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Advanced Technology Development Program for Lithium-Ion Batteries: Gen 2 GDR Performance Evaluation Report

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ABSTRACT

The United States Department of Energy's Advanced Technology Development Program has completed the performance evaluation of the second generation of lithium-ion cells (i.e., Gen 2 cells). This report documents the testing and analysis of the Gen 2 GDR cells, which were used to debug and assess the newly developed Technology Life Verification Test Manual. The purpose of the manual is to project a 15-year, 150,000 mile battery life capability with a 90% confidence interval using predictive models and short-term testing. The GDR cells were divided into two different matrices. The core-life test matrix consisted of calendar- and cycle-life cells with perturbations of the four major acceleration factors (temperature, state-of-charge, throughput, and power rating). The supplemental-life test matrix consisted of cells subjected either to a path dependence study, or a comparison between the standard hybrid pulse power characterization test and the newly-developed minimum pulse power characterization test. Resistance and capacity results are reported.

EXECUTIVE SUMMARY

In conjunction with the Partnership for a New Generation of Vehicles, the Advanced Technology Development (ATD) Program was initiated in 1998 by the U.S. Department of Energy's Office of Advanced Automotive Technologies to find solutions to the barriers that limit the commercialization of high-power lithium-ion batteries. In 2002, this partnership was superseded by FreedomCAR (Freedom Cooperative Automotive Research) and this work is now under the auspices of the FreedomCAR and Vehicle Technologies Program. The second generation of lithium-ion cells (i.e., Gen 2 cells) consisted of a baseline chemistry and two variant chemistries (i.e., Variant C and GDR). This report documents the performance evaluation of the ATD 18650-size Gen 2 GDR cells, which consisted of a change to the baseline negative electrode. The GDR graphite is a round-edge natural graphite that has an amorphous carbon coating at the particle level.

The GDR cells were primarily used to learn and evaluate the new procedures and profiles that have been defined for technology life verification testing. Cell aging consisted of characterization, followed by life testing with periodic breaks for reference performance testing (RPT). Although some cells were subjected to a standard FreedomCAR RPT, which consisted of a $C_1/1$ discharge followed by a low-current hybrid pulse power characterization (L-HPPC) test, most cells were subjected to the newly-developed minimum pulse power characterization (MPPC) test every four weeks during aging. The MPPC test was designed to provide sufficient information about cell degradation while minimizing the time spent off life testing, and avoiding possible deleterious effects (e.g., full charging and discharging). Although the MPPC does provide impedance degradation at two different states-of-charge (SOCs), there are insufficient data for available power calculations. Consequently, the life degradation models need to be based on resistance or area-specific impedance. However, one significant advantage of the MPPC is the ability to determine the true resistance at the reference temperature (e.g., 30°C) since the MPPC profile is performed at two different temperatures (once at the life-test temperature, and once at 30°C).

The majority of the cells was distributed in a core-life test matrix that consisted of calendar- and cycle-life testing at various temperatures (40, 50, and 60°C) and two SOCs (80 and 40% SOC). A smaller group of cells was subjected to supplementary testing, in which various assumptions about what did not affect cell degradation were verified. The GDR supplementary matrix consisted of a path dependence study and an RPT study. In the path dependence study, groups of cells were subjected to calendar-life testing, then switched to cycle-life testing after the discharge impedance increase by a specified amount. Other groups of cells started with cycle-life testing, then switched to calendar-life testing. The RPT study group consisted of cycle-life testing at the most benign and most extreme conditions of the core-life test matrix, but with the L-HPPC test instead of the MPPC test every four weeks.

Unfortunately, the GDR cells showed a very large manufacturing variability and inconsistent results. The data indicate that SOC is the most dominant stress factor, with temperature also showing a small effect. Power ratio and throughput did not appear to be significant stress factors. The data also indicated that the MPPC test yields statistically different results from the L-HPPC test, and it does not eliminate some of the deleterious effects it was designed to resolve. Unlike the Gen 2 Baseline and Variant C cells, the GDR calendar-life cells faded more quickly than the corresponding cycle-life cells (note, however, that the test protocols were different). Both the path dependence and RPT studies were inconclusive.

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CONTENTS

FIGURES

TABLES

ACRONYMS

ANL	Argonne National Laboratory
ASI	area-specific impedance
ATD	Advanced Technology Development
BOL	beginning-of-life
DOD	depth-of-discharge
FreedomCAR	Freedom Cooperative Automotive Research
Gen	Generation
INL	Idaho National Laboratory
L-HPPC	low-current hybrid pulse power characterization
LBNL	Lawrence Berkeley National Laboratory
MPPC	minimum pulse power capability
OCV	open-circuit voltage
OSPS	operating set point stability
RPT	reference performance test
SOC	state-of-charge
SNL	Sandia National Laboratories
TLVT	Technology Life Verification Test
VEC	vinyl ethylene carbonate

Advanced Technology Development Program for Lithium-Ion Batteries:

Gen 2 GDR Performance Evaluation Report

1. INTRODUCTION

In conjunction with the Partnership for a New Generation of Vehicles, the U.S. Department of Energy 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, poor response to abuse scenarios, and poor low temperature performance. In 2002, the Partnership for a New Generation of Vehicles was superceded by FreedomCAR (Freedom Cooperative Automotive Research), and this work is now sponsored by the FreedomCAR and Vehicle Technologies Program. A full description of the ATD Program within the context of the overall FreedomCAR energy storage research and development is provided in Reference 1.

Five DOE National Laboratories are participating in the ATD Program. Argonne National Laboratory (ANL) has overall programmatic and technical lead responsibilities, including cell chemistry. The Idaho National Laboratory (INL) 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 collaboration with Brookhaven National Laboratory, ANL, SNL, and INL. These five National Laboratories are working in close coordination to develop a fundamental understanding of life degradation mechanisms and an accurate life prediction methodology; identify and mitigate factors limiting abuse tolerance; identify low cost materials, components, and technologies; and identify and mitigate factors that contribute to poor performance at low temperatures.

1.1 Gen 2 GDR Cells

1.1.1 Cell Chemistry

The second generation of ATD lithium-ion cells (i.e., Gen 2 cells) included a baseline chemistry and two variants. The first variant chemistry (Variant C) consisted of a change to the composition of the positive electrode. Test results and analysis from the Gen 2 Baseline and Variant C cells are discussed in a separate report (Reference 2). The GDR cell chemistry is defined in Reference 3 and summarized in Table 1. These 18650-size cells were manufactured by Quallion, LLC to ANL specifications. The majority of these cells were manufactured with the same Gen 2 baseline chemistry, but with a "GDR" graphite instead of a MAG-10 graphite for the negative electrode. The GDR graphite is a round-edge natural graphite that has an amorphous carbon coating at the particle level. Potential advantages over the MAG-10 include enhanced safety (due to the rounded edges) and relatively low cost. Some of the GDR cells also included a 2 wt% vinyl ethylene carbonate (VEC) electrolyte additive, and test results for these cells are discussed in Reference 2. It should also be noted that the electrodes for these cells were left in a glove box, unsealed, for 8 to 9 months prior to assembly, which may have contributed to the wide performance variability and rapid degradation.

Table 1. Gen 2 GDR cell chemistry.

	Gen 2 GDR 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	10 wt% PVDF binder 90 wt% GDR graphite
Electrolyte	1.2 M $LiPF_6$ in EC:EMC (3:7 wt%)
Separator	25 μm thick PE (Celgard)

1.1.2 Cell Distribution

Quallion manufactured a total of 54 Gen 2 GDR cells for testing and diagnostics. The cell distribution is shown in Table 2. Of the 37 cells designated for life testing at INL, 34 were allocated for studies related to technology life verification testing, and are discussed in this report. Life testing and analyses for these cells were performed in accordance with the procedures outlined in the *Battery Technology Life Verification Test Manual* (Reference 4), and as detailed in the cell-specific test plan (Reference 5). The cells were tested against the FreedomCAR Minimum Power Assist goals (Reference 6). The other three INL cells were designated for low temperature performance testing, but a test matrix was never developed due to early cell failures. The six ANL life test cells were tested the same way as the Gen 2 Baseline and Variant C cells, and are discussed in Reference 2. Details concerning the other GDR cells (i.e., cells designated for diagnostic or thermal abuse testing) are not discussed in this report.

Table 2. Gen 2 GDR cell distribution.

	Life Testing	Diagnostics	Thermal Abuse	Archive
INL	37 GDR Cells			
ANL	3 GDR Cells 3 GDR Cells with VEC	1 GDR Cell 1 GDR Cell with VEC		4 GDR Cells
SNL			3 GDR Cells	
LBNL		1 GDR Cell 1 GDR Cell with VEC		

1.2 Gen 2 GDR Testing Overview

1.2.1 Technology Life Verification Testing

The purpose of Gen 2 GDR life testing was primarily to help refine various aspects of the Technology Life Verification Test (TLVT) Manual (Reference 4). The goal of TLVT is to verify the 15-year, 150,000 mile FreedomCAR battery life capability at the target confidence level of 90% within one or two years of life testing. The TLVT methodology assumes small measurement-to-measurement errors and cell-to-cell manufacturing differences, and are based on Monte Carlo simulations and the bootstrap method (Reference 7). Although a chemistry-specific mechanistic model is recommended for life predictions, a default empirical model has been provided in the manual based on the ATD Gen 2 Baseline and Variant C life data (References 2 and 4). Life testing consists of a complete full factorial core matrix that takes into account known degradation mechanisms. The example core life test matrix provides adequate coverage of four major stress factors (temperature, SOC, energy throughput, and pulse power rating). The supplemental life test matrix confirms assumptions made when developing the core life test matrix (e.g., path independence).

1.2.2 Gen 2 GDR Life Test Matrix

The Gen 2 GDR TLVT life test matrix is shown in Table 3. Twenty-two cells were used for core life testing (16 cycle-life and 6 calendar-life). Temperature was the only varying stress factor for calendar-life testing. The cycle-life cell matrix consisted of different temperatures, states of charge (SOCs), throughput rates, and pulse power ratings (in accordance with the example acceleration factors in the TLVT Manual). The throughput and pulse power ratings are based on the pulse profile used during cycling (Section 3.3.1).

Twelve cells were assigned to a supplemental life test matrix. Eight of these cells were used to for a path dependence study by switching from calendar- to cycle-life and vice versa. The other four cells were used to study the impact of the newly-developed reference performance test (RPT) for TLVT testing versus the standard FreedomCAR reference performance test (Section 3.2).

1.2.3 Gen 2 GDR Lot Numbers

The Gen 2 GDR cells were manufactured in four different lots over a period of four months. The number of cells per lot for all GDR cells is shown in Table 4. The cells tested under the matrix shown in Table 3, along with the date received, are also shown in Table 4. Twenty-nine GDR cells were received by INL on February 25, 2004. Initial testing was started on April 6, 2004 using 16 cells from Lot F03E916 for the cycle-life testing, four cells each from Lots F03E916 and F04A914 for the path dependence group, and four cells from Lot F04A908 for the RPT study. The remaining cell from Lot F04A914 was placed in cold storage for future low temperature performance testing. After initial characterization testing, cell pairs were assigned to the test matrix based on matching powers (this involved moving cells to different thermal blocks and temperature chambers). Due to poor performance, all testing was stopped on May 24, 2004. Four cells (two each from Lots F04A914 and F04A908) showed more than 26% power fade after only 600 cycles. These four cells were removed from test and shipped back to Quallion for diagnostic analysis on June 22, 2004.

Another eight cells from Lot F04D151 arrived on May 5, 2004. Six of these cells were assigned to the calendar-life test matrix, and two were used as replacements for the path dependence study. An archived cell (see Table 2) from Lot F04D151 was also received from ANL on June 21, 2004. This cell and the INL cell in cold storage were used as replacement cells for the RPT study. Testing was re-initiated on June 4, 2004, but cells were not re-matched according to power performance. The cycle-life cells reached end-of-test on May 11, 2005. The calendar-life and supplemental life test cells reached end-of-test by March 15, 2005.

Table 3. Gen 2 GDR life test matrix.

		# of Cells	Temperature (°C)	SOC (%)	Throughput (mph)	Power Ratio (%)
Core	Cycle-Life 1	2	40	40	20 mph	80%
	Cycle-Life 2	2	40	40	25 mph	96%
	Cycle-Life 3	2	40	80	20 mph	80%
	Cycle-Life 4	2	40	80	25 mph	96%
	Cycle-Life 5	2	50	40	20 mph	80%
	Cycle-Life 6	2	50	40	25 mph	96%
	Cycle-Life 7	2	50	80	20 mph	80%
	Cycle-Life 8	2	50	80	25 mph	96%
	Calendar-Life 1	2	40	80	Standby	0%
	Calendar-Life 2	2	50	80	Standby	0%
	Calendar-Life 3	2	60	80	Standby	0%
Supplemental	Path Dependence 1	2	40	40	Standby / 20 mph	0% / 80%
	Path Dependence 2	2	40	40	20 mph / Standby	80% / 0%
	Path Dependence 3	2	50	80	Standby / 25 mph	0% / 96%
	Path Dependence 4	2	50	80	25 mph / Standby	96% / 0%
	RPT Study 1	2	40	40	20 mph	80%
	RPT Study 2	2	50	80	25 mph	96%

Table 4. Gen 2 GDR lot numbers.

Lot Number	Total Number of Cells	Number of INL Cells	Date Received
F03E916	24	20	2-25-04
F04A914	5	5	2-25-04
F04A908	4	4	2-25-04
F04D151	16 GDR-Only Cells	8 / 1	5-05-04 / 6-21-04
	5 GDR+VEC Cells	-	-

2. BATTERY INFORMATION

2.1 Battery Rating and Limitations

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

		GDR Cells
$C_1/1$ rated capacity		0.9 A·h
$C_1/1$ nominal capacity (average)		0.906 A·h
Cell nominal weight (average)		38.6 g
Electrode Area		810.7 cm²
Battery size factor:		
	Cycle-Life	459
	Calendar-Life	471
	Path Dependence	476
	RPT Study	488
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 (10-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	7.2 A (10-s pulse)
		1.8 A (continuous)
	Maximum charge current	7.2 A (10-s pulse)
		0.9 A (continuous)

3. TESTING

Characterization and life testing were performed in accordance with the *FreedomCAR Battery Test Manual* (Reference 6), the *Battery Technology Life Verification Test Manual* (Reference 4), and the Gen 2 GDR test plan (References 5). FreedomCAR performance goals, procedures, analytical methodologies, and ATD specific testing requirements are detailed in these documents and are summarized below.

3.1 Receipt Inspection

A receipt inspection of all cells was performed prior to testing to verify that there was no damage during shipping. This includes a visual inspection and measuring cell weights, open-circuit voltages (OCV) and impedance at 1 kHz. This inspection showed that the cells were not physically damaged, with no signs of leaking or shorting. The average cell weight was 38.6 ± 0.3 g. The average beginning of life (BOL) real impedance at 1 kHz was 10.9 ± 0.7 mΩ at an average OCV of 3.68 ± 0.02 V (roughly 50% SOC). Receipt inspection data for each cell is shown in Appendix A. Figure 1 shows a Gen 2 GDR cell pictured during the receipt inspection.

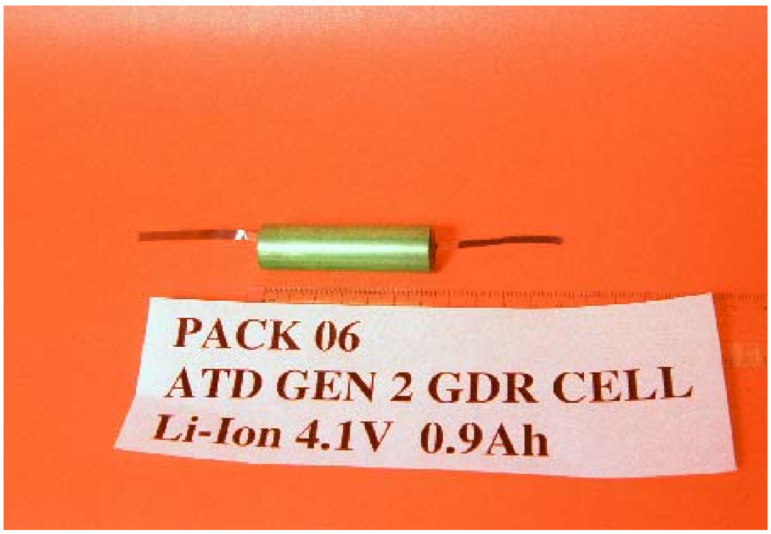

Figure 1. Gen 2 GDR cell.

3.2 Characterization Testing

Following the receipt inspection, characterization testing was performed on all cells prior to aging to establish BOL performance parameters, including capacity, resistance, power, and energy. All characterization testing was performed at 30°C, and was initiated with three consecutive discharges at the $C_1/1$ rate. This test consists of a constant current discharge to the minimum voltage from a fully charged state using the rated capacity defined at the 1-h rate (i.e., subscript "1"). For example, the $C_1/1$ discharge test is performed at 0.9 Ah / 1 h, or 0.9 A.

