36									59.77%
100A55	445	G2.100A55.S445.NA.20.60.G.F	35.31	27.84	21.91	18.55	16.04	14.31									59.49%

Appendix 2

Special Considerations

A2. SPECIAL CONSIDERATIONS

This appendix discusses testing issues and considerations from all three testing laboratories.

A2.1 Lot Numbers

The 30 Baseline cycle-life and 22 Baseline calendar-life cells came from Quallion Lot Number S00J-051. The 54 Baseline accelerated-life cells came from Lot Number S00J-201. The width of each electrode from Lot S00J-201 was made 1.5 mm smaller than Lot S00J-051 to achieve better manufacturability at Quallion. Although this modification was within specifications, it resulted in a 20-mAh drop in capacity. Lot S00J-201 also had a different electrode preparation date. Otherwise, there were no differences in material and process. All Variant C cells came from the same lot (VARIANT C).

A2.2 ATD Labeling Scheme

An ATD labeling scheme was established to provide the diagnostic laboratories with succinct information regarding the EOT status of the test cells. The label is updated periodically as testing progresses and is finalized at EOT. It is in the form of GX[X].AABCC.DEEE.FF.TT.PP.Z.S, where:

GX[X]	=	G2[C]
AA	=	test matrix state-of-charge (%)
B	=	test matrix profile (A, L, or C)
CC	=	test matrix temperature (°C)
D	=	original DOE laboratory (A, B, I, L, or S)
EEE	=	lab-specific cell number
FF	=	target power fade (%)
TT	=	time at life testing (weeks)
PP	=	power fade (%)
Z	=	abnormal condition flag
S	=	status.

The label begins with either G2 for the Baseline cells or G2C for the Variant C cells. The test matrix SOC, profile, and temperature (i.e., AABCC) identify the type of test, where accelerated-life (A), cycle-life (L), or calendar-life (C) testing is performed at a designated SOC and temperature. Next, the original DOE laboratory is identified (A = ANL, B = BNL, I = INEEL, L = LBNL, and S = SNL), along with the laboratory-specific cell number. The testing laboratories established a sequential numbering scheme such that all INEEL cells are numbered from 101 to 1XX, all ANL cells are numbered from 201 to 2XX, and all SNL cells are numbered from 301 to 3XX and 401 through 4XX.

The target power fade (i.e., FF) is the desired power fade at EOT (Section 3.4). Once the actual power fade (i.e., PP) meets or exceeds the target power fade, the cell is removed from test and shipped to a diagnostic laboratory. The time at life testing (i.e., TT) shows the number of weeks the cell has been aging in 4-week increments. If the cell has only been characterized, a target power fade cannot be established (Appendix C in Attachment 1), and power fade is 0% (Section 3.3). Therefore, slots FF.TT.PP are identified as 00.CC.00 to indicate characterization testing only. If, however, a cell fails before characterization testing, the three slots are labeled 00.NA.NA. If a target power fade is not identified (e.g., the accelerated-life Baseline cells), this slot is marked as NA.

The abnormal condition flag identifies any problems, such as shorting (S), venting (V), leaking (L), puncturing (P), or damaged tab(s) (T). Otherwise, the cell is marked good (G). The status flag either shows that the cell is still on test (T), has finished testing (F), or has been sent to a diagnostic laboratory (e.g., A, L, B, or Q for Quallion).

For example, G2.60L25.I110.14.36.16.G.L is INEEL Cell 110, a Gen 2 Baseline cell. It was cycle-life tested at 60% SOC and 25°C for 36 weeks before being taken off test with 16% power fade, having exceeded the target power fade of 14%. The cell was in good condition when it was shipped to LBNL for diagnostic analysis.

A2.3 Calendar-Life Special Considerations

A2.3.1 Tab Welds

The receipt inspection of the Variant C cells prior to testing showed fragile tabs. The cell ends were burned, and the heat-affected zone in the weld area was dull instead of bright. There was no indication of these problems during the receipt inspection of the Baseline cells.

A2.3.2 Early Cell Failures

Five of the Variant C cells arrived with OCVs less than the minimum discharge voltage of 3.0 V (Section 2.1). As a result, these cells were removed from the test matrix and returned to Quallion for analysis prior to testing.

A2.3.3 Low Power Fade

The calendar-life cells that were tested at 55°C were originally slated to test at 45°C. However, the initial power fade after 4 weeks of testing for some cells at 45°C were low. As shown in Table A1.5 of Appendix 1, some cells (e.g., G2.60C55.A211.30.40.31.G.L) showed little or no fade while others (e.g., G2.60C55.A214.33.40.34.G.L) showed power growth. As a result, the test temperature was increased to 55°C to accelerate cell degradation. Therefore, the 55°C calendar-life cell test time dependencies shown in Figures 7, 18, 38, 55, 59, and 62 do not include the 4-week data. The coefficients of determination (R^2) in Tables 5, 10, 14, 19, 21 and 23 also do not include the first 4 weeks of aging.

A2.4 Cycle-Life Special Considerations

A2.4.1 Receipt Inspection

The receiving inspection conducted before testing confirmed that no cells were damaged other than G2C.60L45.I173.00.NA.NA.L.Q (see Section A2.2 for details on the ATD labeling scheme and Section A2.4.5 for information on this cell). This included visual inspection and measuring cell weights, OCVs, and impedance at 1 kHz. Figure A2.1 shows the 15 Variant C cells that arrived on July 30, 2001. Table A2.1 summarizes the average receipt inspection measurements for the 25°C Baseline cell, the 45°C Baseline cell, and the 45°C Variant C cell groups, respectively. All three cell groups show similar weights and OCVs, but the Variant C cells show a lower impedance at 1 kHz. (The Variant C cell group average does not include Cell 173, which was returned to Quallion due to poor performance.)

Figure A2.1. Fifteen Variant C cells, as received.

Table A2.1. Receipt inspection measurements for the three cycle-life cell groups.

Cycle-Life Cell Group	Receipt Inspection Date	Weight (g ± σ)	OCV (V ± σ)	Real Impedance at 1 kHz (mΩ ± σ)
Baseline Cells at 25°C	01/09/01	38.85 ± 0.28	3.56 ± 0.04	12.67 ± 0.97
Baseline Cells at 45°C	01/09/01	38.76 ± 0.14	3.58 ± 0.03	12.26 ± 0.21
Variant C Cells at 45°C	07/30/01	38.33 ± 0.21	3.53 ± 0.25	10.61 ± 0.42

A2.4.2 Temperature Control

All testing was performed with cells placed in environmental chambers to control ambient temperature. The chambers control the temperature to within ±3°C, as specified in the test plan (see Attachment 1). Also, all Gen 2 cells have been placed in thermal blocks in order to more uniformly control the cell temperature and minimize temperature transients. Before testing Gen 2 cycle-life cells, two thermal block temperature control experiments were conducted. Ten 1.5-W heaters were placed in a block to simulate the Gen 2 cells under representative testing loads. Thermocouples were placed on each heater, and seven additional thermocouples were placed in various positions on the block itself. The ambient temperature was brought to 25°C, and after 5 minutes, the heat sources were activated. After 30 minutes, the heat sources were deactivated. This procedure was then repeated at 35, 45, and 55°C. The first control experiment involved controlling the ambient temperature using the resistance temperature detector (RTD) in the environmental chamber. Figure A2.2 shows the results from a block that was controlled using the RTD. The heater (simulated cell) temperatures rise monotonically and become steady at about 5°C hotter than the control (ambient) temperature. The second test involved controlling the ambient temperature using the thermocouples embedded in the block. The results are presented in Figure A2.3. At lower temperatures (i.e., 25 and 35°C), this yielded nonsteady heater temperatures that varied by ±2°C around the target temperature. At higher temperatures (i.e., 45 and 55°C), the heater temperature was steady. For both Figures A2.2 and A2.3, the block temperatures are slightly higher than the heater temperatures, since the thermocouples on the heaters were insulated. These figures demonstrate that controlling the ambient temperature using the RTD is more stable.

Figure A2.4 shows seven Gen 2 cycle-life cells in a thermal block. The sense lead wires were secured to a stress relief fastener above and to the right of each cell, and another fastener on the top of the block. Figure A2.4 also shows the thermocouple attached to each cell using adhesive tape. The adhesive tape is secured to the cell with cable tie. All thermocouple wires are cable-tied together with the voltage and current sense leads, and held in place with a strength relief fastener (as shown on the far left fastener on the top of the thermal block). These restraints allow for some movement of the sense lead wires (e.g., plugging and unplugging the leads from the tester) without stressing the cell tabs.

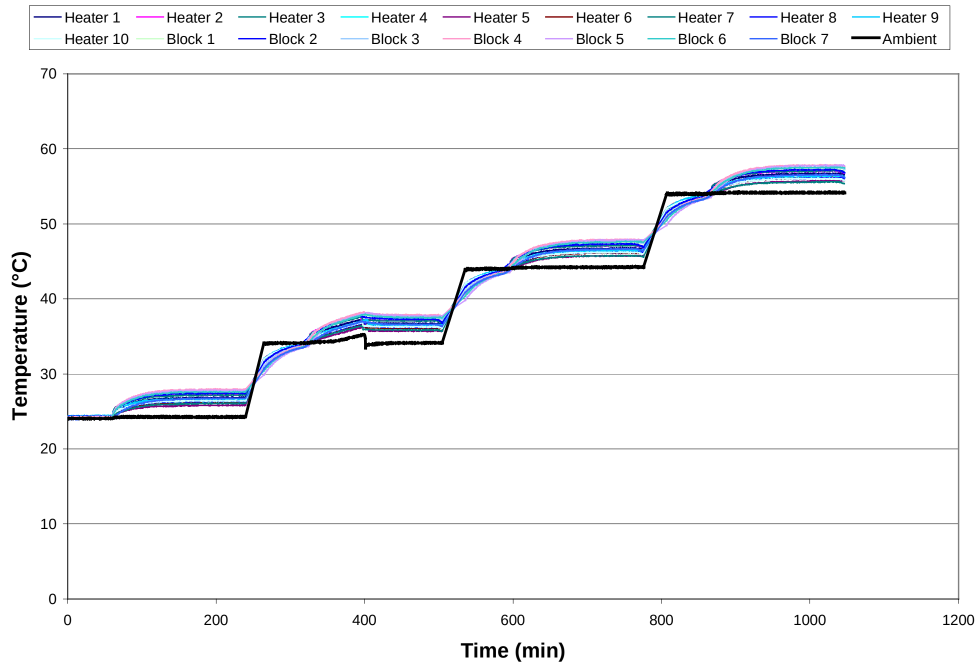

Figure A2.2. Thermal block temperature control experiment with ten heat sources (RTD control).

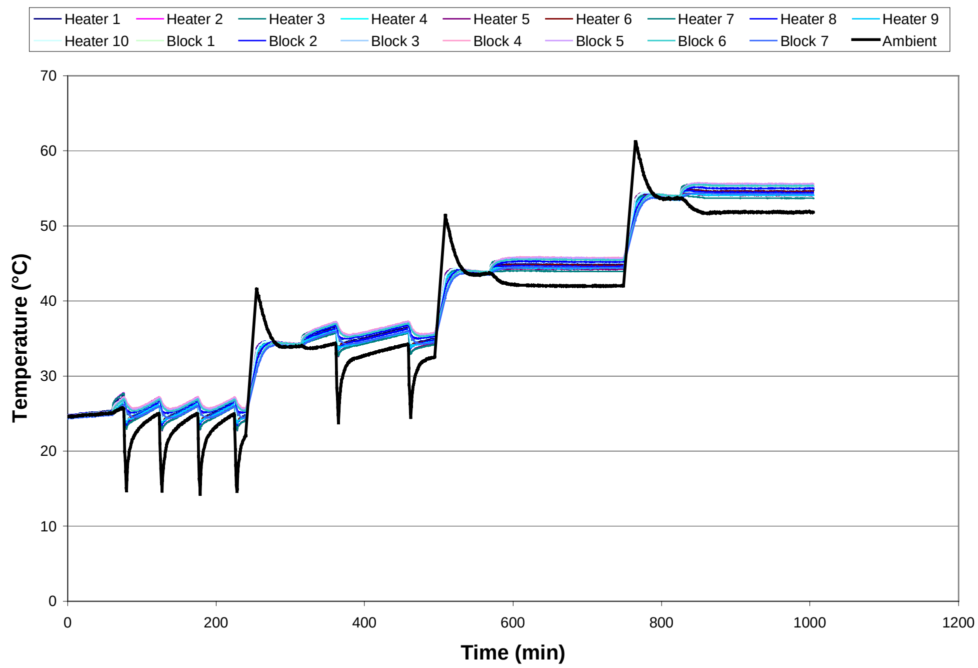

Figure A2.3. Thermal block temperature control experiment with ten heat sources (block control).

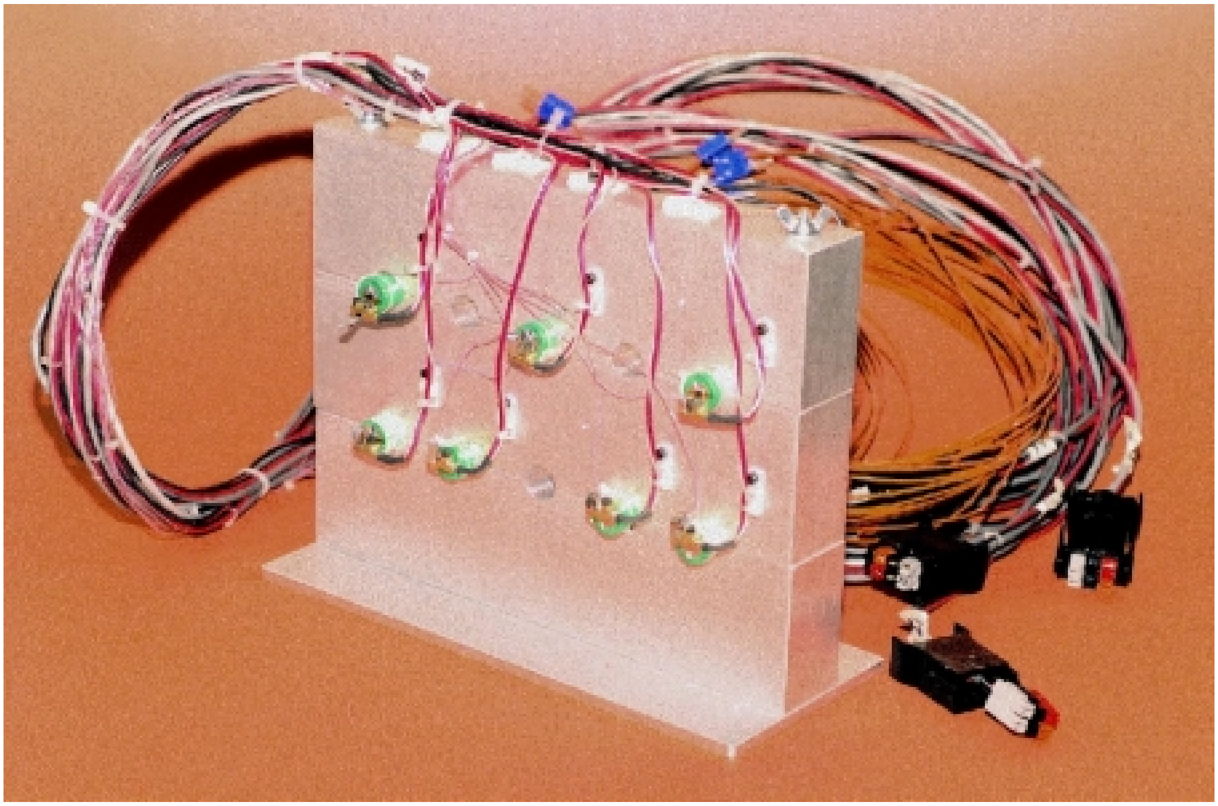

Figure A2.4. Thermal block with seven Gen 2 cycle-life cells.