The low-current hybrid pulse power characterization (L-HPPC) test was performed next. The test profile is shown in Figure 2 and defined in Reference 6. It consists of 10-s constant-current discharge and regen pulses with a 40-s rest period in between, for a total duration of 60 s. The discharge pulse is performed at a $5C_1$ rate (i.e., 4.5 A for the GDR cells). The regen pulse is performed at 75% of the discharge rate (i.e., 3.375 A). 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 6).

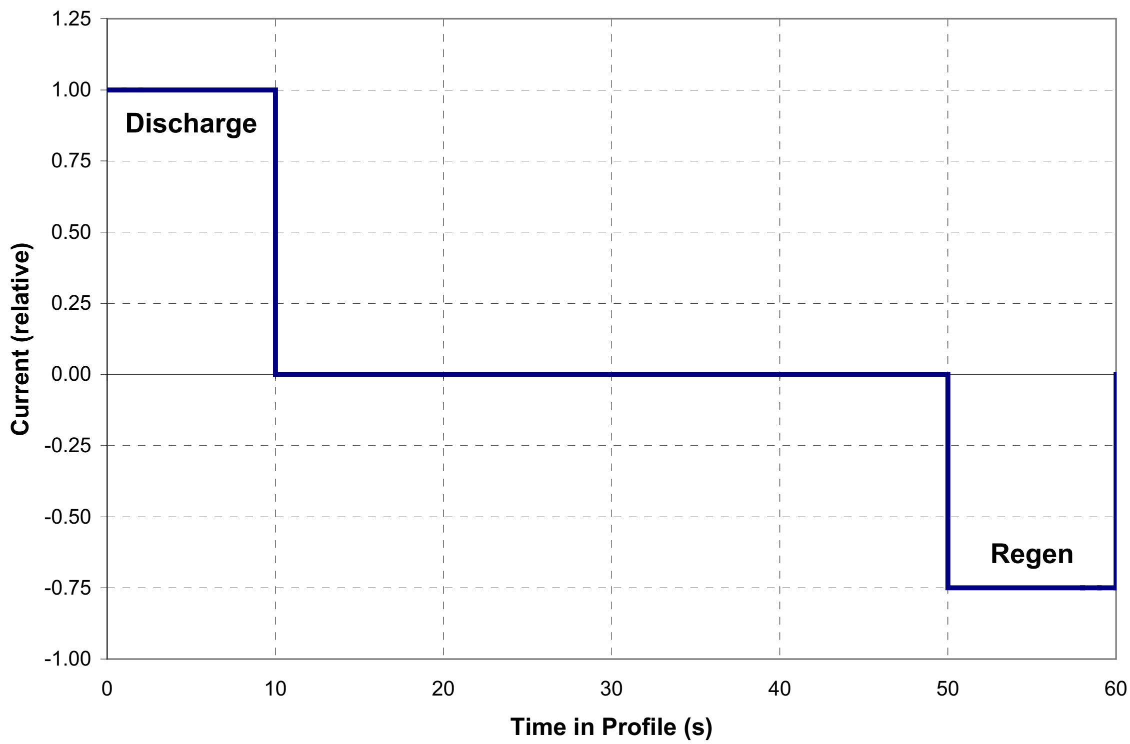

Figure 2. FreedomCAR L-HPPC pulse profile.

Following the L-HPPC test, the OCV was determined as a function of SOC using a newly designed test from the TLVT Manual (Reference 4). Beginning from a fully charged state, the cell is discharged at a $C_1/1$ rate in 5% DOD increments of the rated capacity (i.e., 0.045 Ah) followed by a one-hour rest at OCV to determine the equilibrium voltage. This sequence is repeated until the minimum voltage of 3.0 V is reached.

For most cells (other than the RPT study group), the next characterization test was the newly designed minimum pulse power characterization (MPPC) test as defined in Reference 4 and shown in Figure 3. The purpose of the MPPC is to minimize the irrelevant stresses induced by the full $C_1/1$ and L-HPPC test, such as the time spent at full charge (Reference 8). The MPPC consists of only two L-HPPC pulse profiles (Figure 2), with a $C_1/1$ taper discharge in between. These pulse profiles are performed at two SOC conditions known as SOC_{MAX} and SOC_{MIN}, which are reference conditions representing the anticipated standard operating range for a battery system (typically specified but the manufacturer). The GDR cell SOC range was 80 and 40% SOC, respectively. One significant advantage of the MPPC is that it is performed at both life-test temperature and reference temperature (i.e., 30°C), allowing life predictions to be based on temperature-compensated data. A disadvantage of the MPPC is the inability to acquire accurate power data at the target FreedomCAR goal of 300 Wh due to having performance data at only two SOCs. All TLVT life predictions are based on resistance or the area-specific impedance. The area-specific impedance (ASI) is the cell resistance scaled by the electrode area (810.7 cm^2 for the GDR cells).

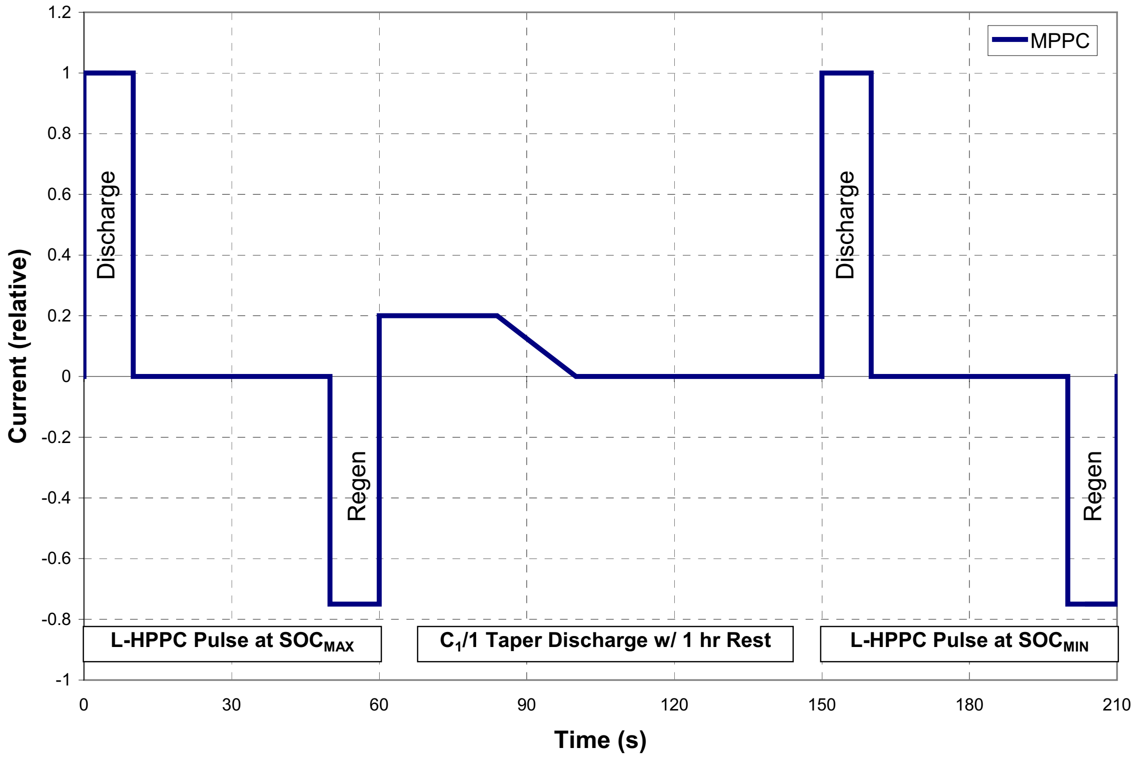

Figure 3. MPPC pulse profile.

3.3 Life Testing

3.3.1 Cycle-Life Testing

Cycle-life testing is based on the FreedomCAR minimum power assist 95th and 99th Percentile profiles, as defined in Reference 6 and shown in Figure 4. It consists of constant power discharge and regen pulses for a total duration of 90 s. These profiles are repeated continuously during the cycle-life test while centered around the specified SOC in Table 3 (80 or 40% SOC). The 95th Percentile profile has a power ratio of 80% (see Table 3) since the "Launch" pulse is a 20 kW pulse (80% of the discharge power goal of 25 kW). Similarly, the 99th Percentile profile has a 96% power ratio with a "Launch" pulse of 24 kW. These constant power profiles are for a full-size battery pack and need to be scaled to cell-size levels using the battery size factor, which is defined in Reference 6. These profiles are also designed for an energy swing of 25 Wh with an assumed energy throughput that corresponds to 20 mph driving. To increase the driving speed to 25 mph (only for the 99th Percentile profile, see Table 3), the pulse durations of the "Launch" and "Regen" power pulses were increased by a ratio of 25/20 mph, with a subsequent decrease in the "Cruise" pulse to maintain a 90-s profile. This resulted in a total energy swing of 30 Wh.

Although the cycle-life profiles defined in the FreedomCAR manual are nominally charge neutral (assuming a 90% round trip efficiency), the actual cycling stability at the target SOC is first established by the operating set point stability (OSPS) test. Generally, the OSPS test consists of 100 consecutive profiles. The requirement is that at its completion, the measured OCV after a 1-h rest is within 2% of the target OCV. If the OCV shows an unstable effect (i.e., charge positive or charge negative), then a 1-s voltage-controlled discharge step is added at the end of the "Launch" pulse, and/or an adjustment to the "Cruise" pulse power level is made, to achieve stable cycling. The OSPS test is repeated, and the voltage/power levels adjusted, until stable cycling occurs. The cell behavior of the GDR cells was such that the OSPS test required 280 cycles to ensure stability in cycling.

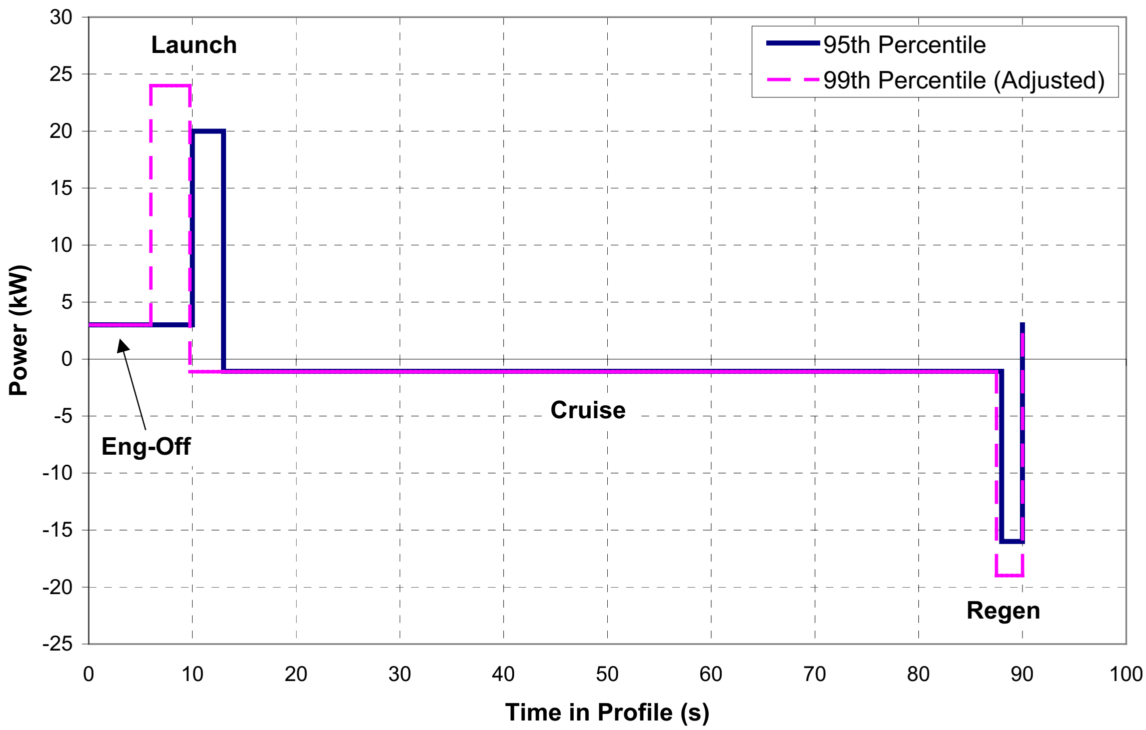

Figure 4. FreedomCAR 95th and 99th Percentile cycle-life profiles.

3.3.2 Calendar-Life Testing

Calendar-life testing consisted of resting at OCV and test temperature without any pulse-per-day testing. The voltage was monitored, and if it dropped below a certain threshold, it was taper charged back up to the original OCV at test temperature, and calendar-life aging continued (Reference 4). For the GDR calendar-life cells aging at SOC_{MAX} (i.e., 80% SOC), the cells would be recharged if the voltage ever dropped below SOC_{MIN} (i.e., 40% SOC). The GDR cells calendar-life aging at SOC_{MIN} would have been recharged if the voltage reached V_{MIN} (3.0 V). However, as discussed in Section 4.3.1, none of the cells self-discharged to the voltage limit during a four-week period.

3.3.3 Path Dependence Testing

Path dependence testing was meant to verify the assumption that a cell's degradation behavior will be similar regardless of the path taken. A group of cells were cycle-life tested until the discharge resistance growth at SOC_{MAX} was ~16%, and then switched to calendar-life testing. Another group did the opposite, starting with calendar-life, then switching to cycle-life.

3.3.4 RPT Study

The RPT study was designed to determine the effect of the MPPC test compared to the standard FreedomCAR RPT, which consists of a $C_1/1$ discharge and L-HPPC test. Consequently, groups of cells were tested using the most benign and most harsh conditions of the TLVT cycle-life test matrix (i.e., Cycle-Life 1 and Cycle-Life 8 in Table 3, respectively), but with a standard FreedomCAR RPT instead of the newly devised TLVT MPPC.

3.4 Reference Performance Testing

Life testing for the Gen 2 GDR cells was interrupted every four weeks (i.e., 26880 cycle-life profiles) for reference performance testing. Most cells (other than the RPT study group) were subjected to the newly developed MPPC test, which was designed to measure changes in resistance as a function of test time (Figure 3). As mentioned above, the RPT study group was subjected to a $C_1/1$ discharge and L-HPPC test instead. These tests were designed to quantify changes in capacity, resistance, power, and energy as a function of test time. *ASI growth* is the percentage increase in cell ASI during the MPPC or L-HPPC test. *Capacity fade* is the percentage loss in the discharge capacity during the $C_1/1$ test. *Power fade* is the percentage loss in the power at 300 Wh from the L-HPPC test (Reference 6). The fades are normalized to the characterization RPT (i.e., at characterization, the ASI growth and capacity and power fades are all 0%).

4. RESULTS

Prior to assembly, the GDR cells were left in a glove box, unsealed, for approximately nine months, and previous calendar-life testing at the ANL showed very poor performance compared to the Baseline and Variant C cells (Reference 2). Consequently, the cells designated for TLVT testing were primarily used to help refine the manual, and were not used for validation purposes. The test results for these cells, as discussed below, also showed very poor performance.

Due to the large number of test conditions (see Table 3), only cell averages or results from representative cells are presented in this section. Individual cell data (e.g., capacity fade, ASI growth, etc.) are shown in Appendix B. Also, a group identifier has been established for this report of the form "AABbCC." The first two characters identify the SOC (i.e., 40 or 80%). The middle character(s) represent the life test condition (i.e., "5" for the 95^{th} Percentile, "9" for the 99^{th} Percentile, "C" for calendar-life testing). An additional character is required for the path dependence group (e.g., "5C" represents a path dependence group that began with cycle-life testing and switched to calendar-life). The last two characters represent the test temperature (i.e., 40, 50, or 60°C). For example, a test condition of "40950" would represent the group of cells that were cycle-life tested at 40% SOC and 50°C using the 99^{th} Percentile profile.

4.1 Capacity

4.1.1 OCV vs. SOC

As discussed in Section 3.2, the GDR cell OCV vs. SOC was based on $C_1/1$ discharges in 5% SOC increments with one-hour rests between each increment (unlike the Gen 2 Baseline and Variant C cells, whose SOCs were based on a continuous full $C_1/25$ discharge, Reference 2). Figure 5 shows the voltage as a function of calculated SOC for a representative GDR cell. The SOCs were determined from the measured capacity of the cell (not rated capacity). Although the GDR cells were never subjected to a $C_1/25$ test, other cell chemistries have indicated that the TLVT method and the full $C_1/25$ discharge yield similar results. The resulting average OCVs corresponding to SOC_{MAX} and SOC_{MIN} for each life-test group were determined from piecewise linear interpolation (Reference 4) and are shown in Table 5. These values were used for subsequent life and reference performance testing.

Table 5. OCV versus SOC for the GDR cell groups.

Cell Group	OCV at SOC_{MAX}	OCV at SOC_{MIN}
Cycle-Life	3.918 V	3.625 V
Calendar-Life	3.913 V	3.621 V
Path Dependence	3.917 V	3.624 V
RPT Study	3.918 V	3.625 V

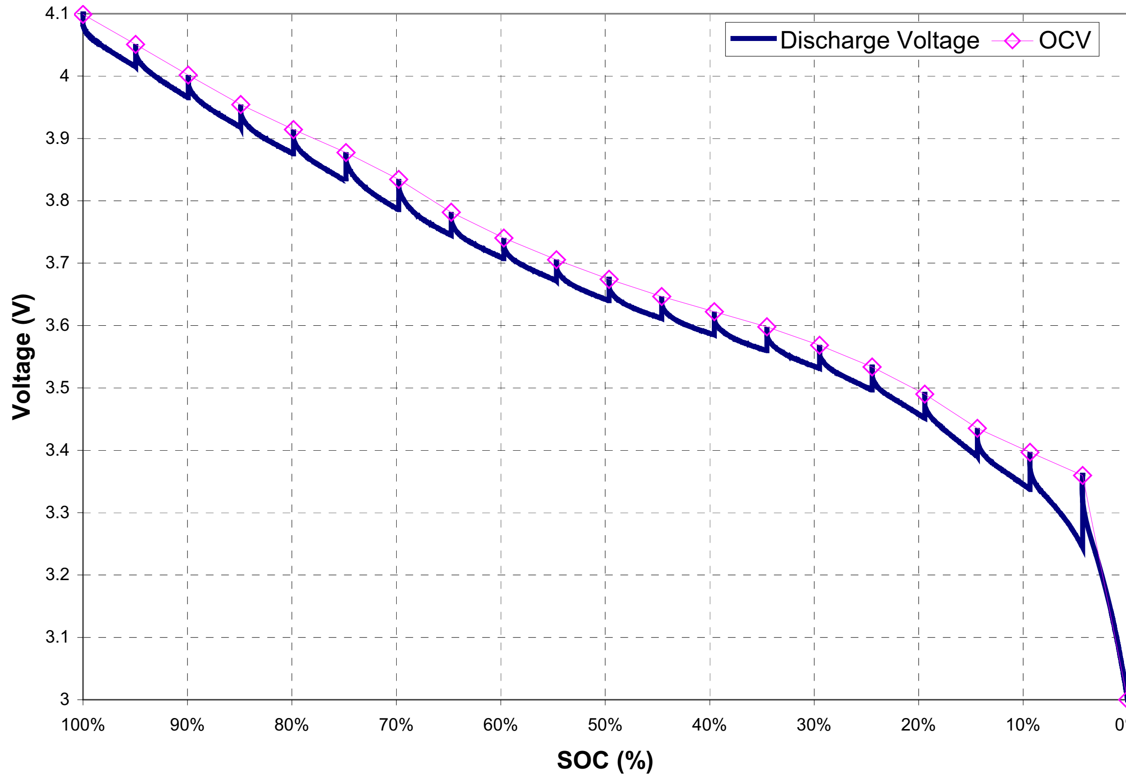

Figure 5. OCV as a function of SOC for a representative GDR cell.

4.1.2 Discharge Capacity

Figure 6 shows the average capacities for each test group for the TLVT cycle- and calendar-life cells through 36 weeks of aging. These capacities were measured from the $C_1/1$ discharge between SOC_{MAX} and SOC_{MIN} at 30°C (data do not include the taper discharge at SOC_{MIN}). The biggest change occurs between characterization and four weeks, which is consistent with the Gen 2 Baseline and Variant C cell results. This behavior may be related to incomplete formation of the solid electrolyte interphase layer (Reference 2). For the cycle-life cells, there does not appear to be any profile dependency (i.e., power ratio does not appear to be a stress factor for these cells), since the capacity fade rates between the 95^{th} and 99^{th} Percentile profiles are similar within each temperature and SOC condition. There is a small temperature effect for the cycle-life cells aged at SOC_{MIN} since the 50°C cell groups show a slightly higher capacity fade than at 40°C. The temperature effect is more pronounced for the cells aged at SOC_{MAX}. The calendar-life cells also show a small temperature effect, and slightly greater fade than the corresponding cycle-life cells after 28 weeks of aging. This is the opposite trend seen with the Baseline and Variant C cells, where the cycle-life cells faded more quickly (Reference 2). The performance trends may be attributable to the difference in calendar-life testing (the Gen 2 Baseline and Variant C calendar-life cells were clamped at a designated voltage with a pulse per day whereas the GDR cells were left at OCV, see Section 3.3.2). Another source for the different performance trends may by the various cell lot numbers used for each group (see Table 4).

Figure 7 shows the average capacities for each test group in the supplemental matrices (path dependence and RPT study). These data also show a larger drop in available capacity between characterization and four weeks. As mentioned in Section 3.3.3, the switch from calendar- to cycle-life (or vice versa) for the path dependence cells occurred when they showed approximately 16% ASI growth.

One group switched after only eight weeks of aging, another two groups were switched after 16 weeks, and the last group (405C40) never showed that much impedance growth. The data show roughly similar capacity fades to the corresponding cycle-life cells. However, the question concerning path dependence is inconclusive (especially when ASI is also considered, see Section 4.2), and may be attributable to the mixture of cells from different lot numbers. The capacities from the RPT study groups are significantly larger than the other groups because they are based on a full discharge (not between SOC_{MAX} and SOC_{MIN}). The fade rate for the 40540 group is similar to the corresponding MPPC group (see Figure 6). However, the 80950 group showed greater fade than its counterpart in Figure 6, having reached EOT after only 20 weeks of aging.

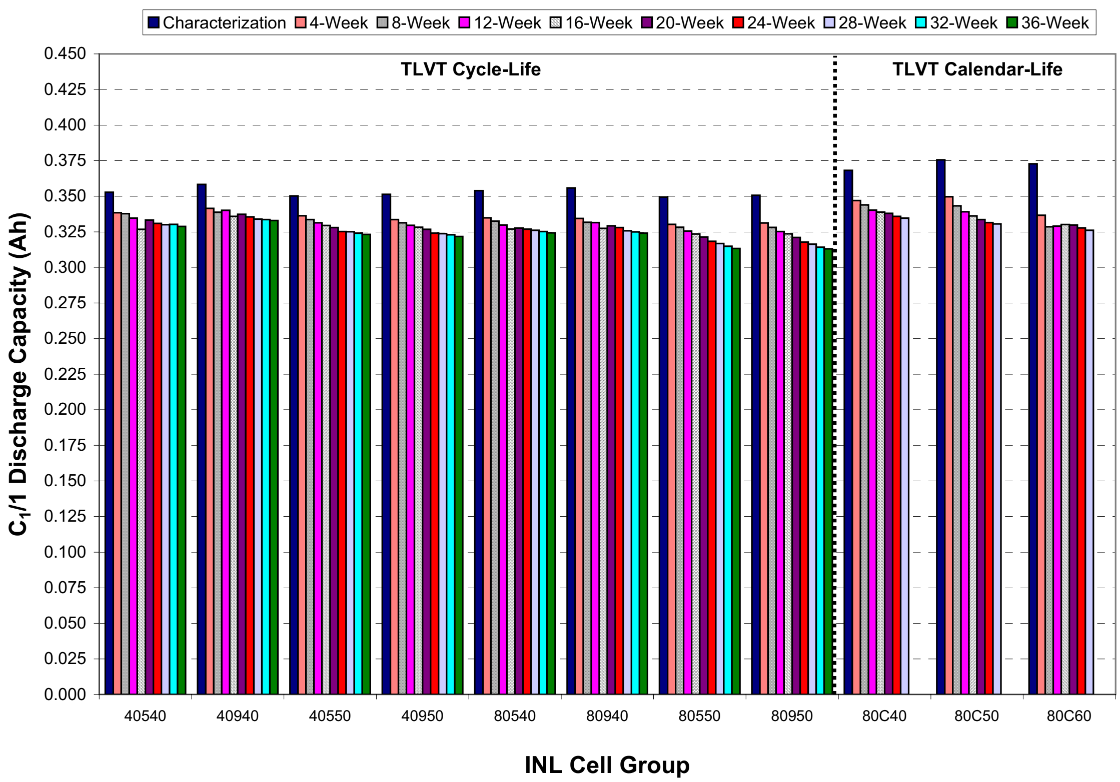

Figure 6. Average $C_1/1$ static capacity for each TLVT core-life matrix group.

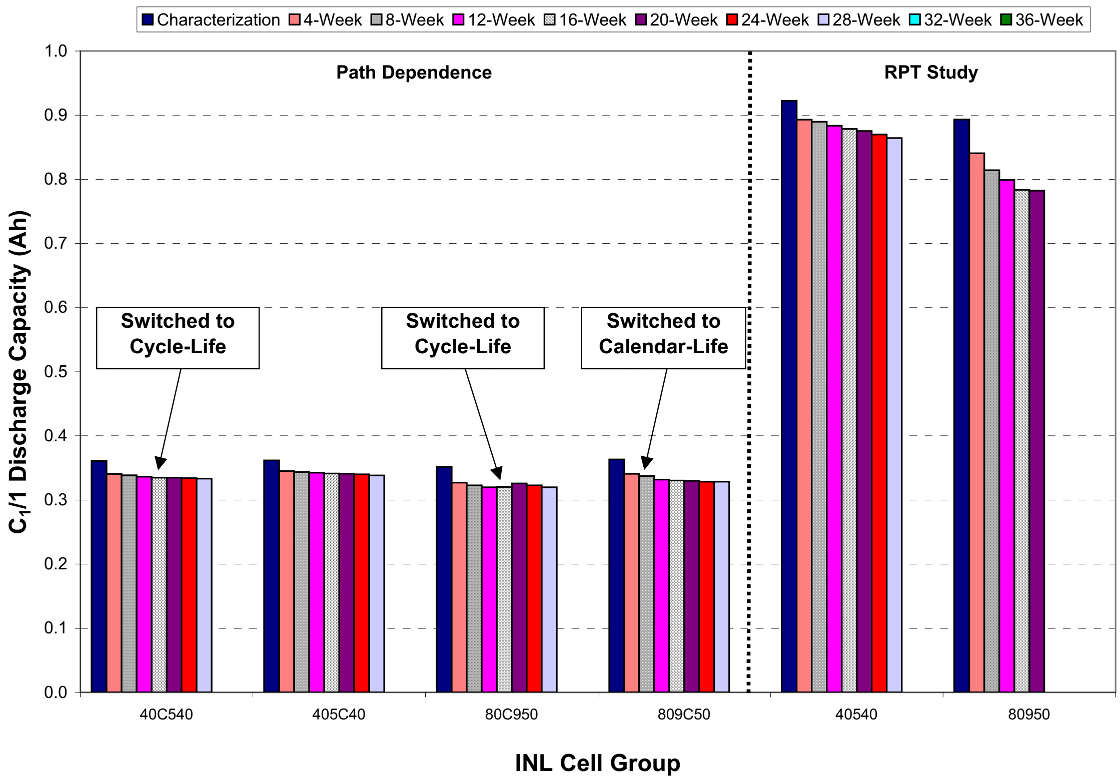

Figure 7. Average $C_1/1$ static capacity for each TLVT supplemental matrix group.

4.2 Area Specific Impedance

4.2.1 SOC_{MIN}

Figure 8 shows the average 30°C discharge ASIs at SOC_{MIN} as a function of test time for the TLVT cycle- and calendar-life core matrix groups. As seen with the capacity data, there is a significant increase in ASI between characterization and four weeks. The cycle-life cells do not appear to show any profile or throughput dependency, but generally show a slight temperature and SOC dependence. The calendar-life cells faded approximately twice as fast as the cycle-life cells, and showed an obvious temperature dependency.

Figure 9 shows the average 30°C discharge ASI at SOC_{MIN} as a function of test time for the supplemental matrices. Based on the data from Figure 8, the cell groups that started with calendar-life (i.e., 40C540 and 80C950) should show a higher initial fade rate. This appears to be the case for the cells aged at SOC_{MIN} (i.e., 40C540), but the opposite is true for the cells aged at SOC_{MAX} (i.e., 80C950 and 809C50). This, combined with the various lot numbers used in these groups, lead to inconclusive results about path dependence. Similarly, the RPT study cell groups came from a mixture of lot numbers, and the cells degraded too quickly to determine any effects between the L-HPPC and MPPC tests.

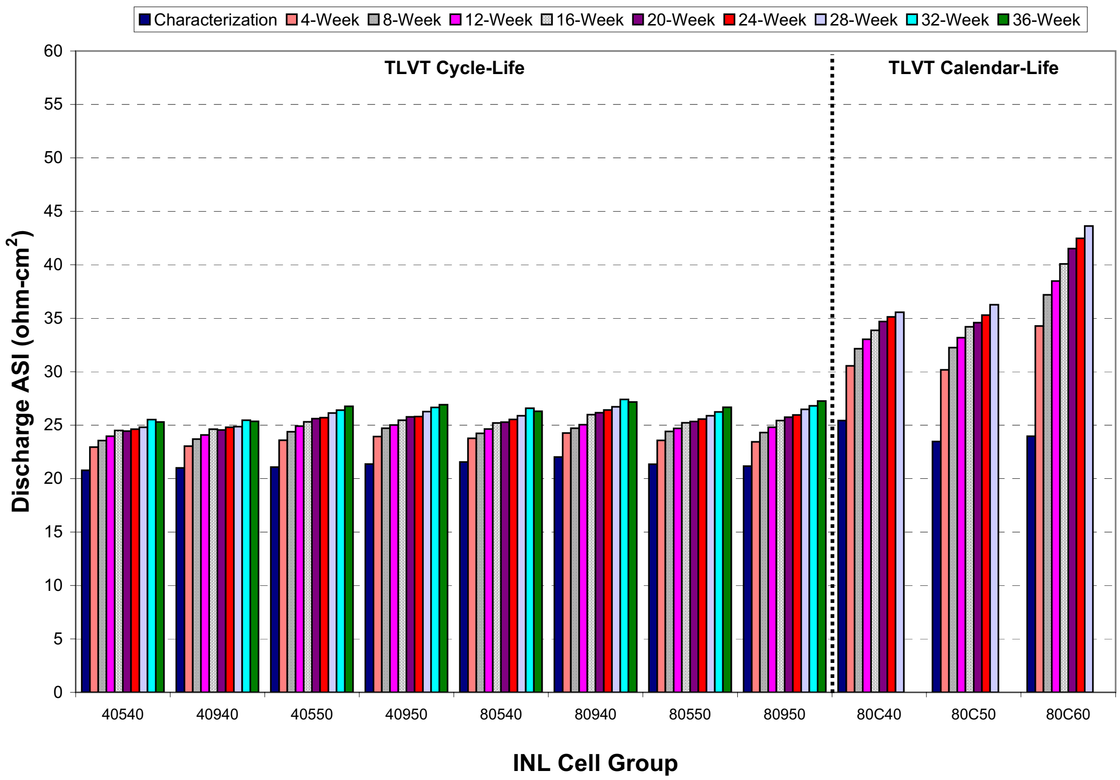

Figure 8. Average discharge ASI at SOC_{MIN} for each TLVT core-life matrix group.