A2.4.3 Tab Issue

The Gen 2 cells arrived with aluminum positive tabs and high-impedance nickel negative tabs. Since the tab welds were very weak and it was difficult to attach test leads, ⅛- by ¼-in. brass connectors were built for all cycle-life cells. The tester voltage and current sense leads were soldered into the brass connectors. In addition, to minimize the tab impedance, thin round vellum insulators (with a small slit in the middle for the tab) were installed on the negative end of each cell. Their purpose is to provide electrical isolation and allow the connectors to be attached as close to the cell as possible, thereby minimizing the impedance of the tab to the tester connector. Figure A2.5 shows a close-up of a cycle-life cell on a thermal block. The vellum insulator and brass connectors on the negative tab are shown, along with the voltage and current sense lead wires (black wires) attached to the cell tab through the brass connector.

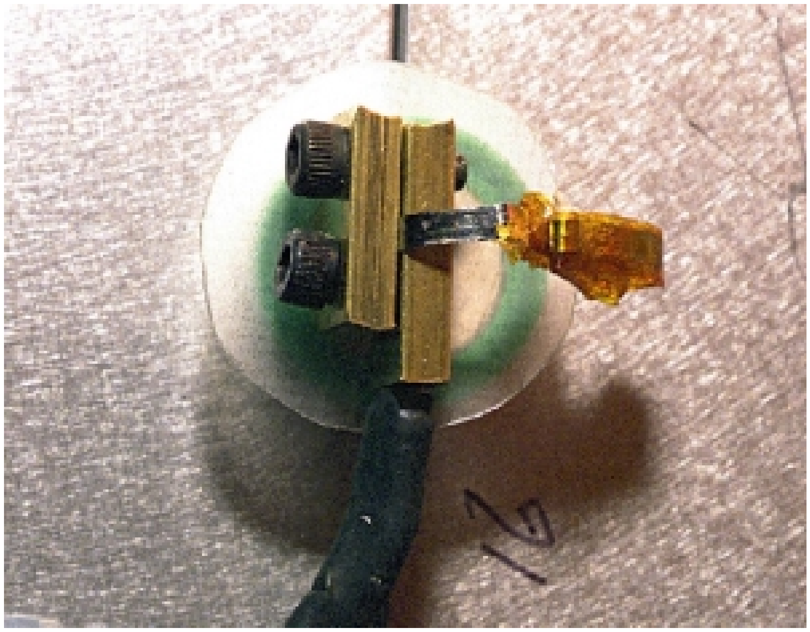

Figure A2.5. ATD Gen 2 cycle-life cell with brass connectors and vellum insulator on the negative tab.

A2.4.4 Tab Failure

On January 23, 2001, the INEEL hooked up one cell (G2.60L25.I101.00.NA.NA.T.A) to the tester and began characterization testing in accordance with the cell-specific test plan (Attachment 1). Shortly after completing five $C_1/1$ static capacity tests and three electrochemical impedance spectroscopy tests at 60% SOC (test descriptions are provided in Section 3), it was discovered that the negative tab had failed. The OCV was measured and it was still at the target, corresponding to 60% SOC (Appendix D of Attachment 1). The cell may have been inadvertently shorted, resulting in a melted tab. The cell did not appear to have any internal damage, and there was no evidence of venting. As directed by the ATD Program Manager, the cell was shipped to ANL for diagnostic work, and the INEEL received a replacement cell (G2.60L25.I176.00.CC.00.G.B) on February 5, 2001. Figure A2.6 shows the failed negative tab on G2.60L25.I101.00.NA.NA.T.A.

A2.4.5 Vent Failure

The receipt inspection (Section A2.4.1) of the cycle-life Variant C cells revealed that one of the cells (G2C.60L45.I173.00.NA.NA.L.Q) had self-discharged below the 3.0 V minimum. This cell also showed high impedance at 1 kHz (15.0 – j2.5 mΩ compared to an average of 10.6 – j0.2 mΩ). Two days later, when all Variant C cells were connected to the tester for $C_1/1$ testing, the open-circuit voltage (OCV) of G2C.60L45.I173.00.NA.NA.L.Q had drifted down to 0.92 V. The $C_1/1$ capacity test showed only 0.67 A·h. Therefore, as directed by the ATD Program Manager, the cell was returned to Quallion. Quallion discovered that the vent on this cell was broken, and some electrolyte had leaked out. Figure A2.7 shows the hole in the vent, along with the electrolyte leakage.

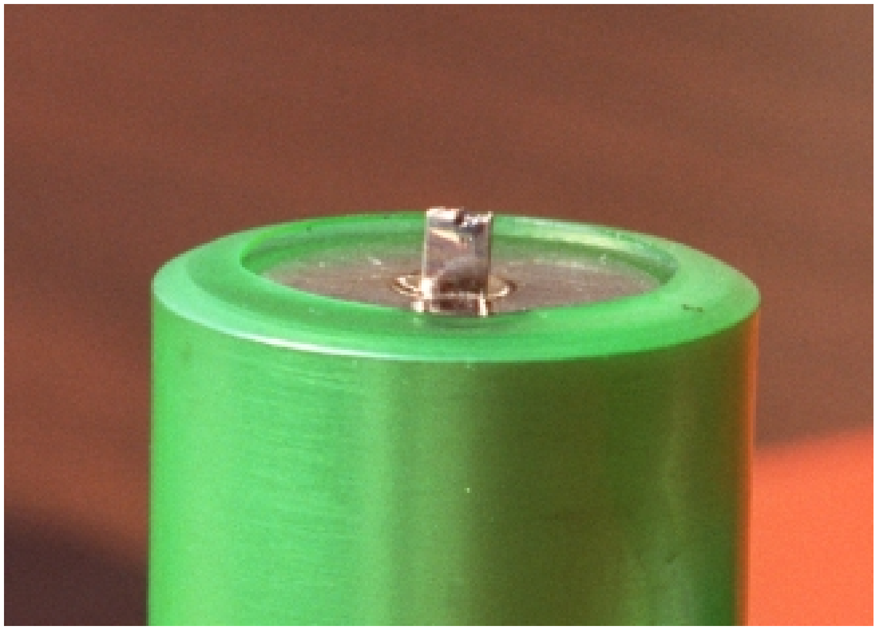

Figure A2.6. G2.60L25.I101.00.NA.NA.T.A with failed tab.

Figure A2.7. G2C.60L45.I173.00.NA.NA.L.Q with broken vent and electrolyte leakage.

A2.5 Accelerated-Life Special Considerations

A2.5.1 Tab Failure

The receipt inspection conducted prior to testing the accelerated-life Baseline cells revealed very fragile tab welds. Specifically, the weld on the positive tab could easily be torn with gentle handling. Figure A2.8 shows how the aluminum/nickel weld can "unzip." Therefore, prior to testing, all accelerated-life cells were reinforced with an aluminum strip. The strip was LASER welded to the positive tabs, as shown in Figure A2.9.

Figure A2.8. Aluminum/nickel welds on the positive tab

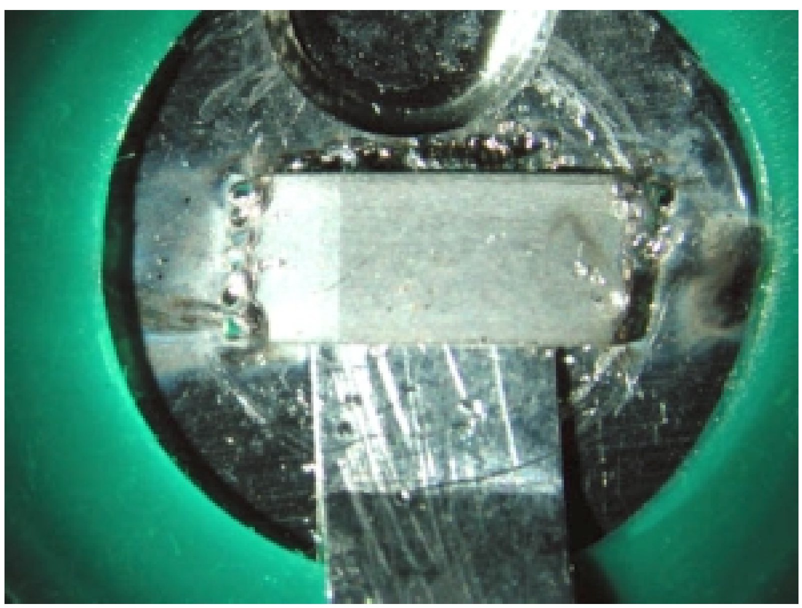

Figure A2.9. Reinforcement aluminum strip on the positive tabs.

A2.5.2 Early Cell Failures

Eight of the accelerated-life cells failed prior to any testing. Seven had self-discharged below the minimum discharge voltage of 3.0 V (Section 2.1). The other cell was punctured at the vent by the probe of a voltmeter. As a result, these cells were removed from the test matrix.

Four cells failed during accelerated-life testing due to equipment or handling problems. Cell G2.60A25.S341.NA.20.11.V.F vented on the 27th or 28th day of aging on February 19, 2002. It was later determined that the cell was testing on a bad Maccor channel. Cell G2.100A25.S342.NA.08.09.D.F was removed from test on October 15, 2002 due to a probable overcharge. It was replaced in the testing matrix with G2.100A25.S434.NA.28.30.G.T. Cell G2.100A35.S435.NA.24.32.D.F was removed from test on April 24, 2002 due to a possible over discharge while discharging to the target SOC for an EIS test. Cell G2.80A25.S447.NA.16.12.D.F was removed from test on January 14, 2002 due to an overcharge during a $C_1/10$ test. These cells failed because the test leads were incorrectly reattached to the cells following an EIS test.

A2.5.3 0°C L-HPPC Test

In addition to the standard RPT, the accelerated-life cells were also regularly subjected to the L-HPPC test at 0°C. Its purpose was to magnify the changes in cell degradation as well as give an indication of the change in rate of the power fade. However, no dramatic effect was realized, and this test was eliminated after the 24-week RPT.

Appendix 3

Testing

A3. TESTING

This appendix presents additional testing details not discussed in Section 3.0 of the main report.

A3.1 Characterization Testing

The characterization tests performed for the calendar-, cycle-, and accelerated-life tests are summarized in Table A3.1. As shown, the accelerated-life cells were subjected to an additional EIS at 100% SOC and a 0°C L-HPPC test (see Section A2.5.3 of Appendix 2).

Table A3.1. Characterization tests performed at each laboratory.

Temperature (°C)	Calendar-Life	Cycle-Life	Accelerated-Life
25	5 C_1/1 discharges	5 C_1/1 discharges	5 C_1/1 discharges
25	C_1/25 discharge	C_1/25 discharge	C_1/25 discharge
25	C_1/25 charge	C_1/25 charge	
25			EIS at 100% SOC
25	EIS at 60% SOC	EIS at 60% SOC	EIS at 60% SOC
25	L-HPPC	C_1/1 and L-HPPC	L-HPPC
0			L-HPPC

The specific equipment used for EIS measurements on the calendar-, cycle- and accelerated-life cells varies, as shown in Table A3.2. Although the equipment is identical for the calendar- and cycle-life cells, the cycle-life cell equipment is much older. This may result in a much higher high-frequency capacitive tail, as seen with the cycle-life EIS results compared to the calendar-life cells (see Figures 43 through 46). EIS measurement issues are discussed in Section A4.1 of Appendix 4.

Table A3.2. EIS equipment.

Equipment	Calendar Life	Cycle Life	Accelerated Life
EG&G potentiostat/galvanostat	Model 273A	Model 273A	Model 273A
Solartron frequency analyzer	Model 1260	Model 1260	Model 1255
Control software	Zplot	Zplot	M398

A3.2 Reference Performance Testing

The sequence and order of tests for the calendar-, cycle- and accelerated-life RPTs is summarized in Table A3.3. The accelerated-life C_1/10 static capacity test was initiated after 8 weeks of aging. The accelerated-life 0°C L-HPPC test was discontinued after 24 weeks (see Section A2.5.3 in Appendix 2).

Table A3.3. Reference performance test sequence.

Temperature (°C)	Calendar-Life	Cycle-Life	Accelerated-Life
25	C_1/1 discharge	C_1/1 discharge	5 C_1/1 discharges
25	C_1/25 discharge	L-HPPC	C_1/25 discharge
25	C_1/25 charge	C_1/25 discharge	EIS at 60% SOC
25	EIS at 60% SOC	C_1/25 charge	EIS at 100% SOC
25	L-HPPC	EIS at 60% SOC	2 C_1/1 discharges
25			C_1/10 discharge
25			L-HPPC
0			L-HPPC

Appendix 4

Results

A4. RESULTS

A4.1 EIS Round Robin

Prior to testing the Gen 2 cells, the three test laboratories (INEEL, ANL, and SNL) validated their respective EIS equipment and testing processes (see Table A3.2 in Appendix 3) by testing a test circuit dummy cell manufactured by SNL. The test cell circuit is shown in Figure A4.1. The theoretical response of this circuit was calculated using Equation A4.1 and is shown in Figure A4.2.

$$Z = \left[R_1 + \frac{R_2 + \omega^2 C^2 R_2 R_3 (R_2 + R_3)}{1 + \omega^2 C^2 (R_2 + R_3)^2} \right] - j \left[\frac{\omega C R_2{}^2}{1 + \omega^2 C^2 (R_2 + R_3)^2} \right]. \qquad \text{(A4.1)}$$

The actual responses from the three testing laboratories, along with the theoretical response, are shown in Figure A4.3. As shown, the different equipment combinations yield different results. All test cell measurements show higher solution resistances than the theoretical response. This is primarily due to the placement of the connectors on the cell tabs. The cell tabs have high impedance and it has been verified that a slight adjustment of the connectors will significantly affect the position of semicircle but not the width. The ANL calendar- and INEEL cycle-life cells show a high-frequency capacitive tail due to the four-terminal connection. The SNL accelerated-life cells show an inductive high-frequency tail due to the three-terminal connection. A three-terminal connection also measures cable impedance and needs to be subtracted out.