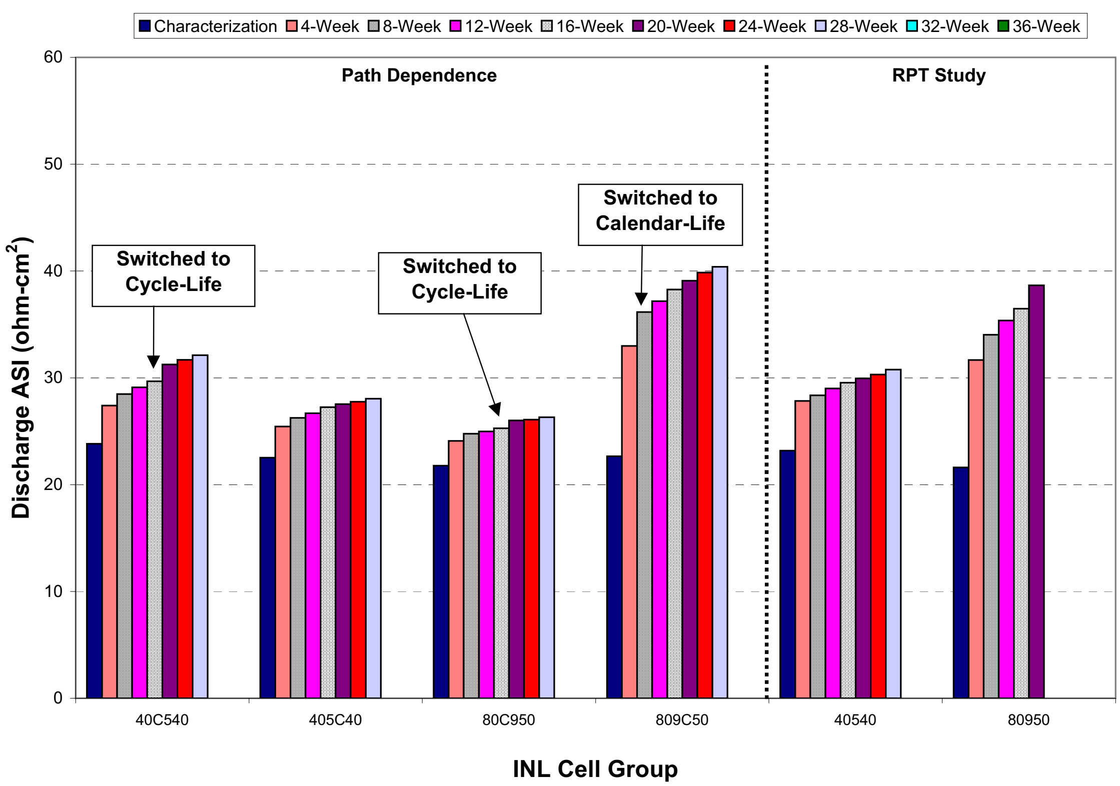

Figure 9. Average discharge ASI at SOC_{MIN} for each TLVT supplemental matrix group.

4.2.2 SOC_{MAX}

Figure 10 shows the average 30°C discharge ASI at SOC_{MAX} as a function of test time for the TLVT cycle- and calendar-life core matrix groups. These data show similar trends to those observed at SOC_{MIN} (Figure 8), with a slight temperature and SOC dependence and no apparent effect due to throughput or power ratio. Interestingly, the cycle-life cells show more overall ASI growth at SOC_{MIN} whereas the calendar-life cells show slightly more overall ASI growth at SOC_{MAX}. A significant reason for this effect is that the cycle-life ASI at SOC_{MAX} does not show a large increase between characterization and the first four weeks of aging, but the calendar-life cells do show that increase. These data indicate that the most stressful acceleration factor for the GDR cells is SOC.

Figure 11 shows the average 30°C discharge ASI at SOC_{MAX} as a function of test time for the cells in the supplemental test matrix. Although the data are inconclusive, the path dependence results at SOC_{MAX} show a little more consistency with the core-life test matrix results. Cells that started with calendar-life showed a higher growth rate than when the cells are switched to cycle-life testing, as was the case for Groups 40C540 and 80C950 (as expected, based on Figure 10). Conversely, Group 809C50 showed a slight increase in growth rate between 8- and 12-weeks of aging once the cells were switched from cycle- to calendar-life. The behavior of the cells, however, is erratic, and show an improvement in ASI after the switch from calendar- to cycle-life (unlike the behavior at SOC_{MIN}, see Figure 9). Similarly, the RPT study groups faded too quickly to draw any conclusions about performance.

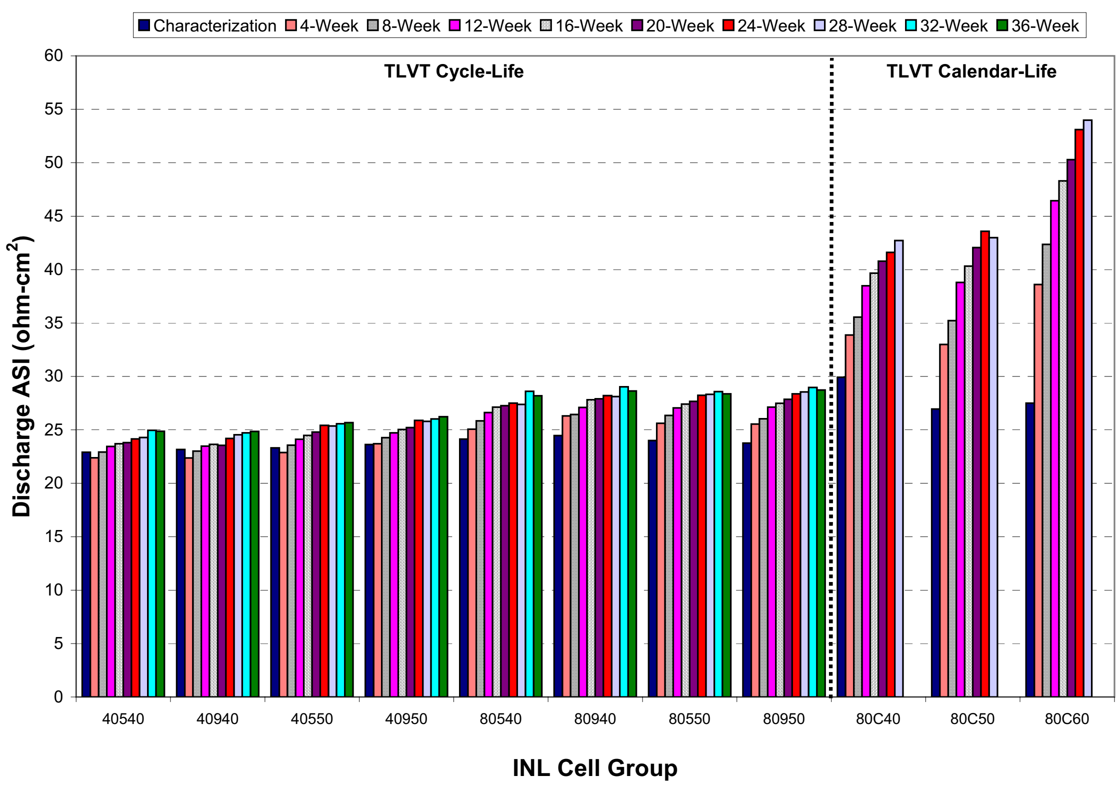

Figure 10. Average discharge ASI at SOC_{MAX} for each TLVT core-life matrix group.

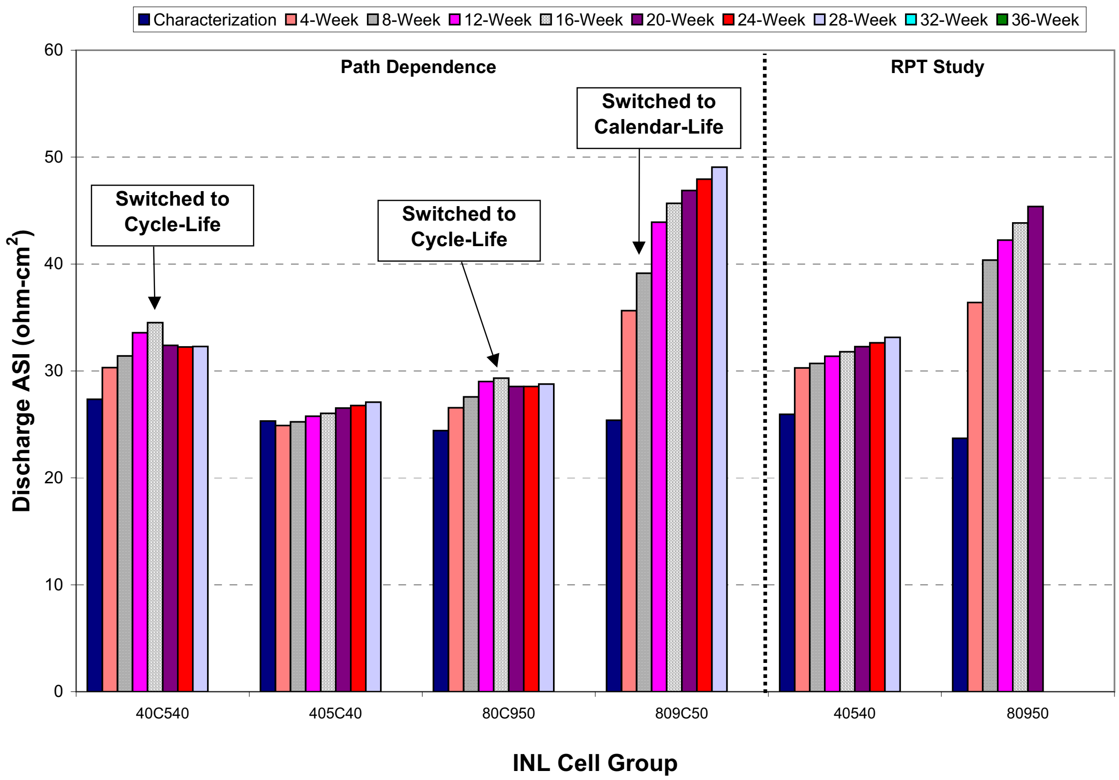

Figure 11. Average discharge ASI at SOC_{MAX} for each TLVT supplemental matrix group.

4.3 Life Testing

4.3.1 Calendar-Life

Figure 12 shows the voltage self-discharge during calendar-life testing at SOC_{MAX} for representative Gen 2 GDR core-life cells tested at 40, 50, and 60°C. The self-discharge for all cells was slow enough not to require any recharging during a four-week period. The BOL initial voltages are slightly lower primarily because of a programming glitch that resulted in an extra eight-hour rest at OCV prior to the start of the calendar-life test. The voltage self-discharge generally increases as a function of test temperature. Interestingly, after 16 weeks of aging, both the 40 and 50°C groups tend to stabilize in self-discharge whereas the 60°C group continues to improve. Consequently, the 50°C group ends up showing the most drift after 28 weeks of aging instead of the 60°C group. This may be attributable to a much higher ASI growth rate at 60°C (see Figure 10), thus increasing the competing reactions to self-discharge.

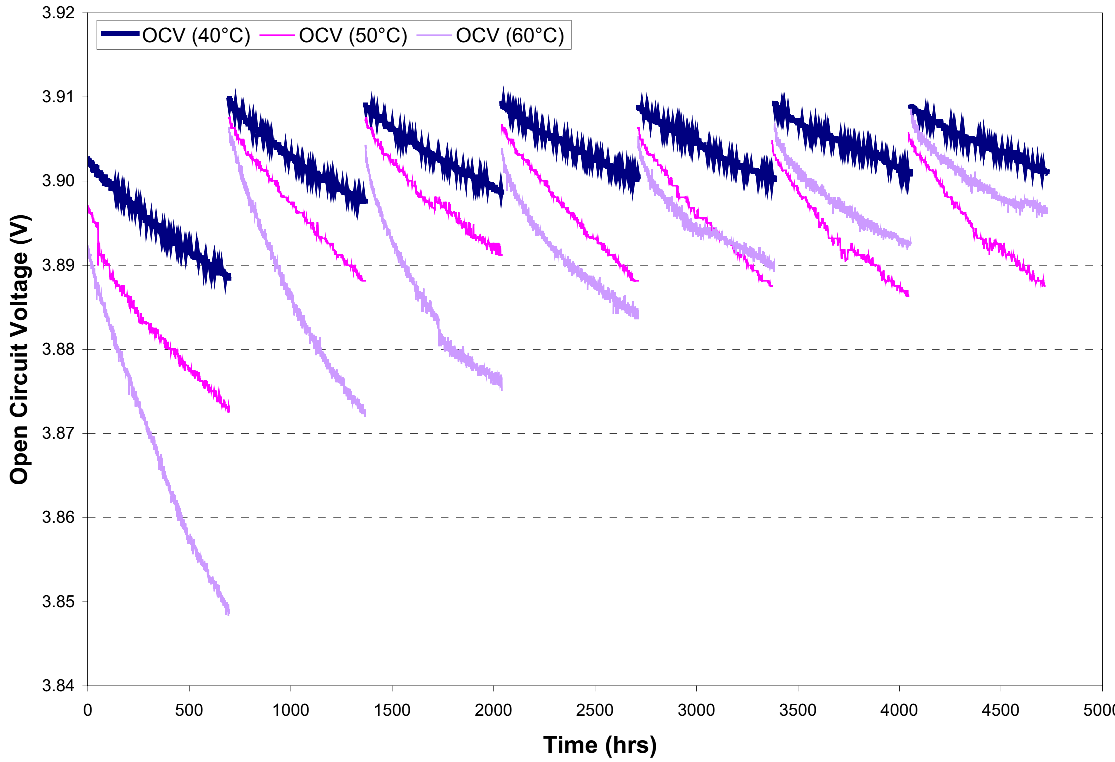

Figure 12. Calendar-life self discharge for representative cells at 40, 50, and 60°C.

4.3.2 Cycle-Life Pulse Resistance

Figures 13 and 14 show the discharge and regen pulse resistances (as calculated from the "Launch" and "Regen" pulses for representative cells in the 40540 and 40950 groups, respectively). Pulse resistances are calculated using the first 280 and last 100 pulses, and every one hundredth pulse in between. The data show slight discontinuities every 672 hours, coincident with the MPPC test. The growth in pulse resistance as a function of test time is similar regardless of test profile or temperature. Figures 15 and 16 show the pulse resistances for representative cells in the 80540 and 80950 groups, respectively. These data show a significantly greater drop in pulse resistance every four weeks as a result of the MPPC test. Furthermore, the growth in pulse resistance is greater than the corresponding groups aged at SOC_{MIN} (compare Figures 13 and 15, and Figures 14 and 16). These observations also indicate that SOC is the highest stress factor for the GDR cells. Figure 15 also shows one of the reasons why the GDR cell behavior was so erratic, and observed trends inconclusive. Several cells were having difficulty maintaining their control voltages during cycling since the resistance was changing so fast, particularly at beginning of life. Consequently, the pulse profile would quickly ramp up to the maximum voltage and show a sudden jump in pulse resistance (e.g., at approximately 1400 hours in Figure 15). The 20-week pulse resistance data for Figure 16 shows a dip due to a rise of the chamber temperature, increasing to as high as 53°C.

One of the objectives of MPPC was to minimize the post-RPT discontinuities. However, as seen in Figures 13 through 16, it does not accomplish this goal. Figure 17 shows the discharge pulse resistance data from Figures 13 and 16 normalized to a representative Gen 2 Baseline cell cycle-life tested at 45°C and 60% SOC (Reference 2). The Gen 2 cell RPT consisted of numerous tests, including a full $C_1/1$ and L-HPPC. It was determined that a full discharge and charge is the primary source of the discontinuity (Reference 8). The MPPC was designed to avoid full charges and discharges, and only operate between two SOC conditions. However, as shown in Figure 17, the MPPC discontinuity at 80% SOC is just as much as was seen for the 45°C Baseline cells. Note that the noisy Gen 2 Baseline cell data is primarily due to the old INL calibration process. The calibration routine was updated prior to the GDR cell testing (References 9 and 10), and the data collected are noticeably improved.

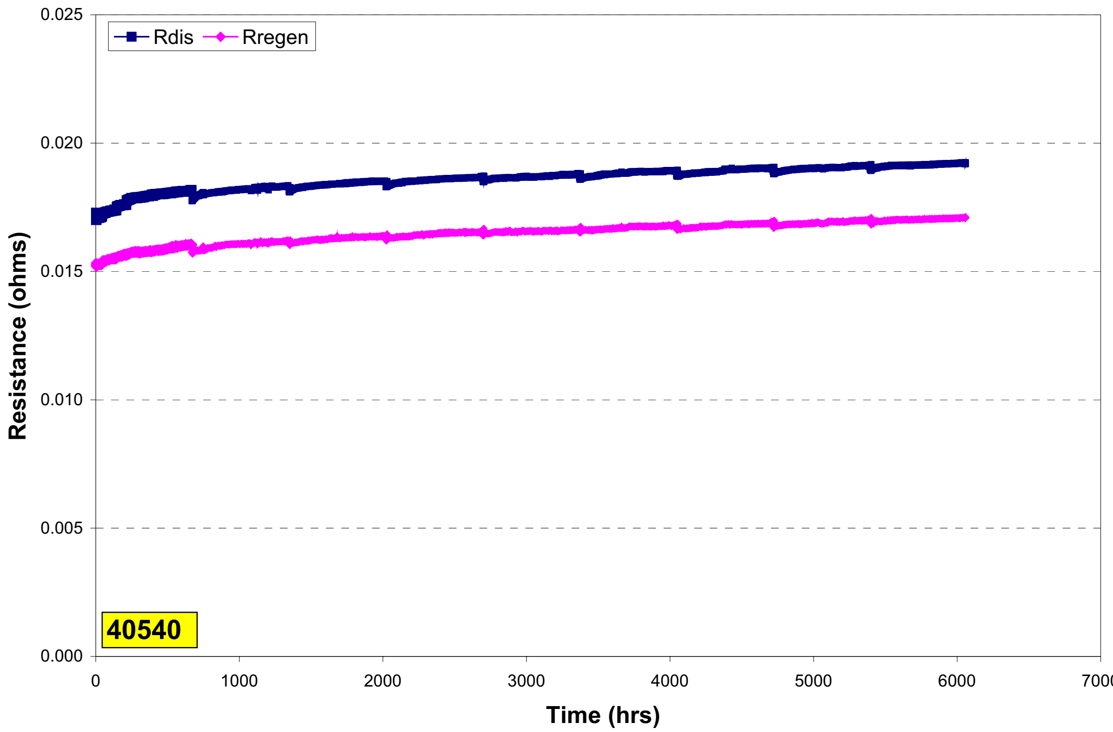

Figure 13. Cycle-life pulse resistance for a representative cell at the 40540 condition.

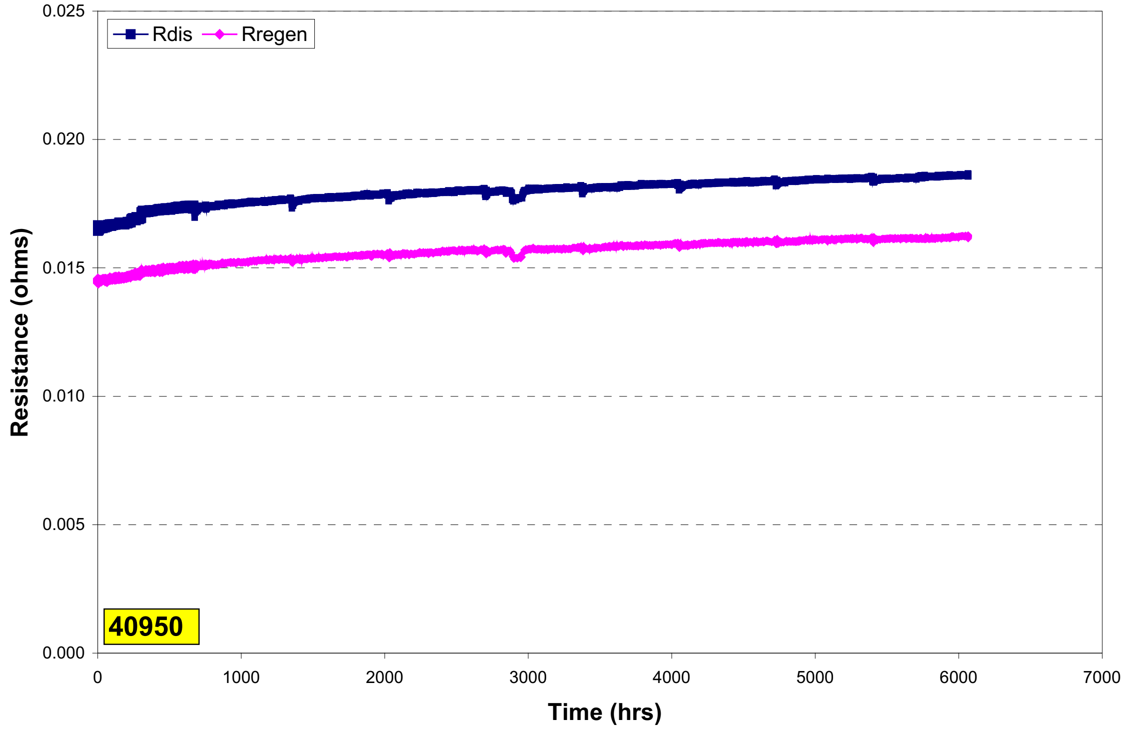

Figure 14. Cycle-life pulse resistance for a representative cell at the 40950 condition.

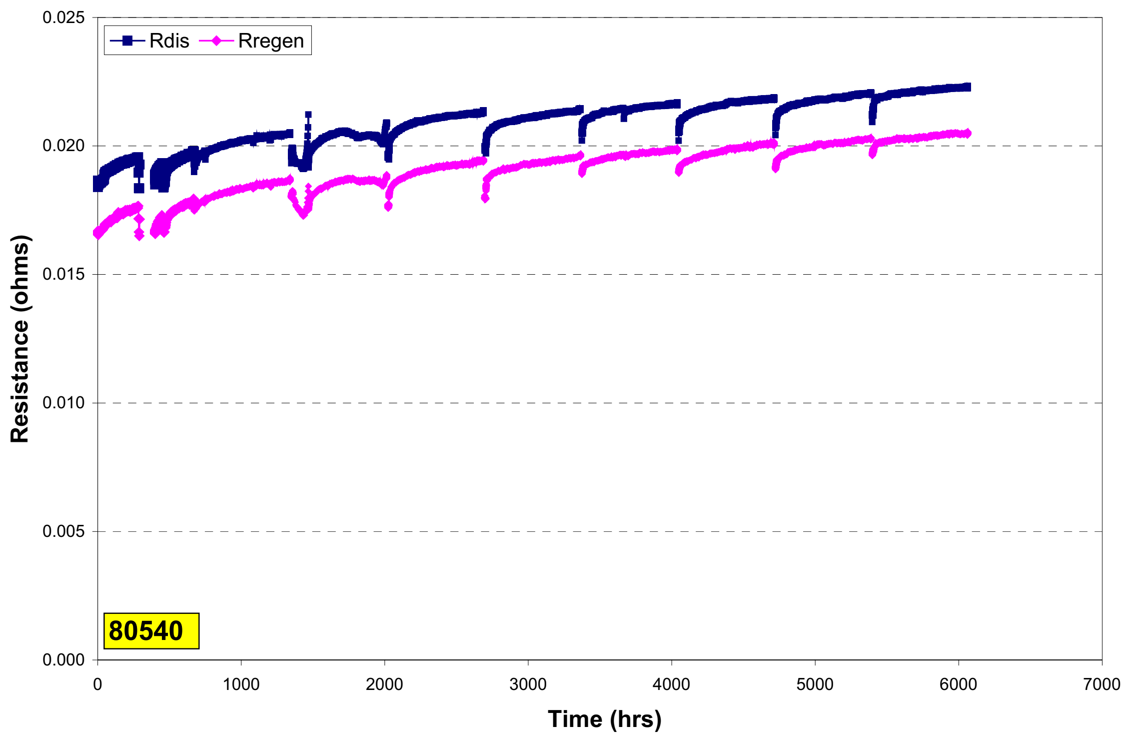

Figure 15. Cycle-life pulse resistance for a representative cell at the 80540 condition.

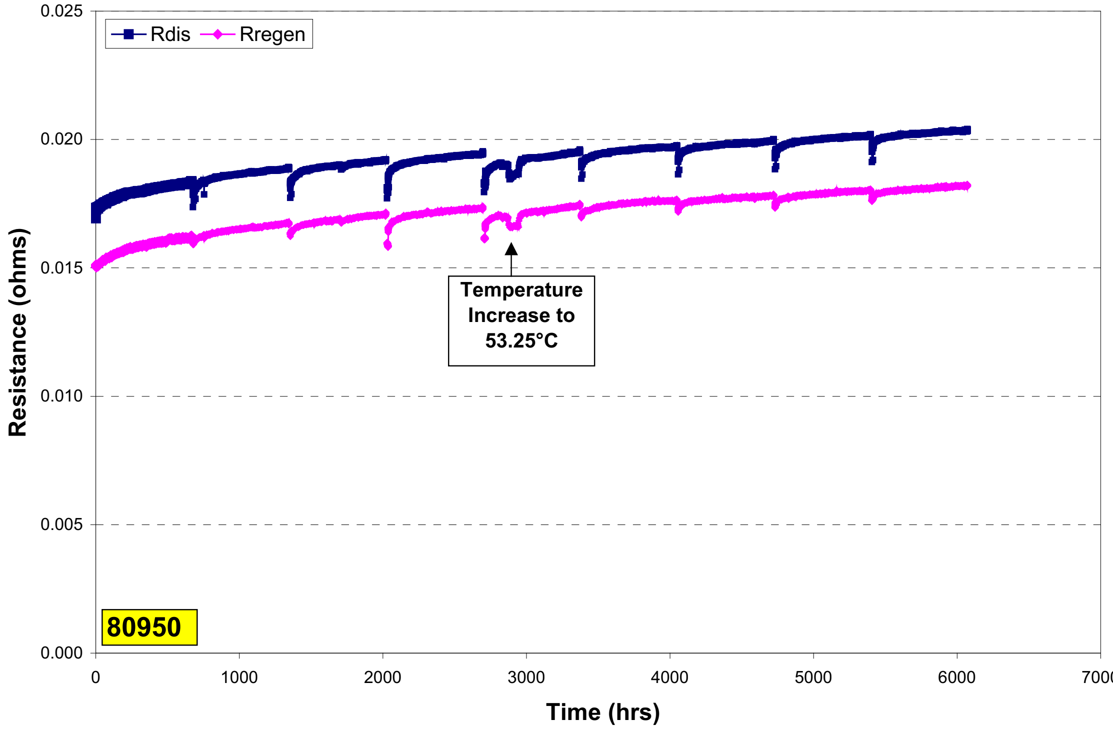

Figure 16. Cycle-life pulse resistance for a representative cell at the 80950 condition.

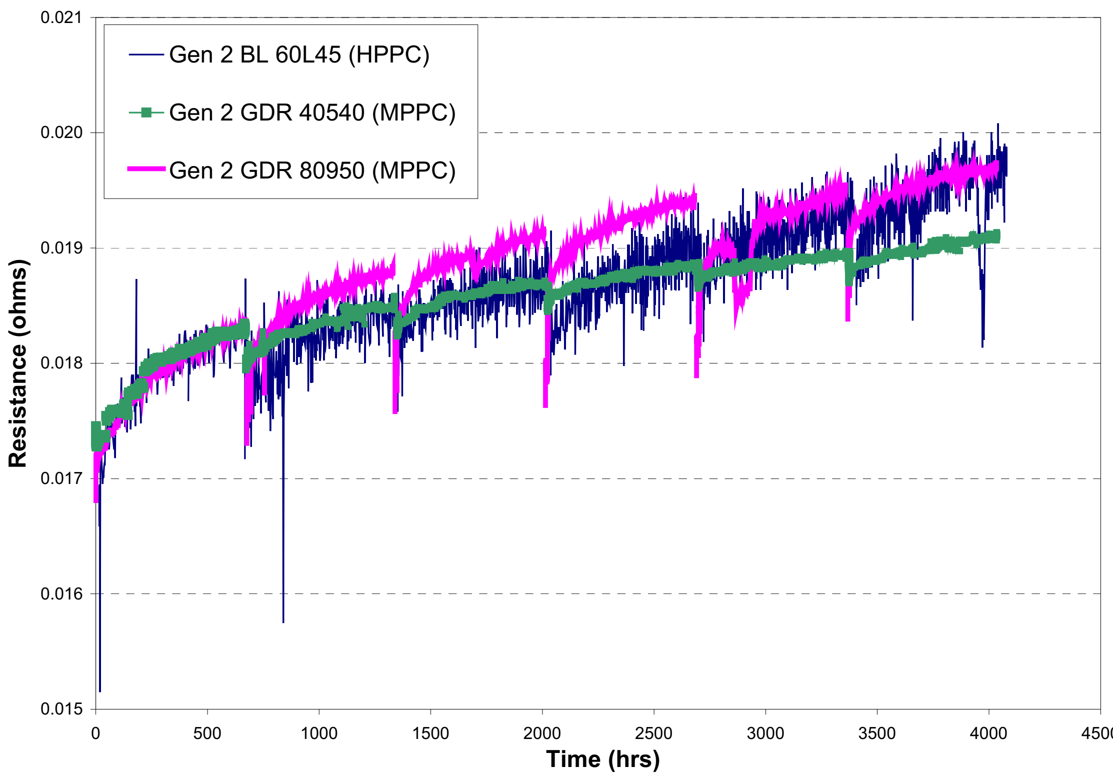

Figure 17. Comparison of pulse discontinuity between Gen 2 Baseline and GDR cells.

4.4 TLVT Applications

4.4.1 Temperature Compensation

One of the advantages of the MPPC test is that the profile shown in Figure 3 is repeated once at the life test temperature, and once at the reference temperature. From these data, a temperature compensated ASI at the exact reference temperature (e.g., 30°C) can be calculated using the methodology defined in the TLVT Manual (Reference 4). Figure 18 shows the average discharge ASI at SOC_{MIN} as a function of test time for both the calculated and temperature-adjusted values for cell group 80950. The INL temperature control is very stable and the compensation does not yield significant differences in performance results. These data are generally representative of all cell groups and SOC conditions with respect to the effect of temperature compensation.

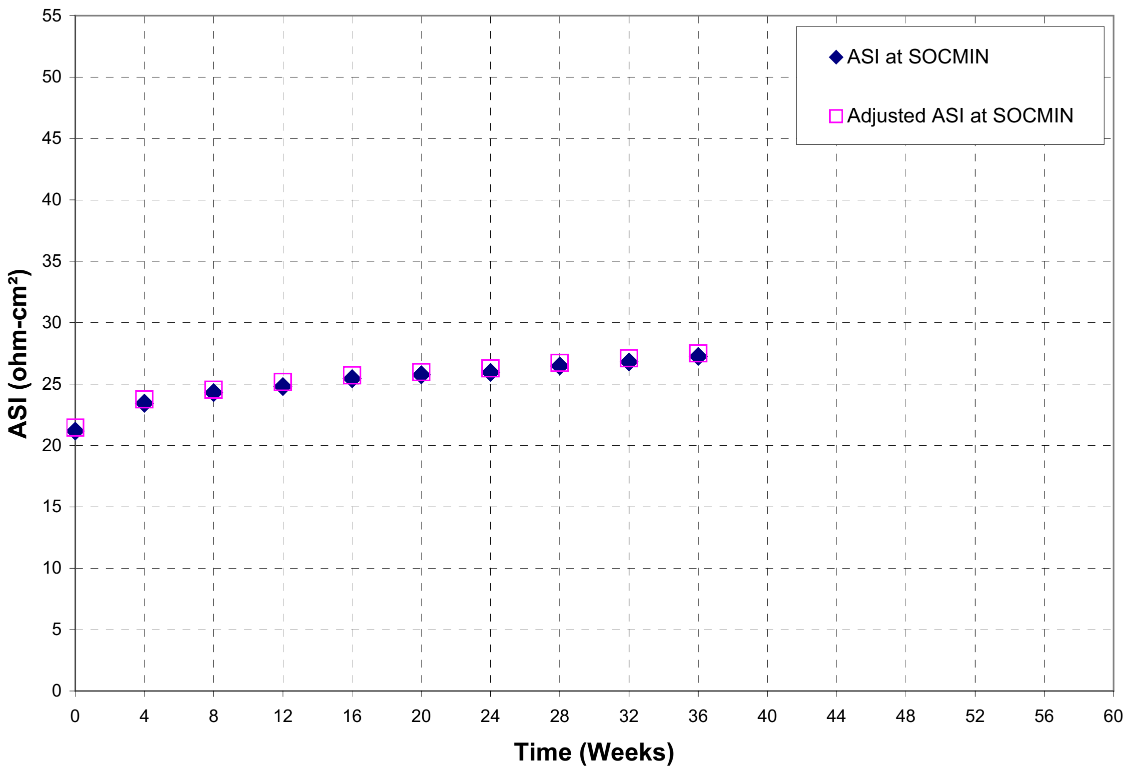

Figure 18. Effect of temperature compensation on the GDR cells (e.g., 80950 at SOC_{MIN})

4.4.2 Effects of MPPC vs. L-HPPC

The TLVT Manual also requires a statistical comparison between the L-HPPC and MPPC ASI data at characterization (Reference 4). The ASI means and standard deviations for SOC_{MAX} and SOC_{MIN} are determined from both the L-HPPC and MPPC tests, and a t-statistic is used to verify the null hypothesis that the two means are not statistically different. For the 16 GDR cycle-life cells, the null hypothesis must be rejected if $|t| > t_{0.025}$ for ($N_{HPPC} - 1$) degrees of freedom (i.e., $|t| = 2.13$). At SOC_{MAX}, $|t| = 3.25$, and at SOC_{MIN}, $|t| = 1.81$. Therefore, the null hypothesis must be rejected at SOC_{MAX}, indicating that the MPPC and L-HPPC do not yield similar results. Figure 19 shows the differences in ASIs between the two tests for all of the INL cycle-life cells. The MPPC consistently over-predicts the L-HPPC data. Similar observations were seen with other, commercially available cells as well (Reference 8).