Figure A4.4 shows the EIS test cell measurements normalized to the theoretical response. This was done by subtracting the real impedance data by the difference between the point at which the test cell initially crosses (or is nearest to) zero and the initial real impedance of the theoretical response. As shown, the semicircles of the three testing laboratories match the theoretical response in faradaic resistance and amplitude. Therefore, although the high-frequency tail and the solution resistances are different among the testing laboratories, the percentage growth of the semicircles (Section 4.3.3) is comparable.

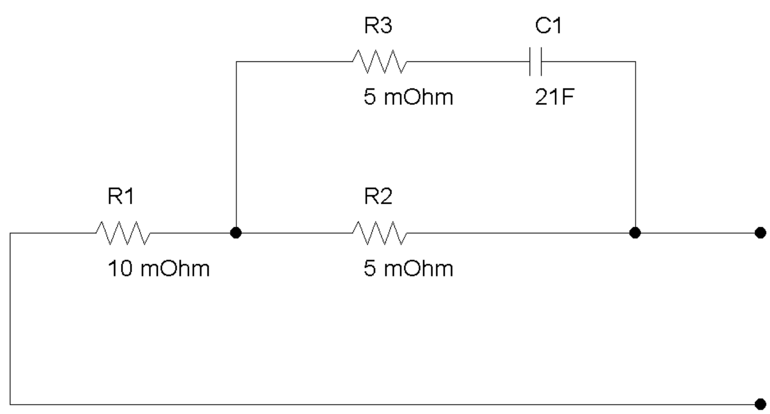

Figure A4.1. Test cell circuit.

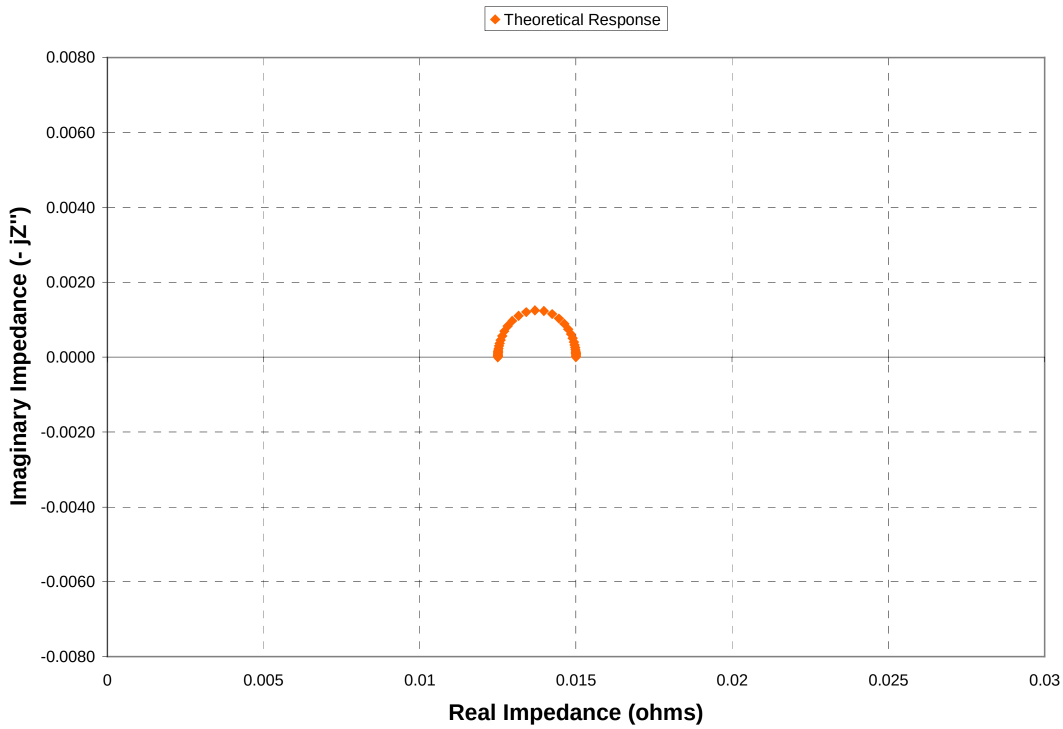

Figure A4.2. Theoretical response of the test cell.

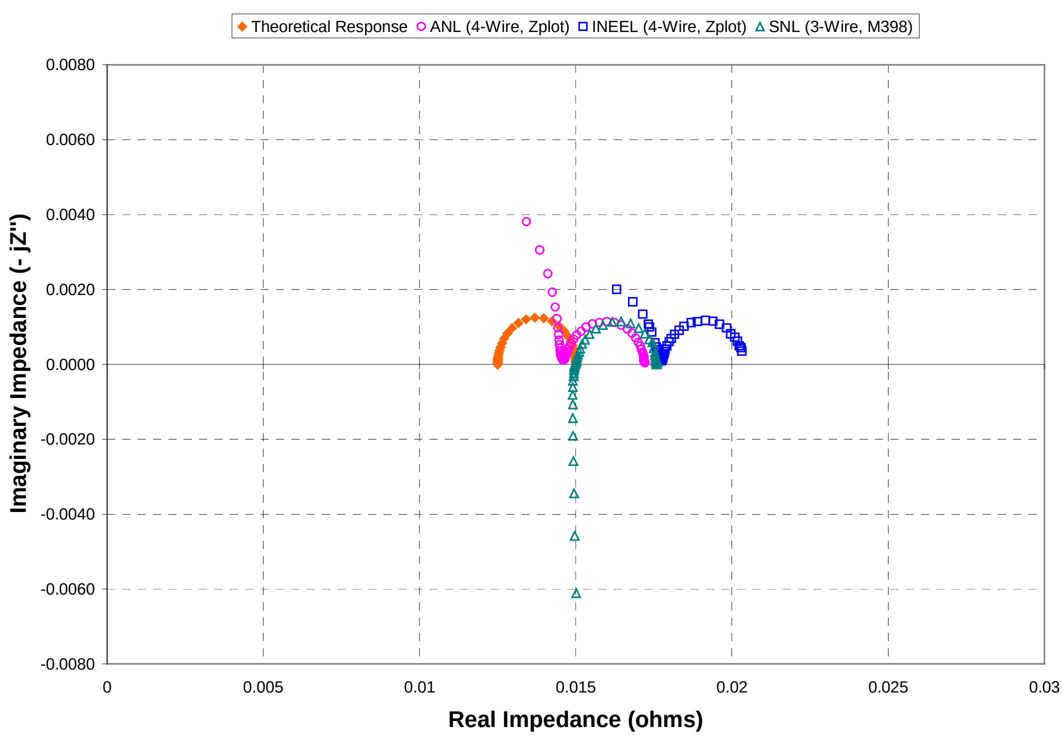

Figure A4.3. Actual response to test cell.

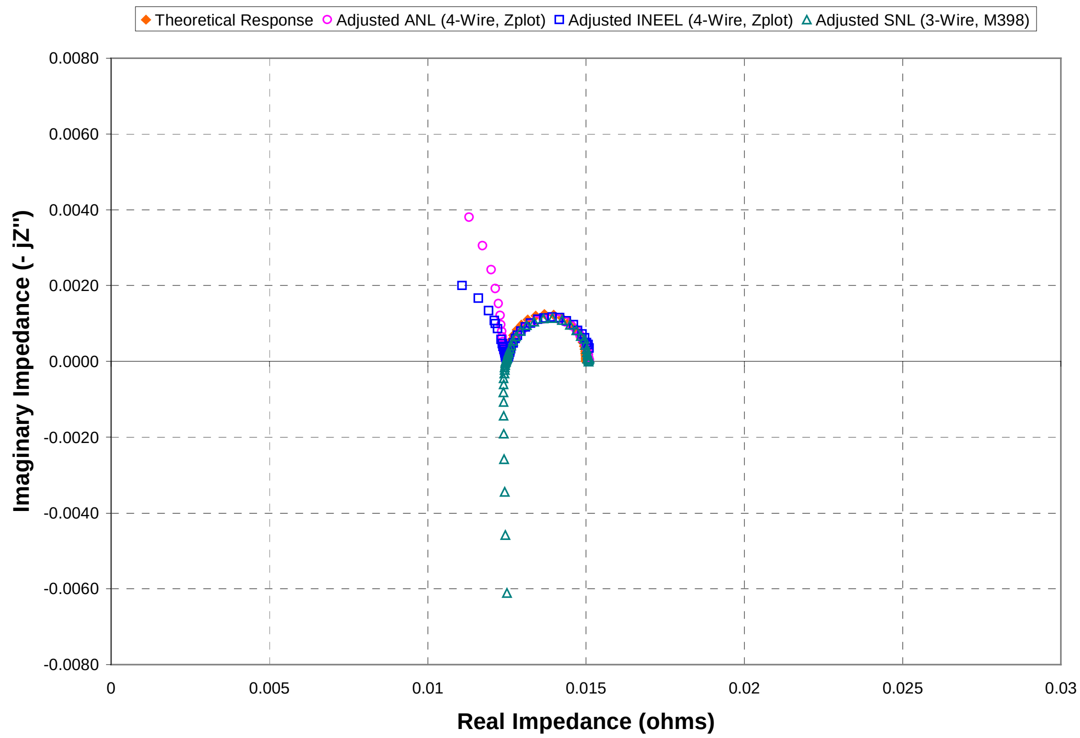

Figure A4.4. Adjusted response to test cell.

Attachment 1*

PNGV Test Plan for Advanced Technology Development Gen 2 Lithium-Ion Cells

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* Attachment 1 is Revision 6a of the ATD Gen 2 test plan. This incorporates some minor editorial changes from the previously released version (Revision 6 on October 5, 2001) and does not impact testing procedures. If significant changes to the test plan are required in the future, INEEL will issue Revision 7 and include the changes from Revision 6a.

Attachment 1
EHV-TP-121
Rev 6a, September 4, 2002

PNGV TEST PLAN
FOR
ADVANCED TECHNOLOGY DEVELOPMENT
GEN 2 LITHIUM-ION CELLS

Reviewed: ______________________________ __________________
INEEL/ANL/SNL Program/Project Engineer — Date

Reviewed: ______________________________ __________________
INEEL/ANL/SNL Laboratory Manager — Date

Approved: ______________________________ __________________
INEEL/ANL/SNL Department Manager — Date

PNGV TEST PLAN
FOR
ADVANCED TECHNOLOGY DEVELOPMENT
GEN 2 LITHIUM-ION CELLS

Concurred: ______________________________ ______________
DOE Program Manager Date

Concurred: ______________________________ ______________
DOE Test Manager Date

Concurred: ______________________________ ______________
DOE Technical Contact Date

PNGV Test Plan
for
ATD GEN 2 Lithium-Ion Cells

1.0 Purpose and Applicability

The intent of this testing is to characterize the performance and to determine the cycle life and calendar life behavior of lithium-ion cells (nominal 1.0 Ah capacity). The cycle life testing will be performed at the Idaho National Engineering and Environmental Laboratory (INEEL) and the calendar life testing will be performed at the Argonne National Laboratory (ANL). This work is being done as part of an Advanced Technology Development (ATD) Program project for the improvement of high-power lithium-ion batteries. The testing is sponsored by the DOE Office of Advanced Automotive Technologies (OAAT) and is under the oversight of OAAT and the designated DOE Program Manager. In general, these cells will be subjected to the characterization, reference performance, and life test procedures that have been defined for the PNGV Program as specified in Reference 2.1. The cells covered by this test plan are 18650-size baseline and variant cells manufactured by Quallion specifically for Gen 2 of the PNGV ATD Program, which have been built to ATD specifications. The baseline cell chemistry is defined in Reference 2.4. The Variant C chemistry uses the baseline chemistry except for the a change to the Cathode.

2.0 References

2.1 PNGV Battery Test Manual, Revision 3, DOE/ID-10597, February 2001
2.2 EST Laboratory Standard Practices
2.3 IHRG# BAT-99-622 Battery and Capacitor Testing in the Energy Storage Technologies Laboratory.
2.4 "Gen 2 Baseline & Variant Cells," ATD Quarterly, Presentation by Gary Henriksen, Albuquerque, N.M., November 2000.

3.0 Equipment and Hardware

3.1 All testing will be performed on laboratory cell test channels with current and voltage capabilities adequate for the specific test procedures to be performed. In general, lower voltage ranges should be used where available (5V preferred, not to exceed 20V) to assure the best voltage resolution and accuracy.

3.2 Except where noted otherwise, testing will be performed with the cells at a temperature of 25 ± 3°C at the beginning of a test sequence, although maintaining a tighter tolerance should be attempted. The preferred means to accomplish this is by the use of a thermal block and a controlled temperature chamber having both heating and cooling capabilities. Unless otherwise specified, all temperature measurement and control should be based upon the cell skin temperature, or equivalent. Test temperature will be controlled by the RTD (Resistance Temperature Detector) in the environmental chamber.

3.3 The temperature of cells under test should be measured using moderately fast response sensors (e.g. ≤3/16" thermistors or pad-type thermocouples such as Omega Model SA-1) adhered to the positive end of each cell. Sensors should be fastened to the cell using a means (e.g. epoxy, tape or clamp) which provides consistent contact.

3.4 AC impedance measurements at 1 kHz will only be made as part of the receipt inspection. Spectral impedance measurements will be made throughout testing. The associated equipment is described in Appendix E.

4.0 Prerequisites and Pre-Test Preparation

4.1 Before testing starts, the cells will be assigned lab-specific identification numbers. A battery notebook for the cells will be started, and both the ATD and test laboratory identification numbers (if different) will be recorded for each cell. The table described in Appendix A should be completed and maintained throughout the ATD test program. Once testing begins, additional information should be added to the table, including the periodic recording of capacity, pulse power, temperature, dates, and other pertinent information. An End-Of-Testing (EOT) labeling convention has been created for Gen 2. The principal purpose is to provide the diagnostics labs succinct information regarding the EOT status of these cells. At a minimum, the label for each cell will be established at the beginning of testing and updated at the end of testing. Optionally, the label may be updated periodically as testing progresses. The ATD labeling convention is as follows:

GX.AABCC.DEEE.FF.TT.PP.Z.S, where

GX[X] G1, G2, or G3 for Gen 1, Gen 2, or Gen 3, respectively, and [X] = A, B, or C as appropriate for each variant.
AA Test Matrix State of Charge, e.g., 60%
B Test Matrix profile, e.g., S, L, C and A, where S = in storage, L = cycle life cell, C = calendar life cell, and A = accelerated life test
CC Test Matrix Temperature, (°C)
D Original DOE Laboratory, A = ANL; B = BNL; I = INEEL; L = LBNL; S = SNL
EEE Sequential cell number as assigned by Original DOE Laboratory:
INEEL: 101 through 1XX
ANL: 201 through 2XX
SNL: 301 through 3XX, and

401 through 4XX

FF Target power fade (%) based on equal power fade increments (see Appendix C).

TT Time at life testing, CC = Characterization or 00, 04, etc (wks)

PP PNGV Power fade relative to the 0 week L-HPPC Reference Performance Test (%). By definition the PNGV power fade at 0 weeks is 00%. (Enter NA for Characterization Power Fade, and ND for No Data.) If the characterization tests are performed within 2 weeks prior to commencing life testing, they are defined as the 0 week L-HPPC Reference Performance Test.

Z Abnormal condition flag: S = shorted; V = vented; P = punctured; L = leaked; T = tab problem; G = Good.

S[S] Status: T = test continuing; F = finished testing and in storage. Or if shipped to another laboratory then, A = shipped to ANL; B = shipped to BNL; I = shipped to INEEL; L = shipped to LBNL; Q = shipped to Quallion; S = shipped SNL. [S] = additional status flags as appropriate to track the history of the cell.

Note: Diagnostic lab cells may utilize this convention by placing an X in any field that is not applicable to that cell.

4.2 The cells will be visually inspected for signs of shipping or other damage. Any signs of damage should be documented. The maximum outside diameter of the cells, the cell lengths, actual weights and open circuit voltages as delivered will be recorded. The cell weights will include the cell current tabs. Also, to further confirm that the cells are not damaged, perform an AC impedance measurement at 1 kHz and record the value for each cell.

4.3 Prior to start of testing, a pre-test readiness review shall be conducted using the released version of this test plan and the associated test procedures. This review should be attended by (as a minimum) the project engineer (or designee), the laboratory manager, and the test engineer assigned to perform this testing. An external readiness review involving DOE and the ATD Program Manager may be required at their discretion, and it may be in addition to, or in lieu of, an internal review. This review may be conducted by conference call.

5.0 <u>Cell Ratings, Test Limitations and Other Test Information</u>

5.1 Ratings

Baseline Cell Rated Capacity:	1.0 Ah (C_1/1 rate)
Variant C Cell Rated Capacity	0.8 Ah (C_1/1 rate)
PNGV Application:	*Power Assist*

Battery Size Factor:	*553 (Baseline)* *651 (Variant C)*

HPPC Pulse Power Voltage Calculation Range:

Vmin	*3.0 V*
Vmax	*4.1 V*

Operating Temperature Range:	-20°C to +60°C
Maximum Discharge Temperature:	60°C, cell temperature
Maximum Charge Temperature:	40°C, cell temperature
Storage Temperature:	10°C ± 3°C

5.2 Nominal Values

Baseline Cell Nominal Capacity:	0.979 Ah
Variant C Cell Nominal Capacity	0.826 Ah
Nominal Weight:	TBD kg
Nominal Volume:	TBD L

5.3 Discharge Limits

Minimum Discharge Voltage:	3.0 V *18 sec pulse* 3.0 V *Continuous*
Maximum Discharge Current:	8.0 A *18 sec pulse* (I_{max}) *2.0 A Continuous*

5.4 Charge and Regen Limits

Maximum Regen Voltage:	4.3 V *10 sec pulse* 4.1 V *Continuous*
Maximum Regen Current:	8.0 A *10 sec pulse* 1.0 A *Continuous*

5.5 Charge Procedure: For the baseline cells, charge at 1.0 A constant current rate to a voltage of 4.1 V (charge at 0.8 A for the Variant C cells); continue to maintain a constant voltage of 4.1 V for 2.5 hours total recharge time. All recharging is to begin at 25 ± 3ºC, unless specifically stated otherwise.

5.6 Recharge Constraints

If a procedure requires a cell to be fully charged at the start of the test sequence, the cell will be considered fully charged (i.e. need not be subjected to a 'top off' charge) if it was fully recharged no more than 72 hours previously, and the SOC is within 2% (see Appendix D).

5.7 Life Cycle Test Conditions:

Nominal State of Charge For Life Cycle and Calendar Life Testing:	60% SOC (see Appendix D for corresponding voltage)

5.8 End-of-Testing Criterion:

1. Completion of the specified life interval (see Appendix C); or
2. When directed by the DOE Program Manager or DOE Technical Contact.

Note: Notify the DOE Program Manager or DOE Technical Contact if the cell is unable to successfully perform the HPPC test through the 60% DOD pulse.

6.0 <u>Safety Concerns and Precautions</u>

In general, the safety issues with these cells are similar to those encountered previously with lithium-ion cells tested for the PNGV program. Thus, the same precautions will be exercised as are normally used for lithium-ion cells.

6.1 Cell Handling

- Cells should be handled whenever possible in the discharged state.
- Safety gloves suitable for handling high-energy batteries should also be worn for cell handling unless the specific operations being performed cannot be accomplished while gloved.
- Due care should be taken to avoid shorting the cell terminals. Caution: the cell case is electrically tied to the positive terminal! Electrically isolate the thermal blocks from the environmental chamber.
- Cells should be shipped in a discharged state (between 10% to 25% SOC).

6.2 Other Safety Precautions

- For both testing and storage, cells should be located within an area shielded from non-deliberate exposure to personnel. Cells that show any signs of deterioration or unanticipated behavior should be segregated from other cells to avoid propagation of damage in the event of a failure.

- Charged cells should not be located close to flammable and/or combustible materials

- Venting of cells should be regarded as a possibility. Lab personnel response to any unanticipated release of fumes or smoke at the test location should be to evacuate the immediate area (e.g., test room). The laboratory manager (or equivalent) and safety personnel should be notified. Approval from the laboratory manager should be obtained prior to reentering the testing area. (Note: if it is very clear that only minor venting is occurring, the situation may be observed at a safe distance to determine whether the release ceases without further action.)

- It has been shown during abuse testing (thermal abuse and intentional overcharging) that the cells experienced catastrophic failure and the vents did not function.

In case of unexpected cell behavior (e.g. venting), the cells should not be approached for at least one hour afterward.

7.0 <u>Tests to be Performed Under this Test Plan</u>

All cells will be subjected to the characterization performance test sequence in Table 1. The cells will be tested according to the Power Assist goals and requirements. Battery Size Factors (BSF) for the four types of Gen 2 cells (e.g. baseline and the three variants) will be calculated using an average of the cells of that type.

All recharging between tests is to be done using the recharge procedure of Section 5.5. In general, a rest step of nominally 60 minutes shall be observed after each charge, and nominally 60 minutes after each discharge, to allow cells to reach stable voltage and temperature conditions prior to proceeding with testing.

Note 1. Except for the HPPC tests, use the corresponding open circuit voltage as a measure of State-of-Charge. (For HPPC tests, removed-capacity will be used as the measure of Depth of Discharge). The following sequence describes a suitable means to reach the target voltage/SOC. Other approaches that accomplish the same end conditions are also acceptable.

1. Using the reference SOC/voltage curve (Appendix D), determine the voltage corresponding to the target SOC (at 25 °C).

2. Discharge the cell at a $C_1/1$ constant current rate from a fully charged condition to the target voltage value at 25 °C.

3. Maintain the target voltage for 2.5 hours or until the current is less than 10 mA, whichever comes first, to ensure that the cell state of charge is stable at this voltage.

4. Place the cell in an open circuit condition.

Note 2. When not under active testing for prolonged periods, the cells shall be stored at 10°C at a low state of charge, e.g., between 10% to 25% SOC.

7.1 Characterization Testing

Perform the tests specified in Table 1 on all cells.

Table 1. Characterization Performance Test Sequence (All Cells)

Item	Performance Test	Frequency
1	**C_1 Static Capacity Tests** *(Reference 2.1, Section 3.2)* This test consists of a constant C_1 discharge at a $C_1/1$ rate at 25ºC (i.e., initial temperature of 25 $\pm$ 3ºC) beginning with a fully charged cell and terminating at the specified cutoff voltage of 3.0 V, NOT rated capacity. Note: Use the value of the last discharge from each cell for reporting the actual C_1 individual cell capacities. Repeat the C_1 test five (5) times and confirm that the measured capacity of the last three tests are within 2%.	5 iterations at beginning of testing
2	**$C_1/25$ Static Capacity Test** *(Reference 2.1, Section 3.2)* Perform one $C_1/25$ discharge and charge at 25 $\pm$ 3°C on all cells. The procedure is as follows: 1. Fully charge the cell, as defined in Section 5.5. 2. Rest for 1 hour at OCV.	1

	3. Discharge at a $C_1/25$ rate until 3.0 V is reached. 4. Rest for 1 hour at OCV. 5. Charge at a $C_1/25$ rate until 4.1 V is reached. Resting for 1 hour between the discharge and charge will result in some cell relaxation, so the initial charge voltage will be greater than 3.0 V. Calculate the relative change in capacity as a function of voltage using the following equation: $\frac{1}{Q} \cdot \frac{d(Ah)}{dV} = \frac{(Ah_2 - Ah_1)/(Cell\ \ Capacity)}{(V_2 - V_1)}$, where Q is the $C_1/25$ discharge capacity. Smooth the data by taking the capacity every ninth point and averaging the voltage during that nine-point period, or use another approach that accomplishes the same goal. Calculate the differential capacitance [1/Q * d(Ah)/dV] using a three-point numerical differentiation to take the derivative of the smoothed data.	
3	**AC Impedance Test** *(Appendix E, and Reference 2.1, Section 3.13)* Spectral impedance measurements will be performed over a range of frequencies from 0.01 Hz to 10 kHz at an appropriate voltage level, 60% SOC and 25°C with 10 points per decade of frequency. Rest between 8 and 12 hours at 60% SOC before commencing the measurements. The AC Impedance Test will be repeated at the end of life testing.	1
4	**Hybrid Pulse Power Characterization Test** *(Reference 2.1, Section 3.3)* The Low Current Test is to be performed at a 5C rate and at 25°C. PNGV Pulse Power Capability will be computed using a voltage range 3.0 V, to 4.1 V. However, as specified in Section 5.0, the maximum allowed voltages during the test are 4.3 V for a 10-second pulse and 4.1 V continuous, and the lower voltage limit is 3.0 V.	1

	See Section 8.4 for HPPC analysis requirements.	

7.2 Life Cycle and Calendar Life Testing *(Reference 2.1, Sections 3.10 and 3.11)*

Appendix C describes the cycle life and calendar life testing schedule and when cells are to be taken off test. Note that a leaking cell is not an end of test criterion.

Table 2. Cycle Life and Calendar Life Test Sequence

Item	Life Cycle Test	Frequency
1	**Reference Performance Tests** Conduct Reference Performance Tests (RPT's) on all cells at 25 ± 3°C within 2 weeks prior to commencing the Calendar Life Tests and the Life Cycle Tests, and every four weeks, thereafter. The RPT consists of one nominal C_1 constant current discharge from 100% SOC to 3.0 V and one L-HPPC (in the same data file), one $C_1/25$ discharge and charge, and one AC spectral impedance measurement, including a measurement at the 1 kHz point (see Section 7.1 (3), AC Impedance Test, and Appendix E). Note: The sequence of tests that constitute the RPT may be done in any order that best meets the capabilities and limitations of each laboratory. However, once a sequence has been established, it should not be changed without a compelling reason and concurrence from the DOE Technical Contact. At the end of testing, also measure and record the weights.	Once at beginning of life testing, and then every four weeks, thereafter
2	**Operating Set Point Stability Test** *(Reference 2.1, Section 3.9)* This test is conducted on all cycle life cells at the beginning of life cycle testing using the same test profile and conditions required for life cycle testing. At the completion of this test, the actual SOC should be within ±2 % of the	*

	target SOC. The OCV versus SOC tables for the baseline and variant cells are given in Appendix D. * As needed	
3	**Cycle Life Testing** *(Reference 2.1, Section 3.10)* Subject the cells to the 25 Wh Power Assist Life Cycle Test Profile *(Reference 2.1, Table 6)* @ 60% SOC at the appropriate temperature. The discharge and regen voltages and currents should be estimated such that the cells do not fail during cycle life testing. Once a BSF has been determined based on the L-HPPC test, Section 7.1 (4), use the pulse power equations in Section 4.3.3 of Reference 2.1 to find V_{min} and V_{max} based on the OCV corresponding to 60% SOC (see Appendix D). Also estimate the associated current values based on these voltage drops. Quantity — Temp 15 (15 Baseline) — 25°C 30 (15 Baseline, 15 Variant C) — 45°C Every four weeks conduct the Reference Performance Tests as described above. Also, if the OCV at the end of the one-hour rest following completion of each four-week block of life cycle testing is not within ± 2% of the target SOC, adjust the control voltage and repeat the OSPS test at the target temperature and SOC prior to resuming life cycle testing.	Continue until an end of testing criterion is met
4	**Calendar Life Testing** *(Reference 2.1, Section 3.11)* Subject the cells to the calendar life test profile *(Reference 2.1, Table 8)* @ 60% SOC and 55 °C. The profile will be scaled based upon a 3C current. An additional pulse at 25 °C will be performed at the start and end of each 4-week interval. Also subject two archived baseline cells to the calendar life test at 60% SOC and 45°C. Quantity — Temp 15 (15 Baseline) — 55°C	Continue until an end of testing criterion is met

	15 (15 Variant C)	45°C	
	2 Archived Baseline Cells	45°C	

8.0 Measurement and Reporting Requirements

Note: These measurement requirements are for INEEL testing. Other labs may record data at different frequencies based upon their data needs and equipment capabilities.

8.1 Measurements

For each group of cells subjected to a common test regime at a given temperature, the ambient temperature for this cell group should also be measured and included in the data for the first (lowest numbered) cell in that group. For data consistency, this should normally be the last recorded variable for that particular cell.

Detailed data acquisition and reporting requirements for the characterization and life cycle tests are as required for the applicable test procedures in Reference 2.1. For measurements made near the start of discharge or regen pulses, current and voltage measurements must be made near-simultaneously. Measurements at other times during pulse steps should have channel-to-channel latency between current and voltage measurements of less than 100 milliseconds. The response of Maccor test channels is considered adequate to meet this requirement provided that a data point is acquired near the beginning of each pulse-type step; the response of other data acquisition systems may need to be reviewed further.

8.2 Data Recording Intervals

During the once-per-day Calendar Life pulse profiles, data should be acquired at a periodic rate of once per second during discharge pulses, regen pulses and the rest intervals between them. This rate may be decreased to once per 2 seconds for pulses or rest intervals that are longer than 30 seconds. Voltage and current data should also be acquired at the beginning and end of each discharge and initial regen pulse.

During the 1-hour HPPC rest intervals and charge periods, data may be acquired once per minute; a data point is also required at the termination of all these periods. Data should be acquired every 10 seconds for $C_1/1$ discharge periods, and every 30 seconds for $C_1/25$ discharge periods. For HPPC discharge pulses, data should be acquired at 2 points per second for the first 12 seconds, and 1 point per second for the last 6 seconds. For HPPC regen pulse, data should be acquired at 5 points per second for the first 2 seconds, and every 0.4 seconds during the last 8 seconds. Data should be acquired every 2 seconds during the 32-second HPPC rest. For rest intervals greater than 1 hour (e.g. calendar life periods), the data may be acquired once per half an hour. In general, specified rest periods should be treated as part of the associated test with respect to data acquisition and archiving; voltage and temperature data should be acquired during these periods.