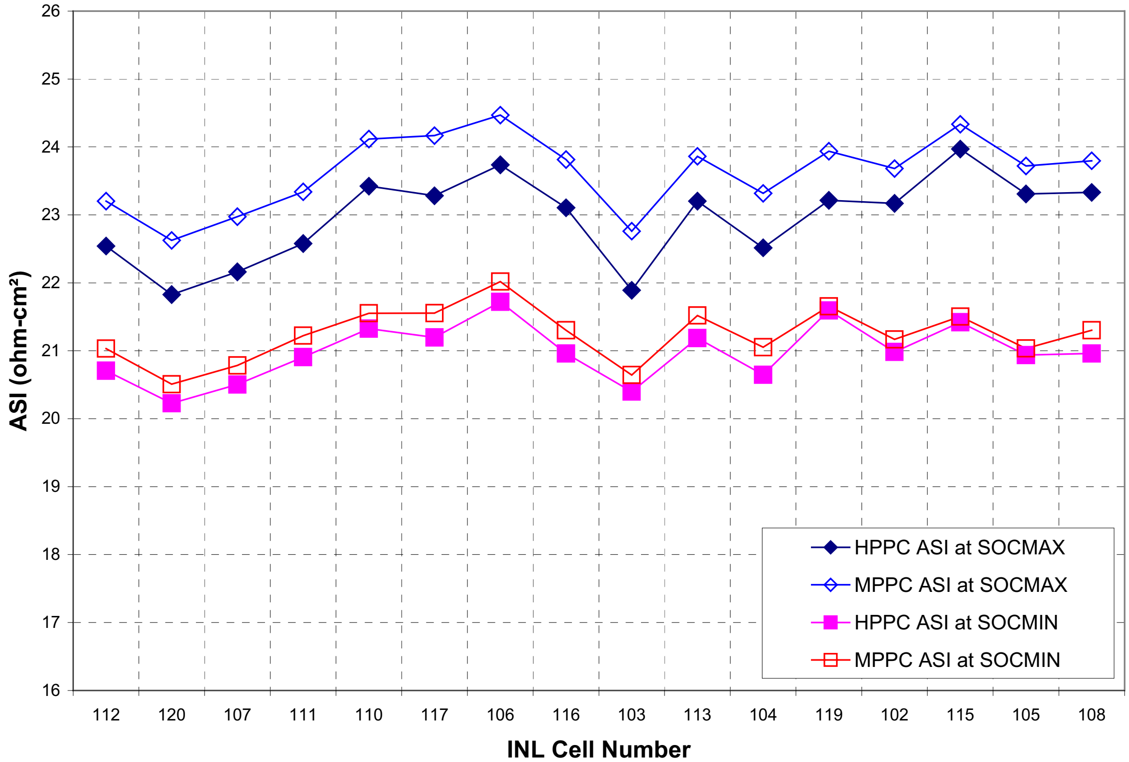

Figure 19. Difference between HPPC and MPPC ASIs at SOC_{MAX} and SOC_{MIN} for the cycle-life cells

4.4.3 ASI Noise Characterization

For accurate life predictions, the TLVT methodology requires cells with a high degree of reproducibility with minimal cell-to-cell variations. Unfortunately, using the noise characterization technique defined in the manual (Reference 4), the GDR cells showed a very high manufacturing variability. The manufacturing variability is split between differences in cell-to-cell electrode areas (S_{AREA}), and differences in cell-to-cell fixed ohmic resistance (S_{OHMIC}). The default values for these variations in the manual are 0.5 and 1.0%, respectively. The measurement error (S_{MEAS}) also needs to be minimal so that cell testing does not negatively impact life projections. The GDR variability is shown in Table 6. Although the GDR manufacturing variabilities are high, the measurement error is very low due to the INL calibration processes (References 9 and 10).

Table 6. ASI noise characterization.

Standard Deviation	TLVT Default Values	Temperature-Compensated ASI
S_{MEAS}	1.0%	0.51%
S_{AREA}	0.5%	2.27%
S_{OHMIC}	1.0%	7.58%

5. CONCLUSIONS

Testing and analysis of the ATD Gen 2 GDR cells has been completed. The purpose of these cells was primarily to assess the newly developed TLVT procedures and profiles. Cells were subjected to various calendar- and cycle-life testing in both core and supplemental matrices. Reference performance testing primarily consisted of the minimum pulse power characterization test instead of the standard FreedomCAR $C_1/1$ and L-HPPC test. Unfortunately, the GDR cell electrodes had remained in an unsealed glove box for a little less than a year prior to assembly, and were made in various lots which yielded different beginning-of-life capacities. As a result, the cells had a large manufacturing variability with erratic behavior and analysis results were inconclusive. However, some general observations can still be made based on these test results.

Like the ATD Gen 2 Baseline and Variant C cells, the GDR cells showed the most performance degradation between characterization and four weeks, and this may be due to incomplete cell formation. The most obvious stress factor for the GDR cells was SOC, with some minor impact with test temperature. Power ratio and throughput had essentially no impact on performance degradation. Unlike the Gen 2 Baseline and Variant C cells, the GDR calendar-life cells aged more rapidly than the cycle-life cells. The GDR cell calendar-life consisted of resting at OCV for four weeks whereas the Baseline and Variant C cells were voltage clamped with a pulse per day. This difference may be a significant source of the difference, but other sources may include the mixture of lot numbers and high manufacturing variability. Likewise, the supplemental path dependence and RPT studies were inconclusive due to rapid degradation and inconsistent behavior.

Although the MPPC test was designed to be a less obtrusive test, the discontinuity in the cycle-life pulse resistance after the reference performance test was sill present. In fact, the discontinuity for the cells aged at SOC_{MAX} was almost as much as was seen with the Gen 2 Baseline cell testing with a full $C_1/1$ and L-HPPC test. Although this could be a function of the MPPC test, it is also possible that the GDR cell variability contributed to this phenomenon as well. Furthermore, the null hypothesis that the ASIs determined from the MPPC and the L-HPPC yield statistically similar results was rejected based on the t-statistic methodology provided in the TLVT Manual. Similar observations were also made with other, commercially available cells. This indicates that the MPPC test requires more scrutiny before it is implemented as the default RPT for life prediction.

6. REFERENCES

1. Tien Q. Duong et al., "Energy Storage Research & Development: FY 2004 Annual Progress Report," U.S. DOE FCVT, January 2005.

2. J. P. Christophersen, I. Bloom, E. V. Thomas, K. L. Gering, G. L. Henriksen, V. S. Battaglia, and D. Howell, "Advanced Technology Development For Lithium-Ion Batteries: Gen 2 Performance Evaluation Final Report," INL/EXT-05-00913, July 2006.

3. Gary Henriksen, "ATD Program Background and Introduction," ATD Merit Review presentation, Argonne, IL, June 2004.

4. *Advanced Technology Development Program For Lithium-Ion Batteries: Battery Technology Life Verification Test Manual*, INEEL/EXT-04-01986, February 2005.

5. *FreedomCAR Test Plan for Advanced Technology Development Gen 2 GDR Cells*, EHV-TP-152, Revision 3, July 2004.

6. *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles*, DOE/ID-11069, October 2003.

7. Efron, B., and Tibshirani, R. J., *An Introduction to the Bootstrap*, New York: Chapman and Hall, 1993.

8. J. P. Christophersen, C. D. Ho, C. G. Motloch, D. Howell, and H. Hess, "Effects of Reference Performance Testing during Aging Using Commercial Lithium-Ion Cells," *J. Electrochem Soc.*, 153 A1406-A1416 (2006).

9. *Uncertainty Study of INEEL EST Laboratory Battery Testing Systems Volume 1: Background and Derivation of Uncertainty Relationships*, INEEL/EXT-01-00505. December 2001.

10. *Uncertainty Study of INEEL EST Laboratory Battery Testing Systems Volume 2: Application of Results to INEEL Testers*, INEEL/EXT-01-00505. March 2003.

Appendix A:

Gen 2 GDR Receipt Inspection

A. GEN 2 GDR RECEIPT INSPECTION

The measured cell weights, OCVs, and impedance measurements at 1 kHz measured during the INL receipt inspection are shown in Tables A.1 (core-life cell matrix) and A.2 (supplemental-life cell matrix).

Table A.1. Gen 2 GDR cell receipt inspection for core-life cells.

	Cell Group	INL Cell #	Quallion Lot Number	Weight (g)	OCV (V)	AC Impedance	
						Real	Imaginary
Cycle-Life Cells	40540	112	F03E916 - 43	38.419	3.68	11.421	-0.853
	40540	120	F03E916 - 55	38.215	3.70	11.582	-0.938
	40940	107	F03E916 - 32	38.407	3.69	10.848	-0.321
	40940	111	F03E916 - 42	38.516	3.69	11.333	-0.821
	80540	110	F03E916 - 37	38.760	3.70	11.378	-1.397
	80540	117	F03E916 - 50	38.288	3.70	11.173	-0.861
	80940	106	F03E916 - 35	38.675	3.70	11.404	-1.111
	80940	116	F03E916 - 49	38.222	3.70	11.088	-0.799
	40550	103	F03E916 - 11	38.705	3.67	11.348	-0.532
	40550	113	F03E916 - 46	38.545	3.70	10.813	-0.978
	40950	104	F03E916 - 12	39.377	3.68	10.917	-0.872
	40950	119	F03E916 - 54	38.435	3.69	11.422	-0.682
	80550	102	F03E916 - 9	38.833	3.70	10.860	-0.696
	80550	115	F03E916 - 48	38.195	3.70	10.854	-0.932
	80950	105	F03E916 - 21	38.594	3.69	11.197	-0.801
	80950	108	F03E916 - 33	38.296	3.69	11.003	0.150
Calendar-Life Cells	80C40	130	F04D151 - 03	38.264	3.64	9.179	1.837
	80C40	135	F04D151 - 38	38.529	3.66	10.031	1.678
	80C50	131	F04D151 - 06	38.321	3.66	9.702	1.746
	80C50	132	F04D151 - 11	38.676	3.66	9.545	1.733
	80C60	133	F04D151 - 14	38.634	3.66	10.239	1.690
	80C60	134	F04D151 - 15	38.493	3.66	9.992	1.834
	Average			**38.52**	**3.68**	**10.788**	**-0.088**
	Standard Deviation			**0.27**	**0.02**	**0.693**	**1.190**

Table A.2. Gen 2 GDR cell receipt inspection for supplemental-life cells.

	Cell Group	INL Cell #	Quallion Lot Number	Weight (g)	OCV (V)	AC Impedance	
						Real	Imaginary
Path Dependence Study	40C540	101	F03E916 - 8	38.571	3.68	10.883	-0.733
	40C540	121	F04A914 - 3	38.794	3.70	11.280	-0.765
	80C950	109	F03E916 - 24	38.340	3.69	11.043	-0.674
	80C950	118	F03E916 - 52	38.541	3.69	11.491	-0.906
	405C40	114	F03E916 - 47	39.052	3.68	11.290	-0.854
	405C40	125	F04A914 - 8	38.723	3.71	11.160	-0.599
	809C50	136	F04D151 - 18	38.392	3.67	10.316	1.784
	809C50	137	F04D151 - 29	38.450	3.66	10.375	1.776
RPT Study	40540	127	F04A908 - 8	38.708	3.70	11.523	-0.939
	40540	128	F04A908 - 9	38.532	3.70	11.994	-0.964
	80950	123	F04A914 - 6	38.725	3.70	11.507	-0.948
	80950	138	F04D151 - 40	38.485	3.66	9.237	0.851
		Average		**38.60**	**3.69**	**11.105**	**-0.408**
		Standard Deviation		**0.18**	**0.02**	**0.674**	**0.958**

Appendix B:

Individual Cell Results

B. INDIVIDUAL CELL RESULTS

This appendix details the discharge capacity and ASI at SOC_{MAX} and SOC_{MIN} (both calculated and temperature compensated) for each ATD Gen 2 GDR cell. 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 Section B.1 for the structure of the ATD label). The remaining columns provide the cell-specific data at each four-week increment starting from BOL (i.e., characterization) through 36 weeks. The last column shows the percent-fade in cell degradation, normalized to the characterization RPT. The cell label and percent-fade (or growth) from beginning of life either has a blue or green background. A green background indicates that the cell was removed from test earlier in life, and 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.

B.1 Cell Labeling Structure

An ATD labeling structure was established to provide the diagnostic laboratories with succinct information regarding the end-of-test status of the test cells. It is in the form of G2[X].AABCC.DEEE.TT.CF.AG.Z.S, where:

G2[X]	=	Gen 2 cell, and [X] = G or V (V is for all cells with VEC electrolyte)
AA	=	Test Matrix State of Charge
B	=	Test Matrix profile, e.g., S, N, and C, where S = in storage, N = no aging, and C = calendar life cell. If cycle-life testing, use "5" for the 95th Percentile profile, and "9" for the 99th Percentile Profile.
CC	=	Test Matrix Temperature, (°C)
D	=	Original DOE Laboratory, A = ANL; B = BNL; I = INEEL; L = LBNL
EEE	=	Sequential cell number assigned by National Laboratory (INL = 101 through 1XX).
TT	=	Time at life testing (weeks), Characterization testing is labeled as "CC".
CF	=	Capacity Fade relative to RPT0. For the MPPC, capacity fade is based on the $C_1/1$ discharge between SOC_{MAX} and SOC_{MIN}. For the L-HPPC test, it is based on the full $C_1/1$ discharge from 100% SOC. Characterization data are labeled as "00".
AG	=	ASI Growth at SOC_{MAX} relative to RPT0. Characterization data are labeled "00".
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; L = shipped to LBNL. [S] = additional status flags as appropriate to track the history of the cell.

The label begins with either G2G for the GDR-only cells, or G2V for the GDR+VEC cells. The test matrix SOC, profile, and temperature (i.e., AABCC) identify the type of test, where cycle-life (5 or 9), or calendar-life (C) testing is performed at a designated SOC and temperature. Next, the original DOE laboratory is identified, along with the laboratory-specific cell number. The testing laboratories established a sequential numbering scheme such that all INL cells are numbered between 100 and 200. The time at life testing (i.e., TT) shows the number of weeks the cell has been aging in four-week increments. This is followed by the total capacity fade (CF) and ASI growth at SOC_{MAX} (AG) at that RPT. 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, or B).

For example, G2G.40550.I113.36.07.10.G.F is INL Cell 113. It was cycle-life tested using the 95th Pecentile profile at 40% SOC (SOC_{MIN}) and 50°C for 36 weeks before being taken off test with a discharge capacity fade (between SOC_{MAX} and SOC_{MIN}) of 7%, and an ASI growth of 10% at SOC_{MAX}. The cell was in good condition when it was removed from test, and is currently in storage at INL.

B.2 Core-Life Test Data

2.2.1 Cycle-Life Data

Table B.1. Cycle-life $C_1/1$ discharge capacity between SOC_{MAX} and SOC_{MIN}.

Core Matrix Cycle-Life Cells			$C_1/1$ Discharge Capacity Between SOC_{MAX} and SOC_{MIN}										
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)	fade (%)
			0.353	0.335	0.328	0.331	0.327	0.323	0.326	0.325	0.324	0.323	**8.54%**
			0.004	0.004	0.019	0.005	0.006	0.021	0.006	0.007	0.007	0.007	**1.46%**
40540	112	G2G.40540.I112.36.07.11.G.F	0.354	0.337	0.335	0.333	0.324	0.332	0.330	0.329	0.329	0.328	7.39%
40540	120	G2G.40540.I120.36.06.06.G.F	0.351	0.340	0.340	0.336	0.329	0.335	0.332	0.331	0.331	0.329	6.21%
40940	107	G2G.40940.I107.36.07.08.G.F	0.357	0.341	0.338	0.340	0.337	0.336	0.335	0.335	0.333	0.333	6.80%
40940	111	G2G.40940.I111.36.07.07.G.F	0.360	0.342	0.339	0.341	0.335	0.338	0.335	0.333	0.334	0.333	7.43%
80540	110	G2G.80540.I110.36.09.18.G.F	0.353	0.333	0.331	0.329	0.324	0.325	0.325	0.324	0.323	0.322	8.61%
80540	117	G2G.80540.I117.36.08.15.G.F	0.355	0.336	0.334	0.331	0.330	0.330	0.329	0.328	0.327	0.326	8.13%
80940	106	G2G.80940.I106.36.09.17.G.F	0.356	0.334	0.332	0.331	0.327	0.329	0.328	0.326	0.325	0.324	8.92%
80940	116	G2G.80940.I116.28.07.13.G.F	0.351	0.336	0.260	0.331	0.315	0.249	0.328				6.71%
40550	103	G2G.40550.I103.36.08.11.G.F	0.354	0.339	0.337	0.335	0.332	0.331	0.327	0.327	0.326	0.325	8.17%
40550	113	G2G.40550.I113.36.07.10.G.F	0.346	0.333	0.330	0.328	0.327	0.325	0.323	0.323	0.322	0.321	7.29%
40950	104	G2G.40950.I104.36.09.11.G.F	0.355	0.338	0.335	0.334	0.332	0.330	0.327	0.327	0.326	0.324	8.69%
40950	119	G2G.40950.I119.36.08.11.G.F	0.347	0.330	0.328	0.326	0.324	0.323	0.321	0.321	0.320	0.319	8.19%
80550	102	G2G.80550.I102.36.10.21.G.F	0.353	0.333	0.330	0.328	0.326	0.324	0.321	0.320	0.318	0.317	10.39%
80550	115	G2G.80550.I115.36.10.15.G.F	0.345	0.327	0.326	0.323	0.321	0.319	0.316	0.313	0.312	0.310	10.34%
80950	105	G2G.80950.I105.36.10.21.G.F	0.356	0.334	0.331	0.330	0.328	0.325	0.322	0.321	0.320	0.318	10.49%
80950	108	G2G.80950.I108.36.11.21.G.F	0.346	0.328	0.325	0.321	0.319	0.317	0.313	0.311	0.309	0.308	11.00%

Table B.2. Cycle-life discharge ASI at SOC_{MAX} and 30°C.

Core Matrix Cycle-Life Cells			30°C Discharge ASI at SOC_{MAX}										
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ω-cm²)	4 wk (Ω-cm²)	8 wk (Ω-cm²)	12 wk (Ω-cm²)	16 wk (Ω-cm²)	20 wk (Ω-cm²)	24 wk (Ω-cm²)	28 wk (Ω-cm²)	32 wk (Ω-cm²)	36 wk (Ω-cm²)	fade (%)
			23.63	24.16	24.63	25.37	25.77	25.84	26.42	26.44	26.93	26.84	**13.55%**
			0.55	1.54	1.54	1.66	1.76	1.80	1.75	1.77	1.86	1.70	**5.26%**
40540	112	G2G.40540.I112.36.07.11.G.F	23.20	23.23	23.94	24.62	24.77	24.66	25.09	25.37	25.68	25.73	10.90%
40540	120	G2G.40540.I120.36.06.06.G.F	22.62	21.53	21.91	22.27	22.66	22.95	23.20	23.20	24.22	24.03	6.21%
40940	107	G2G.40940.I107.36.07.08.G.F	22.97	22.35	22.95	23.37	23.61	23.59	24.13	24.38	24.74	24.77	7.81%
40940	111	G2G.40940.I111.36.07.07.G.F	23.34	22.40	23.07	23.59	23.67	23.53	24.25	24.71	24.71	24.93	6.83%
80540	110	G2G.80540.I110.36.09.18.G.F	24.12	25.23	26.04	26.80	27.33	27.52	27.62	27.60	28.81	28.52	18.24%
80540	117	G2G.80540.I117.36.08.15.G.F	24.17	24.88	25.63	26.44	26.94	27.02	27.38	27.17	28.42	27.87	15.32%
80940	106	G2G.80940.I106.36.09.17.G.F	24.47	26.31	26.44	27.11	27.82	27.91	28.21	28.12	29.03	28.65	17.07%
80940	116	G2G.80940.I116.28.07.13.G.F	23.82	25.10	23.59	25.65	26.61	25.13	27.03				13.49%
40550	103	G2G.40550.I103.36.08.11.G.F	22.76	22.12	22.73	23.37	23.75	24.06	24.88	24.87	25.15	25.21	10.76%
40550	113	G2G.40550.I113.36.07.10.G.F	23.86	23.64	24.40	24.88	25.21	25.53	25.96	25.86	26.01	26.15	9.58%
40950	104	G2G.40950.I104.36.09.11.G.F	23.32	22.87	23.50	24.05	24.41	24.63	25.52	25.39	25.68	25.97	11.39%
40950	119	G2G.40950.I119.36.08.11.G.F	23.94	24.55	25.05	25.41	25.65	25.79	26.25	26.21	26.37	26.50	10.69%
80550	102	G2G.80550.I102.36.10.21.G.F	23.68	25.57	26.30	27.21	27.71	27.98	28.59	28.70	28.92	28.77	21.49%
80550	115	G2G.80550.I115.36.10.15.G.F	24.33	25.67	26.39	26.88	27.14	27.36	27.87	27.93	28.23	27.99	15.04%
80950	105	G2G.80950.I105.36.10.21.G.F	23.72	25.42	25.95	27.08	27.57	27.99	28.48	28.62	29.07	28.76	21.23%
80950	108	G2G.80950.I108.36.11.21.G.F	23.80	25.69	26.15	27.18	27.41	27.72	28.25	28.49	28.87	28.71	20.63%

Table B.3. Cycle-life temperature-compensated discharge ASI at SOC_{MAX} and 30°C.

Core Matrix Cycle-Life Cells			Temperature Compensated 30°C Discharge ASI at SOC_{MAX}										
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ω-cm²)	4 wk (Ω-cm²)	8 wk (Ω-cm²)	12 wk (Ω-cm²)	16 wk (Ω-cm²)	20 wk (Ω-cm²)	24 wk (Ω-cm²)	28 wk (Ω-cm²)	32 wk (Ω-cm²)	36 wk (Ω-cm²)	fade (%)
			24.10	24.39	24.83	25.63	25.95	26.01	26.66	26.72	26.96	27.03	**12.51%**
			0.67	1.65	1.57	1.73	1.79	1.81	1.79	1.78	1.95	1.73	**5.26%**
40540	112	G2G.40540.I112.36.07.11.G.F	24.05	23.82	24.31	25.09	25.03	25.02	25.51	25.80	25.69	26.21	9.01%
40540	120	G2G.40540.I120.36.06.06.G.F	22.90	21.36	21.88	22.23	22.68	22.98	23.28	23.48	23.90	24.03	4.95%
40940	107	G2G.40940.I107.36.07.08.G.F	23.24	22.42	23.04	23.27	23.54	23.67	24.13	24.54	24.29	24.72	6.36%
40940	111	G2G.40940.I111.36.07.07.G.F	23.72	22.31	23.19	23.87	23.96	23.73	24.52	25.15	24.60	25.21	6.27%
80540	110	G2G.80540.I110.36.09.18.G.F	24.76	25.54	26.24	27.04	27.55	27.72	27.98	28.01	28.74	28.83	16.43%
80540	117	G2G.80540.I117.36.08.15.G.F	24.25	24.57	25.58	26.47	26.96	26.99	27.32	27.31	27.91	27.87	14.90%
80940	106	G2G.80940.I106.36.09.17.G.F	24.63	26.24	26.34	27.09	27.77	27.90	28.20	28.30	28.49	28.58	16.07%
80940	116	G2G.80940.I116.28.07.13.G.F	25.55	26.18	23.89	26.17	26.99	25.37	27.46				7.48%
40550	103	G2G.40550.I103.36.08.11.G.F	23.15	22.39	23.03	23.70	23.99	24.34	25.18	25.13	25.45	25.45	9.94%
40550	113	G2G.40550.I113.36.07.10.G.F	24.28	23.89	24.67	25.16	25.41	25.68	26.20	26.06	26.28	26.33	8.46%
40950	104	G2G.40950.I104.36.09.11.G.F	23.66	23.13	23.80	24.37	24.64	24.84	25.80	25.64	25.94	26.21	10.77%
40950	119	G2G.40950.I119.36.08.11.G.F	24.21	24.72	25.24	25.65	25.75	25.88	26.40	26.31	26.46	26.62	9.94%
80550	102	G2G.80550.I102.36.10.21.G.F	24.04	25.81	26.57	27.55	27.95	28.16	28.86	28.99	29.13	28.97	20.50%
80550	115	G2G.80550.I115.36.10.15.G.F	24.82	26.07	26.78	27.34	27.47	27.70	28.31	28.37	28.81	28.38	14.35%
80950	105	G2G.80950.I105.36.10.21.G.F	24.17	25.75	26.31	27.49	27.89	28.30	28.86	29.00	29.42	29.02	20.07%
80950	108	G2G.80950.I108.36.11.21.G.F	24.21	26.00	26.48	27.56	27.66	27.92	28.60	28.76	29.22	28.97	19.65%

Table B.4. Cycle-life discharge ASI at SOC_{MIN} and 30°C.

Core Matrix Cycle-Life Cells			30°C Discharge ASI at SOC_{MIN}										
Test Group AABCC (SOC/B/°C)	Cell #	ATD Label	Char (Ω-cm²)	4 wk (Ω-cm²)	8 wk (Ω-cm²)	12 wk (Ω-cm²)	16 wk (Ω-cm²)	20 wk (Ω-cm²)	24 wk (Ω-cm²)	28 wk (Ω-cm²)	32 wk (Ω-cm²)	36 wk (Ω-cm²)	fade (%)
			21.24	23.52	24.28	24.60	25.18	25.39	25.49	25.82	26.31	26.42	**24.40%**
			0.40	0.48	0.55	0.49	0.52	0.68	0.59	0.73	0.66	0.79	**2.95%**
40540	112	G2G.40540.I112.36.07.11.G.F	21.03	23.34	23.89	24.27	24.79	24.77	24.83	25.07	25.79	25.60	21.71%
40540	120	G2G.40540.I120.36.06.06.G.F	20.51	22.54	23.23	23.65	24.22	24.14	24.41	24.52	25.23	24.99	21.86%
40940	107	G2G.40940.I107.36.07.08.G.F	20.78	22.88	23.50	23.94	24.42	24.35	24.60	24.66	25.27	25.18	21.16%
40940	111	G2G.40940.I111.36.07.07.G.F	21.22	23.20	23.89	24.22	24.83	24.74	24.99	25.08	25.65	25.55	20.37%
80540	110	G2G.80540.I110.36.09.18.G.F	21.55	23.81	24.27	24.65	25.26	25.43	25.65	26.04	26.67	26.44	22.67%
80540	117	G2G.80540.I117.36.08.15.G.F	21.55	23.73	24.20	24.63	25.16	25.15	25.43	25.70	26.48	26.17	21.41%
80940	106	G2G.80940.I106.36.09.17.G.F	22.02	24.27	24.72	25.05	25.98	26.17	26.42	26.72	27.41	27.16	23.36%
80940	116	G2G.80940.I116.28.07.13.G.F	21.30	23.50	25.13	24.38	25.34	26.47	25.46				19.51%
40550	103	G2G.40550.I103.36.08.11.G.F	20.64	23.12	23.86	24.30	24.66	25.05	25.10	25.53	25.84	26.23	27.06%
40550	113	G2G.40550.I113.36.07.10.G.F	21.52	24.08	24.90	25.51	25.96	26.19	26.29	26.73	26.97	27.28	26.75%
40950	104	G2G.40950.I104.36.09.11.G.F	21.05	23.49	24.24	24.55	24.99	25.38	25.46	25.93	26.31	26.61	26.39%
40950	119	G2G.40950.I119.36.08.11.G.F	21.66	24.37	25.18	25.47	25.94	26.18	26.15	26.61	27.00	27.20	25.62%
80550	102	G2G.80550.I102.36.10.21.G.F	21.17	23.39	24.16	24.55	25.23	25.31	25.62	25.95	26.42	26.77	26.48%
80550	115	G2G.80550.I115.36.10.15.G.F	21.50	23.75	24.66	24.85	25.20	25.38	25.51	25.82	26.06	26.58	23.60%
80950	105	G2G.80950.I105.36.10.21.G.F	21.04	23.51	24.25	24.85	25.59	25.94	26.15	26.69	26.99	27.48	30.64%
80950	108	G2G.80950.I108.36.11.21.G.F	21.30	23.37	24.36	24.75	25.29	25.56	25.76	26.26	26.61	27.03	26.88%

Table B.5. Cycle-life temperature-compensated discharge ASI at SOC_{MIN} and 30°C.

Core Matrix			Temperature Compensated 30°C Discharge ASI at SOC_{MIN}										
Cycle-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			21.54	23.76	24.49	24.87	25.41	25.61	25.79	26.10	26.36	26.68	**24.21%**
			0.45	0.68	0.70	0.56	0.53	0.74	0.62	0.71	0.78	0.83	**3.01%**
40540	112	G2G.40540.I112.36.07.11.G.F	21.58	24.13	24.18	24.84	25.22	25.15	25.51	25.79	25.78	26.07	20.78%
40540	120	G2G.40540.I120.36.06.06.G.F	20.58	22.23	23.26	23.65	24.29	24.20	24.53	24.77	24.95	25.06	21.75%
40940	107	G2G.40940.I107.36.07.08.G.F	20.94	22.89	23.47	23.89	24.50	24.47	24.61	24.74	24.89	25.27	20.67%
40940	111	G2G.40940.I111.36.07.07.G.F	21.44	23.02	24.10	24.50	25.17	25.02	25.28	25.46	25.55	25.76	20.12%
80540	110	G2G.80540.I110.36.09.18.G.F	21.89	24.24	24.54	24.93	25.67	25.68	26.14	26.60	26.62	26.97	23.20%
80540	117	G2G.80540.I117.36.08.15.G.F	21.60	23.24	24.14	24.57	25.16	25.12	25.49	25.84	26.10	26.10	20.80%
80940	106	G2G.80940.I106.36.09.17.G.F	22.09	24.17	24.62	24.94	25.87	26.19	26.41	26.80	26.98	27.13	22.82%
80940	116	G2G.80940.I116.28.07.13.G.F	22.33	24.82	26.15	25.03	25.69	27.14	26.19				17.28%
40550	103	G2G.40550.I103.36.08.11.G.F	20.92	23.46	24.10	24.67	24.95	25.35	25.43	25.82	26.21	26.66	27.44%
40550	113	G2G.40550.I113.36.07.10.G.F	21.78	24.36	25.08	25.82	26.17	26.36	26.55	26.93	27.22	27.62	26.79%
40950	104	G2G.40950.I104.36.09.11.G.F	21.34	23.79	24.49	24.89	25.26	25.64	25.79	26.22	26.55	27.00	26.56%
40950	119	G2G.40950.I119.36.08.11.G.F	21.87	24.58	25.42	25.70	26.10	26.32	26.34	26.73	27.23	27.47	25.63%
80550	102	G2G.80550.I102.36.10.21.G.F	21.41	23.63	24.32	24.84	25.44	25.49	25.89	26.15	26.67	27.06	26.39%
80550	115	G2G.80550.I115.36.10.15.G.F	21.86	24.15	24.94	25.34	25.56	25.73	25.93	26.18	26.49	27.08	23.85%
80950	105	G2G.80950.I105.36.10.21.G.F	21.31	23.85	24.50	25.22	25.89	26.18	26.50	26.94	27.28	27.63	29.63%
80950	108	G2G.80950.I108.36.11.21.G.F	21.60	23.66	24.59	25.12	25.53	25.76	26.07	26.51	26.93	27.38	26.76%

2.2.2 Calendar-Life Data

Table B.6. Calendar-life $C_1/1$ discharge capacity between SOC_{MAX} and SOC_{MIN}.

Core Matrix			$C_1/1$ Discharge Capacity Between SOC_{MAX} and SOC_{MIN}										
Calendar-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.372	0.344	0.339	0.336	0.319	0.334	0.332	0.330			**11.19%**
			0.003	0.006	0.008	0.006	0.024	0.004	0.004	0.005			**1.70%**
80C40	130	G2G.80C40.I130.28.10.45.L.F	0.367	0.345	0.342	0.338	0.336	0.335	0.333	0.332			9.64%
80C40	135	G2G.80C40.I135.28.09.40.G.F	0.369	0.349	0.346	0.343	0.342	0.341	0.339	0.338			8.57%
80C50	131	G2G.80C50.I131.28.12.60.G.F	0.375	0.348	0.342	0.338	0.289	0.332	0.329	0.328			12.41%
80C50	132	G2G.80C50.I132.28.12.59.G.F	0.376	0.351	0.345	0.340	0.287	0.335	0.334	0.333			11.54%
80C60	133	G2G.80C60.I133.28.12.95.G.A	0.373	0.338	0.331	0.331	0.332	0.331	0.329	0.327			12.32%
80C60	134	G2G.80C60.I134.28.13.97.G.L	0.373	0.335	0.326	0.327	0.328	0.329	0.327	0.326			12.67%

Table B.7. Calendar-life discharge ASI at SOC_{MAX} and 30°C.

Core Matrix			30°C Discharge ASI at SOC_{MAX}										
Calendar-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			28.13	35.16	37.71	41.24	42.77	44.37	46.10	46.56			**66.12%**
			1.82	3.14	4.00	4.47	4.74	5.04	5.84	6.09			**24.60%**
80C40	130	G2G.80C40.I130.28.10.45.L.F	31.70	36.37	38.27	41.54	42.77	43.96	44.73	45.88			44.76%
80C40	135	G2G.80C40.I135.28.09.40.G.F	28.18	31.39	32.82	35.44	36.56	37.61	38.49	39.56			40.38%
80C50	131	G2G.80C50.I131.28.12.60.G.F	26.86	32.80	34.94	38.49	39.91	41.78	43.38	42.89			59.68%
80C50	132	G2G.80C50.I132.28.12.59.G.F	27.05	33.18	35.52	39.09	40.74	42.33	43.79	43.10			59.35%
80C60	133	G2G.80C60.I133.28.12.95.G.A	27.88	39.04	42.47	46.51	48.52	50.61	53.39	54.40			95.15%
80C60	134	G2G.80C60.I134.28.13.97.G.L	27.13	38.18	42.25	46.37	48.10	49.96	52.81	53.55			97.39%

Table B.8. Calendar-life temperature-compensated discharge ASI at SOC_{MAX} and 30°C.