Data should be acquired at one-second intervals for Operating Set Point Stability (OSPS) tests. Data should also be acquired at one-second intervals during Life Cycle testing for those test profiles that are recorded; however, not all profiles need to be recorded. For Power Assist Life Cycle testing, the first and last 100 profiles of each test interval are required to be recorded, along with at least one complete profile out of every 100.

8.3 Data Access

All data acquired will be archived. The customer designation for this data is DOE, and data should not be marked as "CRADA Protected" or "Protected Battery Information."

8.4 Data Files

Individual HPPC tests should be archived as a single data file. It is recommended that this HPPC file should also include (where available) the associated $C_1/1$ discharge for Power Assist devices.[a] This file may or may not include the charge prior to the start of the test. Life Cycle Test data should be separated into no more than 3 data files for each testing interval: the initial profiles required to be recorded, the final profiles required to be recorded, and all other data acquired between these two groups of profiles. At the completion of testing, the characterization and RPT results should normally be transcribed to a compact disk and sent to the PNGV Technical Contact.

The following four graphs should be prepared for each cell for each set of HPPC tests: (1) ASI (ohm-cm^2) vs. Cell Voltage Measured at the Start of Discharge or Regen Pulse (V); (2) Power Density (mW/cm^2) vs. Equilibrium Open Circuit Voltage Corresponding to the Start of Discharge or Regen Pulse (V); (3) BSF-scaled Power (W) vs. BSF-scaled Cumulative C_1 Energy Removed (Wh); and (4) BSF-scaled Available C_1 Energy (Wh) vs. BSF-scaled Power (W). The power, the point at which the scaled available energy curve crosses the 300 Wh energy goal, will also be reported for each cell for each set of HPPC tests.

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[a] *Combining these files is done to facilitate automated analysis of the results. The revised PNGV goals require that Available Energy is calculated using the HPPC power results and the $C_1/1$ energy (for Power Assist) results simultaneously.*

Within two weeks of completion of each set of RPT's, transcribe the RPT and pulse-per-day calendar life test results to a compact disk and send the CD to the other testing labs. Also within the two week interval, put the final analyzed form of the data on the lab's web site in PDF format.

9.0 Anticipated Results

9.1 Performance and Life Testing

This testing will produce data that characterizes the performance and determines the cycle life and calendar life behavior of lithium-ion cells (1 Ah rated capacity) developed for the ATD Program for the improvement of high-power lithium-ion batteries.

9.2 Testing Deliverables

Summary testing status and results to date will be provided to the DOE Program Manager, DOE Technical Contact, and other ATD program participants on a monthly basis. Detailed test data files for specific tests will be provided to the DOE Program Manager and DOE Technical Contact or to other laboratories for comparison of results, as requested.

10.0 Post-Test Examination and Analysis

At the completion of testing, cells will be provided for post-test analysis to other ATD participants (e.g., LBNL and/or BNL) as shown in Appendix B or as directed by the DOE Technical Contact. Any cell disassembly should be coordinated with the diagnostics labs. Cells to be shipped to other labs should be discharged to between 10% and 25% SOC, or they may be shipped as disassembled components. Shipments of cells or components should be closely coordinated between the shipping and receiving lab including providing complete cell/component identification per Section 4.1 and the table referenced in Appendix A.

11.0 Contact Persons

ATD Program Designated Technical Contact List

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Appendix A

Tabulation of ATD Cell Identification Numbers, Test Conditions, and Results

To help ensure that the correspondence between specific cells, their test conditions, test results, and other pertinent information is identified and maintained throughout the testing program, an Excel table should be used to assign and track information such as weights, impedance, dates, temperature, capacity, and pulse power. Update the table within two weeks of the completion of characterization testing and at the completion of each set of RPT's. Copies of this information should be provided with any batteries furnished to other laboratories for additional testing or post-test analysis.

Appendix B

ATD GEN 2 Cell Distribution Matrix

There are a total of 195 Gen 2 cells (165 Baseline cells and 30 Variant C cells). INEEL will receive 45 cells (30 Baseline and 15 Variant C cells) and ANL will receive 37 (22 Baseline and 15 Variant C). Seven of the ANL baseline cells will be archived. The INEEL baseline cells will be divided into two groups of 15. The complete cell distribution is shown in Table B.1.

Table B.1. Cell Distribution

First 20 cells sent to ANL will be transferred to SNL							
	Baseline			Variant C			**Total**
	Testing	Therm. Ab.	Diag.	Testing	Therm. Ab.	Diag.	
ANL	22		1	15			**38**
BNL			1				**1**
INEEL	30			15			**45**
LBNL			1				**1**
SNL 1	15						**15**
ANL to SNL 2	20						**20**
3	27	48					**75**
4							**0**
Total	**114**	**48**	**3**	**30**	**0**	**0**	**195**
			165			**30**	**195**

The cell being sent for diagnostics after characterization will be shipped to ANL, BNL or LBNL, as directed by the DOE Program Manager. After characterization, the cells will come off test in pairs (see Appendix C). One of these cells will be shipped to ANL and the other to LBNL for diagnostic analysis. ANL and LBNL are responsible for distributing some cells to BNL.

Appendix C

End-of-Test Criterion

After characterization, send one randomly selected cell from each group of 15 to the designated diagnostic lab. After 4 weeks of cycling, remove two more cells from each group of 15 as follows:

- **Baseline Cells:** remove two randomly selected cells
- **Variant Cells:** remove the two cells with the highest power fades

The End-of-Test (EOT) criteria for the remaining 12 cells will be based on equal power fade increments. The objective is to have 2 cells life tested until the power fade reaches 30% and another 2 cells life tested beyond 30% power fade, and the remaining cells removed from test in pairs at approximately equal power fade increments.

***Baseline Cell Initialization**:*
- Calculate the individual cell power fades at 8-weeks using Equation 1
- Calculate the average power fade at 8-weeks using Equation 2 (w = 8 and i = 12 cells)
- Calculate the incremental power fade using Equation 3
- Calculate the target power fade (P_{Target}) using Equation 4

***Variant Cell Initialization**:*
- Calculate the average power fade of the two cells designated to come off test at 4-weeks, i.e., the cells with the highest fades (Equation 2 with w = 4 and i = 2 cells)
  - Calculate the incremental power fade using Equation 3 ($\overline{F}_w$ is from the previous calculation and i = 12)
  - Calculate the target power fade (P_{Target}) using Equation 4

***Baseline and Variant Cells**:*
- Follow the flowchart sequence shown in Figure C.1
- **NOTE:** If a cell fails prematurely, send it to the designated diagnostic lab (as specified by the DOE Program Manager). This means that only one cell should be taken off test once it meets the target power fade. After that cell has been removed, calculate the new target, and start following the sequence shown in Figure C.1 again.

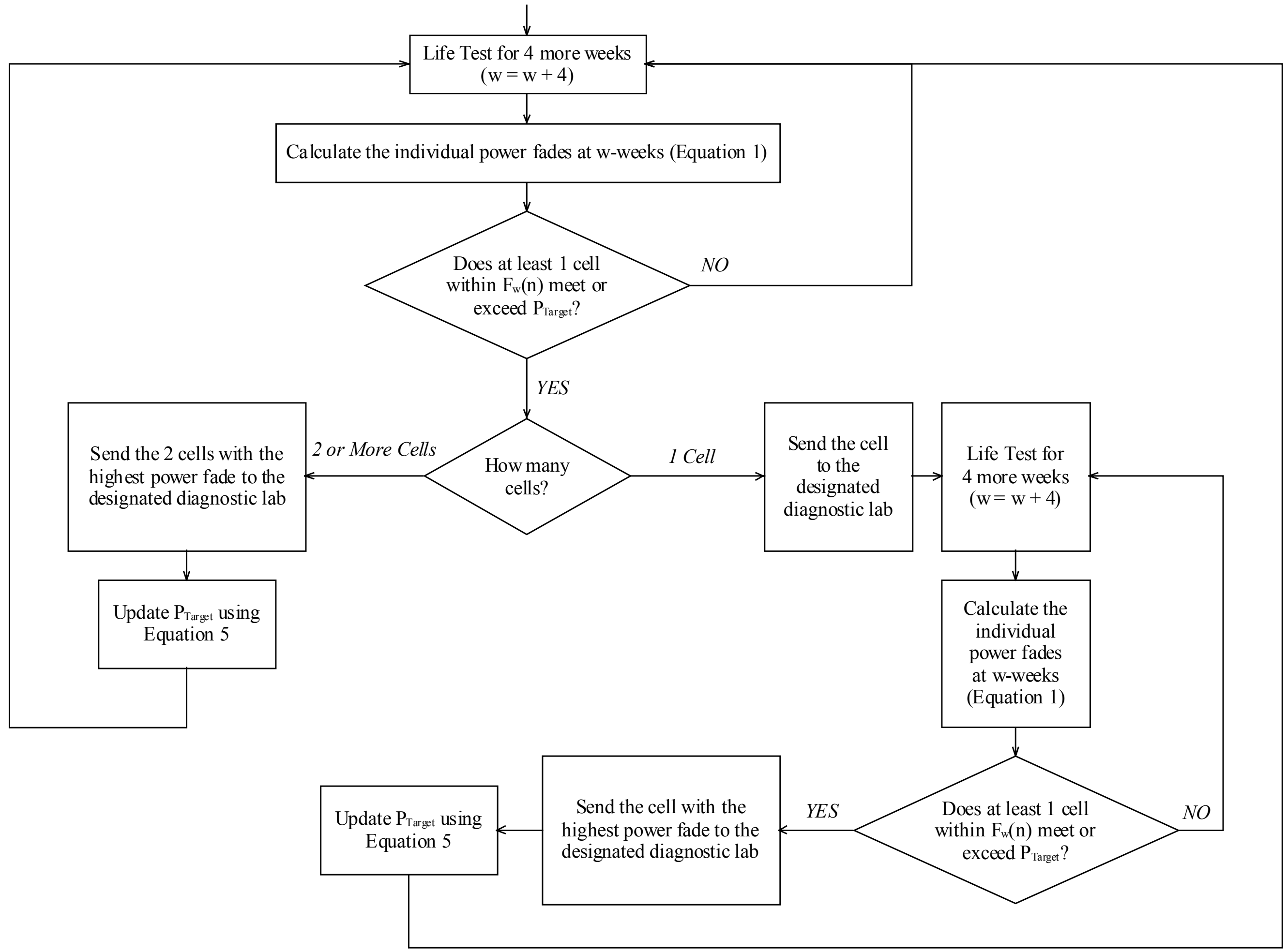

Figure C.1. EOT Criteria Flowchart

Equations:

- w = weeks
- n = cell number
- i = number of cells remaining
- P_0 = Power at 0-weeks (a.k.a. characterization)
- P_w = Power at w-weeks
- $F_w(n)$ = Individual cell power fade for cell n at w-weeks (an array of size i)
- $\overline{F}_w$ = Average power fade at w-weeks
- ΔF = Incremental Power Fade
- P_{Target} = Target power fade for removal of the next pair of cells

$$F_w(n) = \left.\frac{P_0 - P_w}{P_0}\right|_n * 100\% \qquad (1)$$

$$\overline{F}_w = \frac{\sum_i \left.\frac{P_0 - P_w}{P_0}\right|_i}{i} * 100\% \qquad (2)$$

$$\Delta F = \frac{30\% - \overline{F}_w}{\frac{i}{2} - 1} \qquad (3)$$

$$P_{Target} = \overline{F}_w + \Delta F \qquad (4)$$

$$P_{Target} = P_{Target} + \Delta F \qquad (5)$$

Appendix D

ATD GEN 2 Open Circuit Voltage vs. State of Charge Tables and Curves

Table D.1. Calibration Table for ATD Gen 2 Baseline Cells

SOC	Voltage	SOC	Voltage	SOC	Voltage	SOC	Voltage
100%	4.096						
99%	4.084	74%	3.851	49%	3.644	24%	3.499
98%	4.075	73%	3.843	48%	3.639	23%	3.490
97%	4.065	72%	3.833	47%	3.633	22%	3.481
96%	4.055	71%	3.824	46%	3.628	21%	3.472
95%	4.045	70%	3.815	45%	3.623	20%	3.462
94%	4.034	69%	3.805	44%	3.618	19%	3.451
93%	4.023	68%	3.795	43%	3.613	18%	3.440
92%	4.012	67%	3.786	42%	3.608	17%	3.429
91%	4.001	66%	3.776	41%	3.603	16%	3.418
90%	3.990	65%	3.767	40%	3.598	15%	3.406
89%	3.980	64%	3.758	39%	3.594	14%	3.395
88%	3.970	63%	3.749	38%	3.589	13%	3.384
87%	3.960	62%	3.740	37%	3.584	12%	3.374
86%	3.950	61%	3.731	36%	3.578	11%	3.365
85%	3.941	60%	3.723	35%	3.573	10%	3.357
84%	3.932	59%	3.714	34%	3.568	9%	3.349
83%	3.923	58%	3.705	33%	3.562	8%	3.340
82%	3.915	57%	3.698	32%	3.556	7%	3.331
81%	3.906	56%	3.690	31%	3.551	6%	3.320
80%	3.898	55%	3.683	30%	3.544	5%	3.304
79%	3.891	54%	3.675	29%	3.537	4%	3.278
78%	3.883	53%	3.669	28%	3.530	3%	3.235
77%	3.875	52%	3.662	27%	3.523	2%	3.177
76%	3.868	51%	3.656	26%	3.515	1%	3.106
75%	3.860	50%	3.650	25%	3.507	0%	3.000

Note: The voltages are averaged using the C/25 discharge curves from 3 ANL trial cells (Quallion s/n-17, s/n-20, and s/n-29).

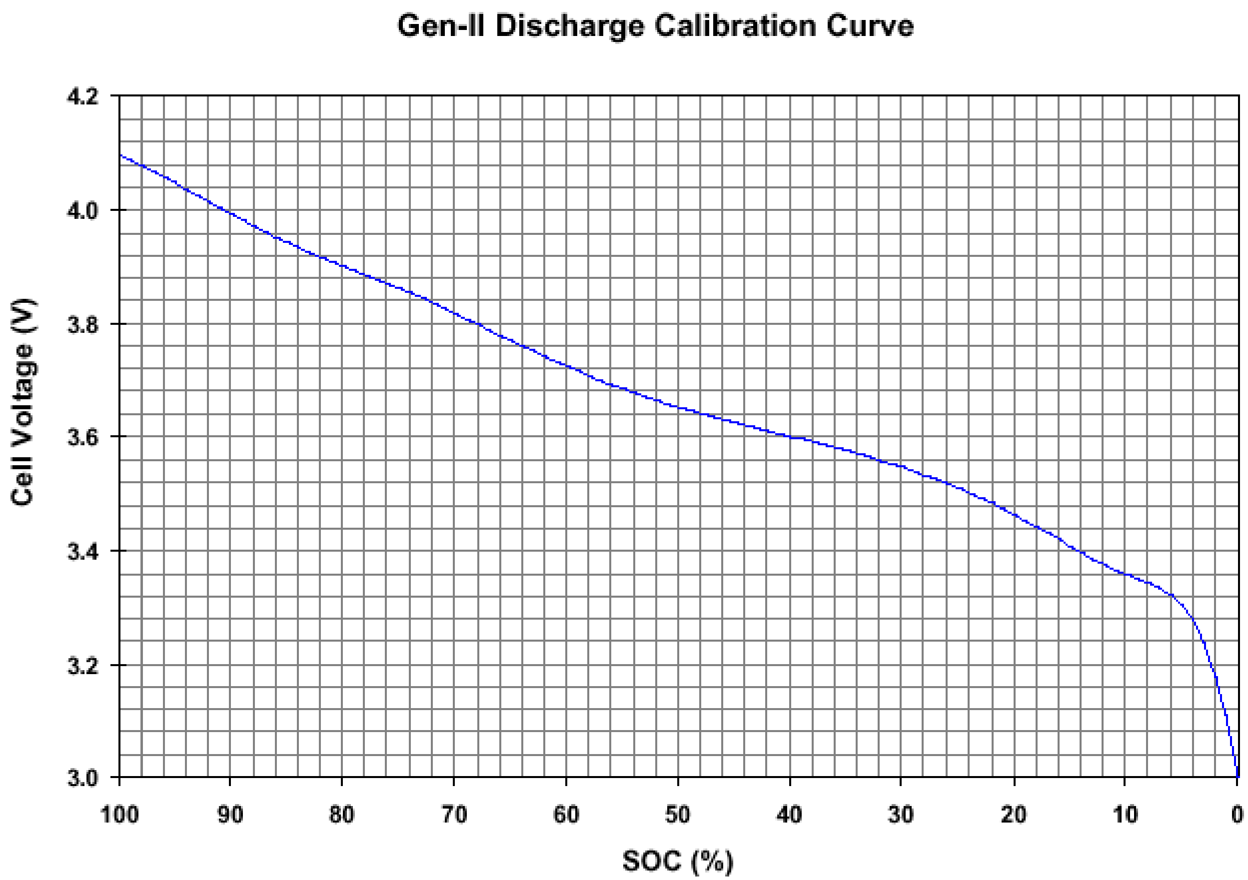

Figure D.1. ATD Gen 2 Baseline Cell OCV vs. SOC Curve

Table D.2. Calibration Table for ATD Gen 2 Variant C Cells

SOC	Voltage	SOC	Voltage	SOC	Voltage	SOC	Voltage
100%	4.099						
99%	4.086	74%	3.866	49%	3.661	24%	3.518
98%	4.076	73%	3.859	48%	3.655	23%	3.510
97%	4.066	72%	3.851	47%	3.649	22%	3.501
96%	4.055	71%	3.843	46%	3.644	21%	3.493
95%	4.045	70%	3.835	45%	3.639	20%	3.484
94%	4.035	69%	3.827	44%	3.634	19%	3.475
93%	4.025	68%	3.818	43%	3.628	18%	3.465
92%	4.015	67%	3.809	42%	3.623	17%	3.456
91%	4.004	66%	3.800	41%	3.618	16%	3.445
90%	3.995	65%	3.790	40%	3.613	15%	3.435
89%	3.985	64%	3.780	39%	3.608	14%	3.423
88%	3.976	63%	3.770	38%	3.604	13%	3.411
87%	3.967	62%	3.760	37%	3.599	12%	3.399
86%	3.958	61%	3.751	36%	3.594	11%	3.386
85%	3.949	60%	3.741	35%	3.589	10%	3.372
84%	3.941	59%	3.733	34%	3.583	9%	3.358
83%	3.933	58%	3.724	33%	3.578	8%	3.343
82%	3.925	57%	3.716	32%	3.573	7%	3.329
81%	3.918	56%	3.708	31%	3.567	6%	3.313
80%	3.910	55%	3.701	30%	3.561	5%	3.294
79%	3.903	54%	3.693	29%	3.555	4%	3.269
78%	3.896	53%	3.686	28%	3.548	3%	3.232
77%	3.888	52%	3.680	27%	3.541	2%	3.180
76%	3.881	51%	3.673	26%	3.534	1%	3.107
75%	3.874	50%	3.667	25%	3.526	0%	3.000

Note: The voltages are averaged using the C/25 discharge curves from 14 INEEL cells.

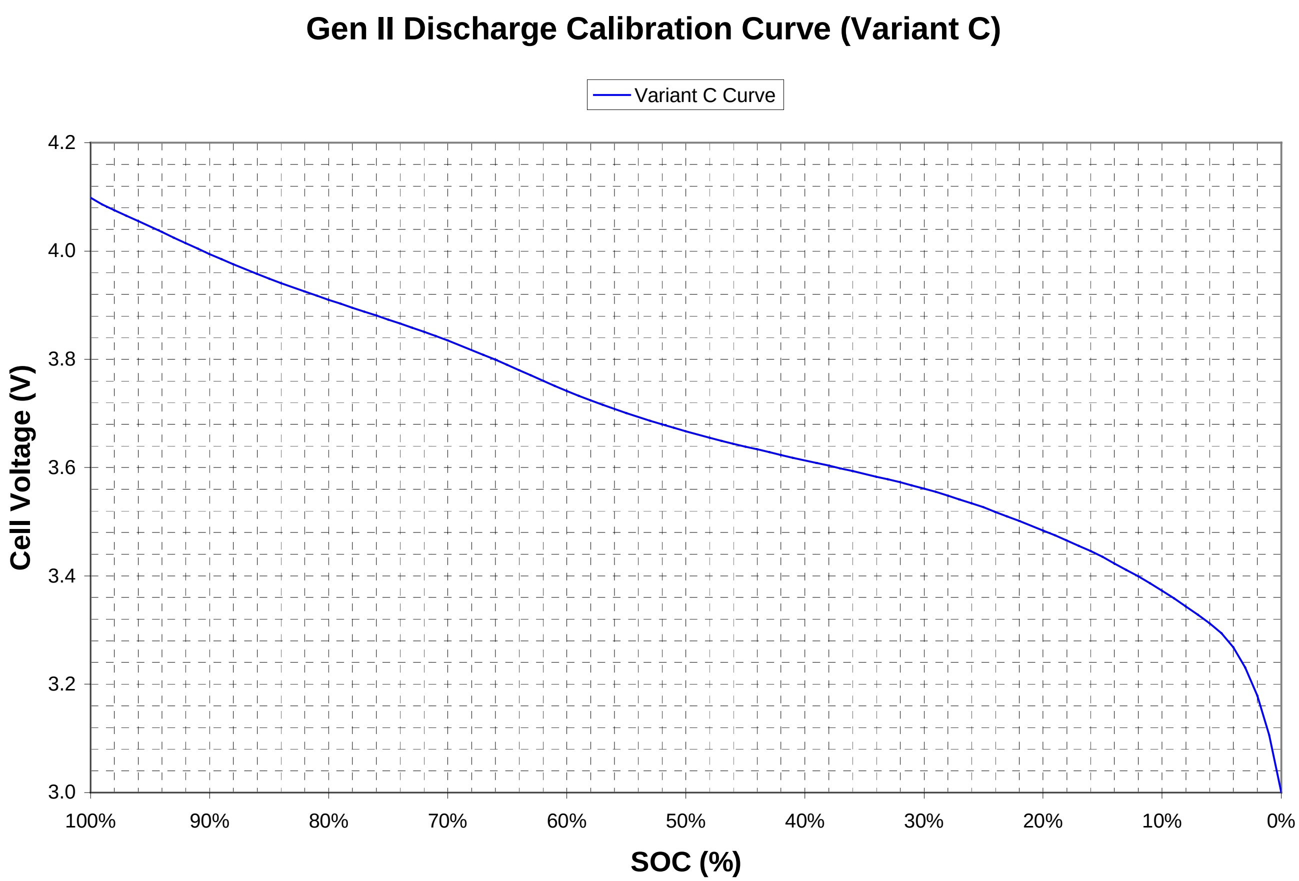

Figure D.2. ATD Gen 2 Variant C Cell OCV vs. SOC Curve

Appendix E

Spectral Impedance Measurements

A representative approach for spectral impedance measurements is described below. The general methodology should be used to the extent possible, although specific equipment may vary amongst the testing labs.

Equipment:

Equipment	INEEL	ANL	SNL
EG&G Potentiostat/Galvanostat	Model 273A	Model 273A	Model 273A
Solartron Frequency Analyzer	Model 1260	Model 1260	Model 1255
Control Software	ZPlot	Zplot	M398

Test Procedure:

Perform this test on each cell, as specified in Appendix C, at 60% SOC and 25°C. Follow the guidance in Appendix C of Reference 2.1 to establish the target SOC. Rest between 8 and 12 hours at 60% SOC before starting the measurements.

Set the initial frequency to 10 kHz and final frequency to 0.01 Hz. Set the voltage of the sine wave to an appropriate voltage level, and the number of points per decade of frequency to 10. Record the magnitude of the impedance (the real and imaginary components) vs. the frequency, temperature, and SOC.

Use a 4-terminal connection to measure impedance.

Attachment 2*

SNL ATD Gen 2 Test Plan

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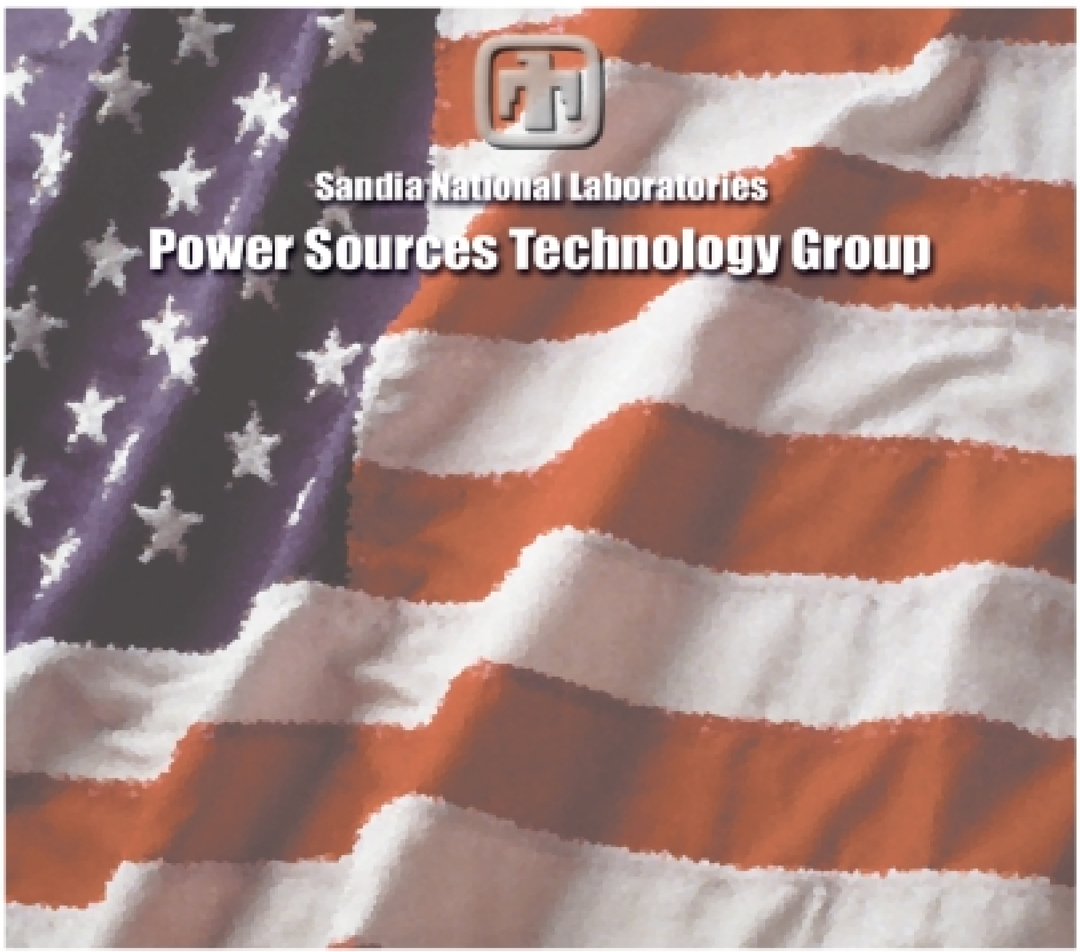
* Attachment 2 is Revision 3a of the SNL ATD Gen 2 test plan. This incorporates some minor editorial changes from the previously released version (Revision 3 on November 5, 2002) and does not impact testing procedures. If significant changes to the test plan are required in the future, SNL will issue Revision 4 and include the changes from Revision 3a.

SNL

ATD Gen 2

Test Plan



SNL TEST PLAN
FOR
ADVANCED TECHNOLOGY DEVELOPMENT
GEN 2 LITHIUM-ION CELLS

Reviewed: ______________________________ _______________
SNL Project Engineer Date

Reviewed: ______________________________ _______________
SNL Program Leader Date

Approved: ______________________________ _______________
SNL Department Manager Date

SNL ATD Gen. 2
Test Plan

1.0 Purpose and Applicability

The intent of this testing is to devise an Accelerated Life Test (ALT) for lithium-ion cells (nominal 1.0 Ah capacity), and to support thermal abuse tests of the same cells. This work is being done as part of an Advanced Technology Development (ATD) Program project for the improvement of high-power lithium-ion batteries. The testing is sponsored by the DOE Office of Advanced Automotive Technologies (OAAT) and is under the oversight of OAAT and the designated DOE Program Manager. In general, these cells will be subjected to the characterization, reference performance, and life test procedures that have been defined for the PNGV Program as specified in Reference 2.1. The cells covered by this test plan are 18650-size baseline and variant cells manufactured by Quallion specifically for Gen 2 of the PNGV ATD Program, which have been built to ATD specifications. The baseline cell chemistry is defined in Reference 2.2.

2.0 References

2.1 PNGV Battery Test Manual, Revision 3, DOE/ID-10597, December 2000
2.2 "Gen 2 Baseline & Variant Cells," ATD Quarterly, Presentation by Gary Henriksen, Albuquerque, N.M., November 2000.
2.3 INEEL "EHV-TP-121", Rev 2, February 26, 2001

3.0 Equipment and Hardware

3.1 All testing will be performed on laboratory cell test channels with current and voltage capabilities adequate for the specific test procedures to be performed. In general, lower voltage ranges should be used where available (5V preferred, not to exceed 20V) to assure the best voltage resolution and accuracy.

3.2 Except where noted otherwise, testing will be performed with the cells at a temperature of 25 $\pm$ 3°C at the beginning of a test sequence. The preferred means to accomplish this is by the use of a thermal block and a controlled temperature chamber having both heating and cooling capabilities. Unless otherwise specified, all temperature measurement should be based upon the cell skin temperature, or equivalent. Test temperature will be controlled by the RTD (Resistance Temperature Detector) in the environmental chamber.

3.3 The temperature of cells under test should be measured using moderately fast response sensors (e.g. pad-type thermocouples) adhered to the positive end of each cell. Sensors should be fastened to the cell using a means (e.g. epoxy, tape or clamp) which provides consistent contact.