Core Matrix			Temperature Compensated 30°C Discharge ASI at SOC_{MAX}										
Calendar-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			28.70	35.68	38.16	41.83	43.41	44.92	46.80	47.27			**65.21%**
			1.24	2.97	4.04	4.69	4.77	4.91	5.79	6.02			**24.47%**
80C40	130	G2G.80C40.I130.28.10.45.L.F	30.95	35.55	37.59	40.45	41.82	42.71	43.81	44.92			45.15%
80C40	135	G2G.80C40.I135.28.09.40.G.F	29.27	32.16	33.25	36.12	37.39	38.41	39.30	40.39			38.02%
80C50	131	G2G.80C50.I131.28.12.60.G.F	27.66	33.53	35.65	39.25	40.98	43.10	44.78	44.22			59.87%
80C50	132	G2G.80C50.I132.28.12.59.G.F	28.16	34.38	36.36	40.05	41.89	43.74	45.43	44.57			58.28%
80C60	133	G2G.80C60.I133.28.12.95.G.A	28.41	39.48	42.98	47.46	49.26	50.96	53.82	55.03			93.69%
80C60	134	G2G.80C60.I134.28.13.97.G.L	27.75	38.97	43.11	47.65	49.13	50.60	53.66	54.47			96.24%

Table B.9. Calendar-life discharge ASI at SOC_{MIN} and 30°C.

Core Matrix			30°C Discharge ASI at SOC_{MIN}										
Calendar-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			24.29	31.67	33.86	34.89	36.05	36.93	37.63	38.48			**58.78%**
			1.13	2.26	2.81	2.99	3.35	3.74	3.91	4.15			**19.18%**
80C40	130	G2G.80C40.I130.28.10.45.L.F	26.42	32.05	33.81	34.72	35.62	36.45	36.84	37.25			40.99%
80C40	135	G2G.80C40.I135.28.09.40.G.F	24.44	29.06	30.49	31.34	32.11	32.93	33.43	33.87			38.59%
80C50	131	G2G.80C50.I131.28.12.60.G.F	23.31	29.91	31.92	32.85	33.78	34.28	35.05	36.09			54.82%
80C50	132	G2G.80C50.I132.28.12.59.G.F	23.61	30.46	32.58	33.51	34.61	34.88	35.54	36.43			54.26%
80C60	133	G2G.80C60.I133.28.12.95.G.A	24.30	34.66	37.63	38.95	40.66	41.95	42.94	44.17			81.80%
80C60	134	G2G.80C60.I134.28.13.97.G.L	23.64	33.89	36.75	37.99	39.50	41.10	42.01	43.08			82.21%

Table B.10. Calendar-life temperature-compensated discharge ASI at SOC_{MIN} and 30°C.

Core Matrix			Temperature Compensated 30°C Discharge ASI at SOC_{MIN}										
Calendar-Life Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			24.66	32.26	34.21	35.48	36.52	37.35	38.28	39.18			**59.18%**
			0.77	2.13	2.86	3.23	3.35	3.63	3.86	4.17			**19.16%**
80C40	130	G2G.80C40.I130.28.10.45.L.F	26.02	31.22	32.76	33.63	34.63	35.00	35.79	36.20			39.13%
80C40	135	G2G.80C40.I135.28.09.40.G.F	24.96	29.97	31.11	32.07	32.93	33.79	34.40	34.76			39.24%
80C50	131	G2G.80C50.I131.28.12.60.G.F	23.84	30.80	32.60	33.59	34.62	35.33	36.27	37.45			57.09%
80C50	132	G2G.80C50.I132.28.12.59.G.F	24.33	31.77	33.22	34.59	35.56	36.10	36.94	37.98			56.07%
80C60	133	G2G.80C60.I133.28.12.95.G.A	24.67	35.16	38.02	39.88	41.11	42.25	43.51	44.74			81.32%
80C60	134	G2G.80C60.I134.28.13.97.G.L	24.14	34.62	37.54	39.13	40.28	41.61	42.77	43.99			82.24%

B.3 Supplemental-Life Test Data

2.3.1 Path Dependence Data

Table B.11. Path dependence $C_1/1$ discharge capacity between SOC_{MAX} and SOC_{MIN}.

Supplemental Matrix			$C_1/1$ Discharge Capacity Between SOC_{MAX} and SOC_{MIN}										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.359	0.338	0.336	0.333	0.332	0.333	0.331	0.330			**8.16%**
			0.006	0.010	0.011	0.011	0.010	0.009	0.009	0.010			**1.69%**
40C540	101	G2G.40C540.I101.28.09.12.G.F	0.357	0.331	0.329	0.327	0.326	0.327	0.326	0.325			8.94%
40C540	121	G2G.40C540.I121.28.06.23.G.F	0.365	0.350	0.348	0.345	0.344	0.342	0.342	0.341			6.42%
80C950	109	G2G.80C950.I109.28.09.19.G.L	0.354	0.328	0.325	0.323	0.324	0.328	0.326	0.322			8.92%
80C950	118	G2G.80C950.I118.28.09.17.G.A	0.349	0.326	0.321	0.317	0.317	0.324	0.320	0.317			9.19%
405C40	114	G2G.405C40.I114.28.08.10.G.F	0.358	0.337	0.336	0.335	0.334	0.333	0.332	0.330			7.82%
405C40	125	G2G.405C40.I125.28.05.04.G.F	0.365	0.353	0.351	0.350	0.349	0.349	0.348	0.347			5.03%
809C50	136	G2G.809C50.I136.28.10.96.G.L	0.366	0.344	0.340	0.334	0.332	0.331	0.329	0.328			10.26%
809C50	137	G2G.809C50.I137.28.09.91.G.A	0.360	0.337	0.334	0.330	0.329	0.329	0.328	0.329			8.73%

Table B.12. Path dependence discharge ASI at SOC_{MAX} and 30°C.

Supplemental Matrix			30°C Discharge ASI at SOC_{MAX}										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			25.62	29.35	30.84	33.07	33.90	33.59	33.88	34.31			**34.01%**
			1.56	4.57	5.79	7.49	8.15	8.68	9.10	9.48			**37.00%**
40C540	101	G2G.40C540.I101.28.09.12.G.F	26.09	28.35	29.16	30.77	31.37	29.29	29.17	29.31			12.33%
40C540	121	G2G.40C540.I121.28.06.23.G.F	28.62	32.27	33.64	36.38	37.68	35.51	35.33	35.28			23.27%
80C950	109	G2G.80C950.I109.28.09.19.G.L	24.46	27.30	28.09	29.31	29.45	28.82	28.89	29.08			18.91%
80C950	118	G2G.80C950.I118.28.09.17.G.A	24.39	25.82	27.07	28.73	29.20	28.29	28.21	28.48			16.79%
405C40	114	G2G.405C40.I114.28.08.10.G.F	23.80	24.14	24.41	24.94	25.18	25.60	25.89	26.22			10.14%
405C40	125	G2G.405C40.I125.28.05.04.G.F	26.82	25.65	26.07	26.60	26.92	27.49	27.66	27.96			4.24%
809C50	136	G2G.809C50.I136.28.10.96.G.L	25.41	35.77	39.36	44.10	45.90	47.20	48.41	49.67			95.51%
809C50	137	G2G.809C50.I137.28.09.91.G.A	25.39	35.52	38.93	43.72	45.47	46.54	47.46	48.45			90.87%

Table B.13. Path dependence temperature-compensated discharge ASI at SOC_{MAX} and 30°C.

Supplemental Matrix			Temperature Compensated 30°C Discharge ASI at SOC_{MAX}										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			25.47	29.13	30.75	32.88	33.69	33.34	33.73	34.19			**34.04%**
			1.39	4.81	6.07	7.79	8.40	9.09	9.48	9.89			**37.27%**
40C540	101	G2G.40C540.I101.28.09.12.G.F	25.62	27.71	28.72	30.12	30.79	28.44	28.54	28.71			12.08%
40C540	121	G2G.40C540.I121.28.06.23.G.F	28.01	31.55	33.20	35.72	36.94	34.54	34.47	34.49			23.13%
80C950	109	G2G.80C950.I109.28.09.19.G.L	24.58	27.28	28.19	29.28	29.46	28.76	28.98	29.20			18.81%
80C950	118	G2G.80C950.I118.28.09.17.G.A	24.34	25.62	27.01	28.50	29.01	28.04	28.06	28.35			16.46%
405C40	114	G2G.405C40.I114.28.08.10.G.F	23.47	23.58	24.06	24.48	24.77	25.06	25.48	25.80			9.93%
405C40	125	G2G.405C40.I125.28.05.04.G.F	26.40	25.36	25.65	26.25	26.53	27.07	27.30	27.59			4.53%
809C50	136	G2G.809C50.I136.28.10.96.G.L	25.66	36.07	39.86	44.53	46.28	47.77	49.03	50.35			96.19%
809C50	137	G2G.809C50.I137.28.09.91.G.A	25.65	35.87	39.34	44.15	45.79	47.03	48.01	49.03			91.17%

Table B.14. Path dependence discharge ASI at SOC_{MIN} and 30°C.

Supplemental Matrix			30°C Discharge ASI at SOC_{MIN}										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			22.69	27.49	28.92	29.49	30.12	30.97	31.35	31.72			**39.51%**
			1.03	3.84	4.92	5.24	5.57	5.73	6.01	6.14			**25.14%**
40C540	101	G2G.40C540.I101.28.09.12.G.F	23.01	25.65	26.40	26.81	27.20	28.45	28.78	29.17			26.77%
40C540	121	G2G.40C540.I121.28.06.23.G.F	24.63	29.17	30.57	31.43	32.16	34.06	34.60	35.06			42.32%
80C950	109	G2G.80C950.I109.28.09.19.G.L	21.74	24.03	24.74	24.93	25.23	25.98	26.08	26.34			21.14%
80C950	118	G2G.80C950.I118.28.09.17.G.A	21.83	24.17	24.80	25.02	25.32	26.04	26.08	26.28			20.41%
405C40	114	G2G.405C40.I114.28.08.10.G.F	21.56	23.84	24.44	24.87	25.24	25.48	25.67	25.84			19.87%
405C40	125	G2G.405C40.I125.28.05.04.G.F	23.48	27.05	28.07	28.51	29.28	29.60	29.85	30.24			28.78%
809C50	136	G2G.809C50.I136.28.10.96.G.L	22.48	33.23	36.51	37.60	38.76	39.58	40.41	40.96			82.21%
809C50	137	G2G.809C50.I137.28.09.91.G.A	22.82	32.74	35.81	36.75	37.77	38.60	39.31	39.84			74.55%

Table B.15. Path dependence temperature-compensated discharge ASI at SOC_{MIN} and 30°C.

Supplemental Matrix			Temperature Compensated 30°C Discharge ASI at SOC_{MIN}										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			22.60	27.24	28.75	29.29	29.86	30.67	31.16	31.55			**39.22%**
			0.96	4.11	5.19	5.54	5.80	6.08	6.32	6.49			**26.19%**
40C540	101	G2G.40C540.I101.28.09.12.G.F	22.70	25.02	25.77	26.11	26.53	27.51	28.07	28.48			25.46%
40C540	121	G2G.40C540.I121.28.06.23.G.F	24.31	28.27	30.02	30.75	31.38	33.01	33.73	34.21			40.72%
80C950	109	G2G.80C950.I109.28.09.19.G.L	21.84	24.02	24.81	24.95	25.28	25.94	26.15	26.42			20.95%
80C950	118	G2G.80C950.I118.28.09.17.G.A	21.80	24.00	24.69	24.87	25.14	25.79	25.92	26.13			19.85%
405C40	114	G2G.405C40.I114.28.08.10.G.F	21.31	23.24	24.00	24.33	24.72	24.80	25.15	25.32			18.84%
405C40	125	G2G.405C40.I125.28.05.04.G.F	23.26	26.66	27.59	28.12	28.76	29.09	29.43	29.77			27.97%
809C50	136	G2G.809C50.I136.28.10.96.G.L	22.62	33.58	36.92	38.02	39.05	40.19	41.03	41.67			84.20%
809C50	137	G2G.809C50.I137.28.09.91.G.A	22.98	33.16	36.18	37.17	38.02	39.02	39.80	40.39			75.76%

2.3.2 RPT Study Data

The RPT Study cell group was based on full $C_1/1$ and L-HPPC test every four weeks. Consequently, no temperature compensation was performed on the data (no L-HPPC at test temperature), but the available power at 300 Wh was calculated and scaled by the battery size factor (488, see Section 2.1).

Table B.16. RPT study $C_1/1$ discharge capacity between full charge and discharge.

Supplemental Matrix			Full $C_1/1$ Discharge Capacity										
Path Dependence Cells													
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(Ah)	(%)
			0.908	0.867	0.852	0.841	0.831	0.829	0.870	0.864			**9.39%**
			0.043	0.048	0.056	0.062	0.066	0.068	0.006	0.006			**3.68%**
40540	127	G2G.40540.I127.28.07.28.G.L	0.921	0.890	0.887	0.880	0.875	0.870	0.866	0.860			6.58%
40540	128	G2G.40540.I128.28.06.27.G.A	0.924	0.896	0.893	0.887	0.882	0.881	0.874	0.868			6.00%
80950	123	G2G.80950.I123.20.13.95.G.A	0.845	0.795	0.771	0.752	0.738	0.731					13.48%
80950	138	G2G.80950.I138.20.12.88.G.L	0.942	0.886	0.857	0.846	0.829	0.833					11.51%

Table B.17. RPT study interpolated discharge ASI at SOC_{MAX} and 30°C.

Supplemental Matrix Path Dependence Cells			30°C Discharge ASI at SOC_{MAX} (Interpolated)										
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			24.83	33.35	35.55	36.81	37.82	38.83	32.64	33.14			**59.55%**
			1.36	3.56	5.62	6.32	6.98	7.63	0.96	1.00			**36.92%**
40540	127	G2G.40540.I127.28.07.28.G.L	26.42	30.95	31.44	32.04	32.47	32.98	33.32	33.85			28.09%
40540	128	G2G.40540.I128.28.06.27.G.A	25.48	29.65	29.98	30.71	31.14	31.58	31.96	32.43			27.25%
80950	123	G2G.80950.I123.20.13.95.G.A	23.76	36.48	40.63	42.81	44.35	46.34					95.01%
80950	138	G2G.80950.I138.20.12.88.G.L	23.65	36.32	40.13	41.68	43.34	44.42					87.84%

Table B.18. RPT study interpolated discharge ASI at SOC_{MIN} and 30°C.

Supplemental Matrix Path Dependence Cells			30°C Discharge ASI at SOC_{MIN} (Interpolated)										
Test Group	Cell #	ATD Label	Char	4 wk	8 wk	12 wk	16 wk	20 wk	24 wk	28 wk	32 wk	36 wk	fade
AABCC (SOC/B/°C)			(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(Ω-cm²)	(%)
			22.40	29.76	31.20	32.18	33.01	34.30	30.30	30.77			**55.81%**
			0.96	2.24	3.31	3.71	4.03	5.06	0.90	0.98			**26.79%**
40540	127	G2G.40540.I127.28.07.28.G.L	23.48	28.35	28.95	29.67	30.15	30.65	30.93	31.46			33.99%
40540	128	G2G.40540.I128.28.06.27.G.A	22.88	27.35	27.79	28.34	28.93	29.24	29.67	30.08			31.50%
80950	123	G2G.80950.I123.20.13.95.G.A	21.90	31.69	34.35	35.55	36.66	38.46					75.60%
80950	138	G2G.80950.I138.20.12.88.G.L	21.33	31.64	33.71	35.17	36.28	38.85					82.15%

Table B.20. RPT study available power at 300Wh.

Supplemental Matrix Path Dependence Cells			Available 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	fade
AABCC (SOC/B/°C)			(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(%)
			32.55	24.64	23.48	22.75	22.13	21.43	24.51	24.11			**35.00%**
			1.07	2.39	3.18	3.41	3.58	3.97	0.59	0.63			**12.82%**
40540	127	G2G.40540.I127.28.07.28.G.L	31.47	26.26	25.88	25.28	24.76	24.27	24.09	23.67			24.78%
40540	128	G2G.40540.I128.28.06.27.G.A	31.91	27.12	26.55	26.09	25.65	25.40	24.92	24.56			23.05%
80950	123	G2G.80950.I123.20.13.95.G.A	33.01	22.55	20.52	19.56	18.77	17.80					46.06%
80950	138	G2G.80950.I138.20.12.88.G.L	33.83	22.64	20.96	20.06	19.34	18.23					46.12%