4.0 Prerequisites and Pre-Test Preparation

4.1 Before testing starts, the cells will be assigned lab-specific identification numbers. An End-Of-Testing (EOT) labeling convention has been created for Gen 2. The principal purpose is to provide the diagnostics labs succinct information regarding the EOT status of these cells. At a minimum, the label for each cell will be established at the beginning of testing and updated at the end of testing. Optionally, the label may be updated periodically as testing progresses. The ATD labeling convention is as follows:

GX.AABCC.DEEE.FF.TT.PP.Z.S, where

GX[X] G1, G2, or G3 for Gen 1, Gen 2, or Gen 3, respectively, and [X] = A, B, or C as appropriate for each variant.
AA Test Matrix State of Charge, e.g., 60%
B Test Matrix profile, e.g., S, L and C, where S = in storage, L = cycle life cell, C = calendar life cell, A = accelerated life test cell, T = thermal abuse cell, D = dead cell, F = safety test.
CC Test Matrix Temperature, (°C)
D Original DOE Laboratory, A = ANL; B = BNL; I = INEEL; L = LBNL; S = SNL
EEE Sequential cell number as assigned by Original DOE Laboratory:
INEEL: 101 through 1XX
ANL: 201 through 2XX
SNL: 301 through 3XX, and
401 through 4XX
FF Target power fade (%) based on equal power fade increments
TT Time at life testing, CC = Characterization or 00, 04, etc (wks)
PP Power fade relative to 0 week L-HPPC Reference Performance Test cross over point (%). By definition the power fade at 0 weeks is 00%. (Enter NA for Characterization Power Fade, and ND for No Data.)
Z Abnormal condition flag: S = shorted; V = vented; P = punctured; L = leaked; T = tab problem; G = Good, D = dead/won't cycle, Q = low voltage.
S[S] Status: T = test continuing; F = finished testing and in storage. Or if shipped to another laboratory then, A = shipped to ANL; B = shipped to BNL; I = shipped to INEEL; L = shipped to LBNL; S = shipped to SNL. [S] = additional status flags as appropriate to track the history of the cell.

Note: Diagnostic lab cells may utilize this convention by placing an X in any field that is not applicable to that cell

4.2 The cells will be visually inspected for signs of shipping or other damage. Any signs of damage should be documented. The actual weights and open circuit voltages as delivered will be recorded. The cell weights will include the cell current tabs. Also, to further confirm that the cells are not damaged, perform an AC impedance measurement at 1 kHz and record the value for each cell.

5.0 Cell Ratings, Test Limitations and Other Test Information

5.1 Ratings

Rated Capacity:	1.0 Ah (C_1/1 rate)
PNGV Application:	*Power Assist*
Battery Size Factor:	*553 (Baseline)*

HPPC Pulse Power Voltage *Calculation* Range:

V_{min}	3.0 V
V_{max}	4.1 V

Operating Temperature Range:	-20°C to +60°C
Maximum Discharge Temperature:	60°C
Maximum Charge Temperature:	40°C
Storage Temperature:	10°C ± 3°C

5.2 Nominal Values

Nominal Capacity:	0.94 Ah

5.3 Discharge Limits

Minimum Discharge Voltage:	3.0 V	18 sec pulse
	3.0 V	Continuous
Maximum Discharge Current:	8.0 A	18 sec pulse (I_{max})
	2.0 A	Continuous

5.4 Charge and Regen Limits

Maximum Regen Voltage:	4.3 V	10 sec pulse
	4.1 V	Continuous
Maximum Regen Current:	8.0 A	10 sec pulse
	1.0 A	Continuous

5.5 Charge Procedure: Charge at 1.0 A constant current rate to a voltage of 4.1 V; continue to maintain a constant voltage of 4.1 V for 2.5 hours total recharge time. All recharging is to begin at 25 ± 3ºC, unless specifically stated otherwise.

5.6 Recharge Constraints

If a procedure requires a cell to be fully charged at the start of the test sequence, the cell will be considered fully charged (i.e. need not be subjected to a 'top off' charge) if it was fully recharged no more than 72 hours previously.

5.7 Life Cycle Test Conditions:

Nominal State of Charge For ALT: 60%, 80%, or 100% SOC

5.8 End-of-Testing Criterion:

1. After a minimum of 4 aging cycles and 30% power fade.

or

2. If the cell is unable to successfully perform the HPPC test through the 80% SOC pulse interval

or

3. When directed by the DOE Program Manager or DOE Technical Contact.

or

4. When the cells have more than 50% power fade.

6.0 Safety Concerns and Precautions

In general, the safety issues with these cells are similar to those encountered previously with lithium-ion cells. Thus, the same precautions will be exercised as are normally used for lithium-ion cells.

6.1 Cell Handling

- Cells should be handled whenever possible in the discharged state.
- Personnel handling or approaching the cells should wear eye protection.
- Due care should be taken to avoid shorting the cell terminals. Caution: the Gen 2 cell case is electrically tied to the positive terminal Cells should be shipped in a discharged state (between 10% to 25% SOC).

6.2 Other Safety Precautions

- For both testing and storage, cells should be located within an area shielded from non-deliberate exposure to personnel. Cells that show any signs of deterioration or unanticipated behavior should be segregated from other cells to avoid propagation of damage in the event of a failure.
- Charged cells should not be located close to flammable and/or combustible materials
- Venting of cells should be regarded as a possibility. Lab personnel response to any unanticipated release of fumes or smoke at the test location should be to evacuate the immediate area (e.g., test room). The laboratory manager (or equivalent) and safety personnel should be notified. Approval from the laboratory manager should be obtained prior to reentering the testing area. (Note: if it is very clear that only minor venting is occurring, the situation may be observed at a safe distance to determine whether the release ceases without further action.)
- It has been shown during abuse testing (thermal abuse and intentional overcharging) that the cells may experience catastrophic failure and the vents not function

- In case of unexpected cell behavior (e.g. venting), the cells should not be approached for at least one hour afterward.

7.0 Tests to be Performed Under this Test Plan

All cells will be subjected to the characterization performance test sequence. The cells will be tested according to the Power Assist goals and requirements. The Battery Size Factors (BSF) for the Baseline cells is in Section 5.1.

All recharging between tests is to be done using the recharge procedure of Section 5.5. In general, a rest step of nominally 60 minutes shall be observed after each charge, and nominally 60 minutes after each discharge, to allow cells to reach stable voltage and temperature conditions prior to proceeding with testing.

Note 1. Except for the HPPC tests, use the corresponding open circuit voltage as a measure of State-of-Charge. (For HPPC tests, removed-capacity will be used as the measure of Depth of Discharge). The following sequence describes a suitable means to reach the target voltage/SOC. Other approaches that accomplish the same end conditions are also acceptable.

Note 2. When not under active testing for prolonged periods, the cells shall be stored at 10°C.

Please see Appendix A for descriptions of tests

Physical Set Up

Cells

Cells will have heat shrink applied to both leads, red heat shrink will be used for (+) leads and black heat shrink will be used for (-) leads. The heat shrink will leave enough bare lead to make a voltage sense connection at the cell and a solder connection at the end of the lead. Current control wires from the block will be soldered to the ends of the leads and covered in heat shrink. (It is suggested that the heat shrink be only partially collapsed so that the cell can be disconnected without cutting)

If necessary to provide a snug fit in thermal block the cell may be wrapped with aluminum foil.

The cells shall be oriented in the block so that current control wires can be soldered to the ends of the leads, and thermocouple sensors may be affixed to the (+) end of the cell.

Blocks

(-) Voltage sense lines will be fed through to the back (-) side of the block. Tape (-) V sense lines to block so that when the tester line is clipped to the cell lead there is very low stress on the lead.

Tape (+) V sense lines to block (Use glass cloth electrical tape such as Scotch 69) so that when the tester line is clipped to the cell lead there is very low stress on the lead.

Place block in temperature chamber, tape thermocouple leads to cell, plug control lines from tester into receptacles on thermal block. Carefully draw excess tester cable out of temperature chamber. To remain consistent with other labs, chamber temperature will be controlled based on chamber air. An equilibration time of at least 8 hours will be allowed for all temp changes.

Test Sequence

Characterization (at 25°C)
- Static Capacity
- SOC Adjustment 60%
- EIS
- L-HPPC

RPT (at 25°C)
- Static Capacity
- SOC Adjustment 100%, EIS
- SOC Adjustment 60%, EIS
- C/10 Capacity
- L-HPPC
- L-HPPC at 0°C Eliminated 3/02 (RPT 7)

Aging (at variable temp & SOC)
- SOC Adjustment 60%, 80% or 100%
- Temp Adjustment
- PAC or Calendar Test
- Temp adjustment back to 25°C

Repeat RPT & Aging as determined for each cell.

8.0 Measurement and Reporting Requirements

8.1 Measurements

Cell surface temperature shall be recorded when possible, otherwise for each group of cells subjected to a common test regime at a given temperature, the temperature of the block for this cell group should also be measured.

Detailed data acquisition and reporting requirements for the characterization and life cycle tests are as required for the applicable test procedures in Reference 2.1. For measurements made near the start of discharge or regen pulses, current and voltage measurements must be made near-simultaneously. Measurements at other times during pulse steps should have channel-to-channel latency between current and voltage measurements of less than 100 milliseconds.

8.2 Data Recording Intervals

During all RPT tests data shall be recorded at a rate sufficient to have several data points per step of the test.

During the 4 week PAC test, the first and last 100 profiles of each test interval are required to be recorded, along with at least one complete profile out of every 100 in between.

8.3 Data Access

All data acquired will be archived. The customer designation for this data is DOE, and data should **not** be marked as "CRADA Protected" or "Protected Battery Information."

8.4 Data Files

A Current & Voltage vs. Time trace for all tests

The following five graphs will be prepared for each cell for each set of HPPC tests: (1) Open Circuit Voltage and Resistance vs. Depth of Discharge; (2) Pulse Power Density vs. Depth of Discharge; (3) Pulse Power Capability vs. Energy Removed; (4) Energy Available vs Power; (5) HPPC Power vs. Energy Removed Scaled for nominal BSF.

After all RPTs an overlay of Energy Available vs. Power shall be created for each cell showing the progression of power fade. This will be scaled to show the PNGV target performance.

See Appendix D for detailed description of analysis.

Transcribe the data to a compact disk and send the CD to the other testing labs. Also put the final analyzed form of the data on the Sandia web site in PDF format.

9.0 Anticipated Results

9.1 Accelerated Life Test (ALT)

This testing will produce data that demonstrates the aging behavior of lithium-ion cells (1 Ah rated capacity) developed for the ATD Program for the improvement of high-power lithium-ion batteries.

9.2 Testing Deliverables

Summary testing status and results to date will be provided to the DOE Program Manager, DOE Technical Contact, and other ATD program participants on a Regular basis. Detailed test data files for specific tests will be provided to the DOE Program Manager and DOE Technical Contact or to other laboratories for comparison of results, as requested.

10.0 Post-Test Examination and Analysis

At the completion of testing, cells will be provided for post-test analysis to ATD participants as directed by the DOE Technical Contact. Any cell disassembly should be coordinated with the diagnostics labs. Cells to be shipped to other labs should be discharged to between 10% and 25% SOC, or they may be shipped as disassembled components. Shipments of cells or components should be closely coordinated between the shipping and receiving lab including providing complete cell/component identification.

11.0 Contact Persons

ATD Program Designated Technical Contact List

NAME	Email	ORG.	PHONE	FAX
Tien Duong	Tien.duong@hq.doe.gov	DOE	(202) 586-2210	(202) 586-1600
Tom Tartamella	tt4@daimlerchrysler.com	PNGV	(248) 838-5337	(248) 838-5338
Vince Battaglia	batman@anl.gov	ANL/DOE	(202) 488-2461	(202) 488-2413
Tim Murphy	murphytc@inel.gov	INEEL	(208) 526-0480	(208) 526-4822
Chet Motloch	motlcg@inel.gov	INEEL	(208) 526-0643	(208) 526-0969
Gary Henriksen	henriksen@cmt.anl.gov	ANL	(630) 252-4591	(630) 252-4176
Ira Bloom	bloom@cmt.anl.gov	ANL	(630) 252-4516	(630) 252-4176
Kalil Amine	amine@cmt.anl.gov	ANL	(630) 252-3838	(630) 252-4176
Jim McBreen	jmcbreen@bnl.gov	BNL	(516) 344-4513	(516) 344-1470
Frank McLarnon	frmclarnon@lbl.gov	LBNL	(510) 486-4636	(510) 486-4260
Dan Doughty	dhdough@sandia.gov	SNL	(505) 845-8105	(505) 844-6972
Rudy Jungst	rgjungs@sandia.gov	SNL	(505) 844-1103	(505) 844-6972

Appendix A

Test Definitions

Static Capacity:

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Discharge to 3 V at 1 A
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Repeat for total of 5 cycles
Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Discharge to 3 V at 0.04 A
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor

C/10 Capacity

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5hours.
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Discharge to 3 V at 1 A
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Repeat for total of 2 cycles
Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor
Discharge to 3 V at 0.1 A
Rest 1 hour (OCV no current or voltage control) 0 Current for Maccor

SOC Adjustment, 100%

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)

SOC Adjustment, 80%

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)
Discharge to 3.898 V at 1 A, hold at 3.898 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)

SOC Adjustment, 60%

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)
Discharge to 3.723 V at 1 A, hold at 3.723 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)

SOC Adjustment, 0%

Discharge to 3.0 V at 1 A.

EIS

Wait a minimum of 12 hours after SOC adjustment.
Use model 273A or 273 potentiostat & model 1255 FRA.
Use M398 or Zplot software.
Sweep from 10 kHz to 0.01 Hz and take 8 points per decade

HPPC

Charge to 4.1 V at 1 A current, hold at 4.1 V while current decays. Total charge time 2.5 hours.
Rest 1 hour (OCV no current or voltage control)
Remove 10% of nominal capacity with a 6 min 1 A discharge
Rest 1 hour (OCV no current or voltage control)
Apply a discharge pulse of 5 A for 18 seconds. If cell voltage drops to 3.0 V, lower current for the balance of the 18 seconds.
Rest for 32 seconds (OCV no current or voltage control)
Apply a regeneration pulse of 3.75 A for 10 seconds. If cell voltage rises to 4.3 V lower current for the balance of the 10 seconds.
Remove the balance of another 10% of nominal capacity with a 5 min 7.5 second 1 A discharge.
Repeat rest and pulse train for a total of 9 cycles.

Calendar (pulse a day)

Rest for 1 hr.
Discharge at 18.08 Watts for 9 seconds.
Rest 27 seconds (OCV no current or voltage control) 0 Current for Maccor
Charge at 28.93 Watts for 2 seconds.
Charge at 19.89 Watts for 4 seconds.
Charge at 10.85 Watts taper with voltage limit from OSPS for 4 seconds.
Rest 23 hr 59 min 14 s (86,354 seconds) Hold voltage for Maccor, keep voltage adjusted for Digatron.
Repeat for total of 28 cycles.

PAC C-J (Modified PAC for ALT Screening Matrix)

Discharge at **A** Watts for **U** seconds. End test if V < 3.0.
Rest **V** seconds (OCV no current or voltage control)
Charge at **B** Watts for **W** seconds.
Charge at **C** Watts for **X** seconds.
Charge at **D** Watts taper with voltage limit from OSPS for **Y** seconds.
Rest **Z** seconds (OCV no current or voltage control)
Continue cycling for 28 days. Record data for 1st and last 100 cycles otherwise record

data for 1 of every 100 cycles.

PAC	A(W)/U (sec)	V(sec)	B(W)/W (sec)	C(W)/X (sec)	D(W)/Y (sec)	Z(sec)
C	24 / 18	5	38.4 / 4	26.4 / 8	14.4 / 8	5
D	24 / 9	63	38.4 / 2	26.4 / 4	14.4 / 4	62
E	18 / 9	15	28.8 / 2	19.8 / 4	10.8 / 4	14
F	18 / 18	53	28.8 / 4	19.8 / 8	10.8 / 8	53
G	18 / 18	5	28.8 / 4	19.8 / 8	10.8 / 8	5
H	18 / 9	63	28.8 / 2	19.8 / 4	10.8 / 4	62
I	24 / 9	15	38.4 / 2	26.4 / 4	14.4 / 4	14
J	24 / 18	53	38.4 / 4	26.4 / 8	14.4 / 8	53

These tests have been broken into segments for the Maccor tester due to the size of the data files created.

Reduce all rest steps by 0.5 seconds due to Maccor switching time.

Appendix B

ATD GEN 2 Cell Distribution Matrix

There are a total of **195** Gen 2 cells (165 Baseline cells and 30 Variant C cells). INEEL will receive 45 cells (30 Baseline and 15 Variant C cells) and ANL will receive **37** (22 Baseline and 15 **Variant C**). Seven of the ANL baseline cells will be archived. The INEEL baseline cells will be divided into two groups of 15. The complete cell distribution is shown in Table B.1.

Table B.1. Cell Distribution

First 20 cells sent to ANL will be transferred to SNL								
		Baseline			Variant C			**Total**
		Testing	Therm. Ab.	Diag.	Testing	Therm. Ab.	Diag.	
ANL		22		1	15			**38**
BNL				1				**1**
INEEL		30			15			**45**
LBNL				1				**1**
SNL	1	15						**15**
ANL to SNL	2	20						**20**
	3	27	48					**75**
	4							**0**
Total		**114**	**48**	**3**	**30**	**0**	**0**	**195**
				165			**30**	**195**

SOC	25°C	35°C	45°C	55°C	Total
60%	3	3	3	3	12
80%	3	3	3	5	14
100%	3	3	5	5	16
Total	9	9	11	13	42

Cell	°C	% SOC	Cycles / day	Discharge (W)	Pulse Duration (S)
1	55	80	1800	24	18
2	55	80	600	24	9
3	55	60	1800	18	9
4	55	60	600	18	18
5	35	80	1800	18	18
6	35	80	600	18	9
7	35	60	1800	24	9
8	35	60	600	24	18

Appendix C

ATD GEN 2 Open Circuit Voltage vs. State of Charge Tables and Curves

Table C.1. Calibration Table for ATD Gen 2 Baseline Cells

SOC	Voltage	SOC	Voltage	SOC	Voltage	SOC	Voltage
100%	4.096						
99%	4.084	74%	3.851	49%	3.644	24%	3.499
98%	4.075	73%	3.843	48%	3.639	23%	3.490
97%	4.065	72%	3.833	47%	3.633	22%	3.481
96%	4.055	71%	3.824	46%	3.628	21%	3.472
95%	4.045	70%	3.815	45%	3.623	20%	3.462
94%	4.034	69%	3.805	44%	3.618	19%	3.451
93%	4.023	68%	3.795	43%	3.613	18%	3.440
92%	4.012	67%	3.786	42%	3.608	17%	3.429
91%	4.001	66%	3.776	41%	3.603	16%	3.418
90%	3.990	65%	3.767	40%	3.598	15%	3.406
89%	3.980	64%	3.758	39%	3.594	14%	3.395
88%	3.970	63%	3.749	38%	3.589	13%	3.384
87%	3.960	62%	3.740	37%	3.584	12%	3.374
86%	3.950	61%	3.731	36%	3.578	11%	3.365
85%	3.941	60%	3.723	35%	3.573	10%	3.357
84%	3.932	59%	3.714	34%	3.568	9%	3.349
83%	3.923	58%	3.705	33%	3.562	8%	3.340
82%	3.915	57%	3.698	32%	3.556	7%	3.331
81%	3.906	56%	3.690	31%	3.551	6%	3.320
80%	3.898	55%	3.683	30%	3.544	5%	3.304
79%	3.891	54%	3.675	29%	3.537	4%	3.278
78%	3.883	53%	3.669	28%	3.530	3%	3.235
77%	3.875	52%	3.662	27%	3.523	2%	3.177
76%	3.868	51%	3.656	26%	3.515	1%	3.106
75%	3.860	50%	3.650	25%	3.507	0%	3.000

Note: The voltages are averaged using the C/25 discharge curves from 3 ANL trial cells (Quallion s/n-17, s/n-20, and s/n-29).

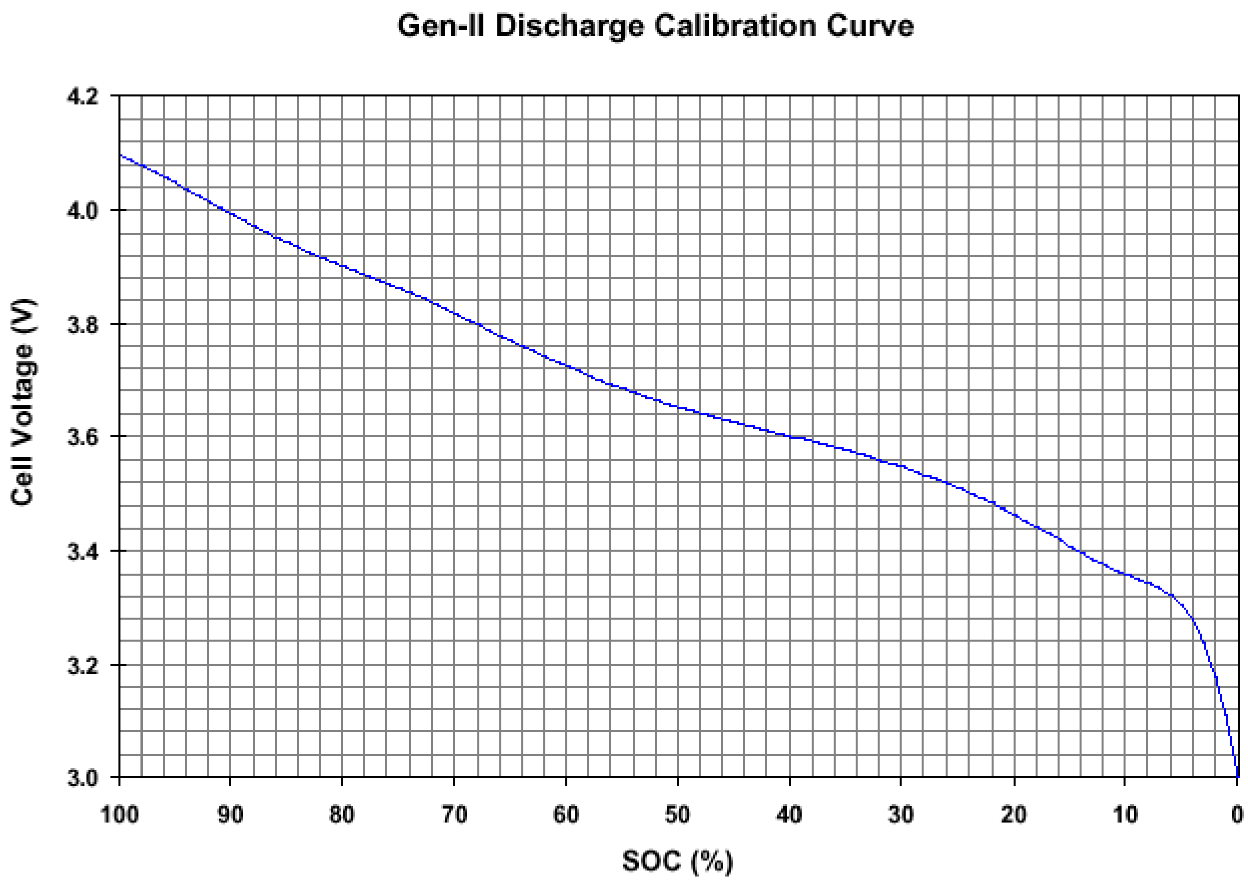


Figure C.1. ATD Gen 2 Baseline Cell OCV vs. SOC Curve

Appendix D

Data Handling

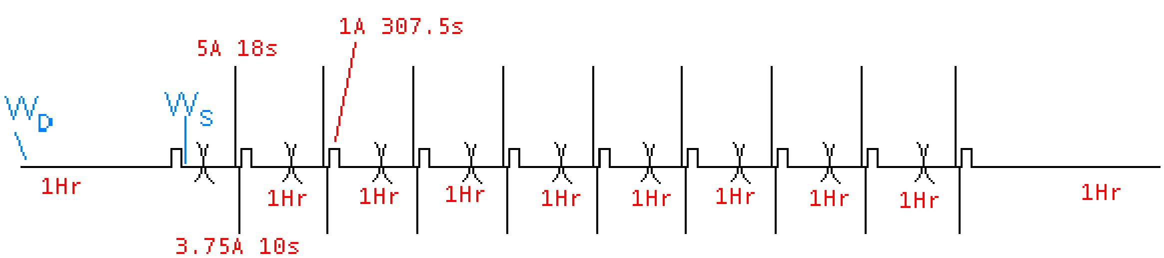
All data is to be processed within 2 weeks of test completion.
All Gen. 2 data will be stored on PSTG drive “U”- (Folder ATD-G2-Test on computer ‘ds09snlnt’). [SNL internal ONLY]
Raw data for Digatron and Maccor tests will also be kept on a Jaz cartridge.

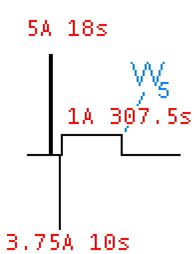
Graphing Data

Current, Voltage and Temperature (where applicable) data vs. Time will be plotted for all RPT tests run on Digatron or Maccor.
For HPPC tests make a second plot of Voltage vs. Time and showing a 3 V cutoff line. This will make it apparent what pulse the cell fails on.
For Static Capacity tests make a plot of Capacity vs. Cycle #. The capacity for the 5th C/1 cycle will be added to a composite chart showing capacity for all cells and all RPTs.

Analyzing Data

For ambient HPPC tests data shall be processed using a macro that produces charts similar to those called for in the PNGV gen. 3 test manual.





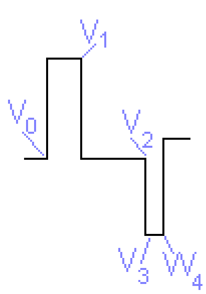


Chart 1

Title: (Centered) "Open Circuit Voltage and Resistance vs. State of Charge //
Cell ### RPT XX"

X Axis ("State of Charge (%)")
SOC from table

Y Axis (" Resistance (Ohms)")
Pink Line $(V_0-V_1)/I_1$ – Discharge Resistance $=R_{Dis}$
Blue Line $(V_3-V_2)/I_3$ – Regen Resistance $=R_{reg}$
Green Line V_0 (secondary axis- "Open Circuit Voltage (V)")

Chart 1A

Title: (Centered) "Open Circuit Voltage and ASI vs. State of Charge //
Cell ### RPT XX"

X Axis ("State of Charge (%)")
SOC from table

Y Axis ("ASI (Ohms-cm^2)")
Pink Line $((V_0-V_1)/I_1)$ * 846.3 (Electrode Area) – Discharge Resistance $=R_{DisA}$
Blue Line $((V_3-V_2)/I_3)$ * 846.3 (Electrode Area) – Regen Resistance $=R_{regA}$
Green Line V_0 (secondary axis- "Open Circuit Voltage (V)")

Chart 2

Title: Pulse Power Capability vs SOC // Cell ### RPT XX

X Axis ("State of Charge (%)")
SOC from table

Prior to 5/02 V_2 was taken directly from the data file. For the sake of conformity all old data and all subsequent data now use an interpolated value of V_2.
Y Axis ("Pulse Power Capability (W)")
Pink Line $3.0*(V_0-3.0)/R_{Dis}$ – Discharge Pulse Power Capability
Blue Line $4.1*(4.1-V_2)/R_{Reg}$ – Regen Pulse Power Capability

Chart 2A

Title: Pulse Power Density vs SOC // Cell ### RPT XX

X Axis ("State of Charge (%)")
SOC from table

Y Axis ("Pulse Power Density (mW/cm^2)")
Pink Line ((3.0*(V_0-3.0)/ R_{Dis}) / 846.3)*1000 – Discharge Pulse Power Capability
Blue Line ((4.1*(4.1-V_2)/ R_{Reg}) / 846.3)*1000 – Regen Pulse Power Capability

Chart 3

Title: Pulse Power Capability vs Energy Removed // Cell ### RPT XX
Prior to 5/02 Wh values were derived by summing Wh values from the data file. For the sake of conformity all old data and all subsequent data now interpolate a Wh value based on a C/1 discharge from the static capacity test.
For Maccor:
X Axis ("Energy Removed (Wh)")
W_F= W_S+W_1 for first point
W_F= W_F-W_3 for second point
W_F= W_F+W_3-W_4+W_1+W_5 for third point…

For Digatron:
X Axis ("Energy Removed (Wh)")
Pink line value W_D-W_1
Pink line value W_D-W_3

Y Axis (" Pulse Power Capability (W)")
Pink Line 3.0*(V_0-3.0)/ R_{Dis} –Discharge Pulse Power Capability
Blue Line 4.1*(4.1-V_2)/ R_{Reg} – Regen Pulse Power Capability

Chart 4

Title: Energy Available vs Power // Cell ### RPT XX

X Axis ("Power (W)")
Derived from Chart 3 using same method as Gen 1

Y Axis ("Energy Available (Wh)")
Derived from Chart 3 using same method as Gen 1

Chart 5

Title: HPPC Power vs Energy Removed Scaled by BSF // Cell ### RPT XX

X Axis ("Energy Removed (Wh x BSF)")
Point on chart 3 * 553

Y Axis ("Discharge Power Capability (W x BSF)")
Pink Line Point on chart 3 * 553– Discharge Pulse Power Capability
Blue Line Point on chart 3 * 553 – Regen Pulse Power Capability

A final chart shall be made for each cell demonstrating the change in Energy Available vs Power (Chart 4).

After all RPTs an overlay of Energy Available vs. Power shall be created for each cell showing the progression of power fade. This will be scaled to show the PNGV target performance.