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Uncertainty Study of INEEL EST Laboratory Battery Testing Systems

Volume 2

Application of Results to INEEL Testers

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ABSTRACT

The Energy Storage Testing Laboratory at the Idaho National Engineering and Environmental Laboratory presently serves as an independent test facility for testing hybrid vehicle battery technologies in various development programs. The parameters important to these tests are either directly measured or derived from the direct measurements. The program managers of the sponsoring programs expressed a need to understand the confidence that could be placed in the results of this testing; thus, the uncertainty of the parameters was investigated.

Volume 1 of this study presents the derivation of the analytical expressions for both the measured and derived parameters, as well as the calculated uncertainty values. Volume 2 of the study applies the previously reported analytical work to an actual tester and calculates the uncertainties. A computerized worksheet demonstrates how the results are obtained.

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FIGURES

TABLES

ACRONYMS[a]

Ah	ampere-hour
ATD	Advanced Technology Development (Program)
dB	decibel
DC	direct current
DOE	U. S. Department of Energy
DVM	digital voltmeter
EST	Energy Storage Testing (Laboratory)
HPPC	Hybrid Pulse Power Characterization (Test)
I_{avg}	average current (over some defined interval)
INEEL	Idaho National Engineering and Environmental Laboratory
LSB	least significant bit
PNGV	Partnership for a New Generation of Vehicles
ppm	parts per million
RSS	root sum square (square root of the sum of the squares)
SD	self-discharge
sps	samples per second
STD	standard deviation
tc	thermocouple
V_{avg}	average voltage (over some defined interval)
Wh	watt-hour
% F.S.	percent of full scale
% Rdg	percent of reading
ΔI	current change (between two defined time points)
ΔV	voltage change (between two defined time points)

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[a] Abbreviations for fundamental measurement units (volt, ampere, degree, second, etc.) are not listed.

1. INTRODUCTION

1.1 Background

The Energy Storage Testing (EST) Laboratory at the Idaho National Engineering and Environmental Laboratory (INEEL) was established in 1983 for testing full-size electric vehicle batteries in support of the U.S. Department of Energy (DOE) Electric and Hybrid Vehicle Program. Presently, the laboratory serves as an independent test facility for testing hybrid vehicle battery technologies in various development programs. These include the DOE-sponsored Advanced Technology Development (ATD) Program, which seeks to improve the electrochemical performance of lithium ion cells; and the FreedomCAR (formerly Partnership for a New Generation of Vehicles, or PNGV) Program, which is jointly sponsored by DOE and the U.S. automobile manufacturers.

The FreedomCAR/PNGV program is designed around a set of interrelated goals derived from vehicle requirements and constraints. A successful battery must satisfy all of these goals simultaneously. The associated testing process uses custom test procedures to measure various aspects of battery performance for direct comparison with these goals. These procedures typically subject a device under test to a prescribed sequence of controlled current, power, or voltage steps, each lasting from a few seconds to an hour or more. The ATD program also adopted many of these procedures (or variants of them) as useful means of comparing high-power cell performance.

Many of the battery performance results important to these programs are not directly measured as simple parameters. Instead, they must be calculated from the results of various time-based measurements made under particular test conditions. The program managers of the sponsoring programs expressed a need to understand the confidence that could be placed in the results of this testing, specifically with respect to the uncertainty of the reported results. This need led directly to the measurement uncertainty evaluation detailed in this report.

1.2 Measurement Parameters Treated

The parameters important to INEEL hybrid vehicle battery testing are of two groups: directly measured parameters and various parameters derived from these fundamental measurements. Directly measured parameters include temperature, voltage, and current (all as functions of time, which is an independent variable whose measurement uncertainty is not treated in this study.) The derived parameters treated in the study are:

Power

Capacity

Energy

Source impedance (battery resistance)

Efficiency (round trip)

Self-discharge

Discharge pulse power capability

Regen pulse power capability

Available energy.

In general, these parameters are defined as treated in Reference 1, which is the standard testing manual for the INEEL EST Laboratory. In particular, *source impedance* is the battery resistance calculated from the Hybrid Pulse Power Characterization (HPPC) test; *self-discharge* is the quantity determined by the self-discharge Test; and the *discharge* and *regen pulse power capabilities* and *available energy* are the corresponding parameters calculated from the HPPC Test. The other derived parameters are not limited to specific test procedures in the manual.

1.3 Study Outline and Content of This Report

The INEEL Energy Storage Testing Laboratory measurement uncertainty study consisted of several parts: (a) analytical expressions were derived for the uncertainty of directly measured parameters, (b) analytical expressions were developed for derived parameters, (c) uncertainty values were calculated for measured parameters using the manufacturer's specifications where possible, and (d) testing was performed to confirm the reasonableness of these calculated values, or to directly estimate uncertainties where test equipment manufacturer values were unavailable. As a separate concern, (e) the effects of potential data aliasing errors were derived, and limited testing was conducted to verify the predicted results. Finally, (f) numerical results were calculated for the derived parameters for specific test stations in the laboratory.

The results of parts (a) and (b) of this study, along with the analysis for part (e), are documented in Volume 1 of this report. This second volume details the results of parts (c), (d), and (f), evaluated using a Maccor battery test station as an example. A computerized worksheet is provided to demonstrate how the results are applied. Results for other types of INEEL battery test stations will be published as uncertainty test results are available. This multivolume approach has been adopted primarily because the INEEL EST Laboratory operates continuously; test stations may be required continuously for months to conduct life testing of specific devices.

1.4 Example Study Results Using Maccor Testers

It is generally not possible to present a simple set of uncertainty values for INEEL battery measurements because of the multiplicity of tester types and generations used, as well as the varying ranges of measurement and control provided by the testers. In addition, the uncertainties for many of the derived parameters are a function of the measured value rather than the measurement ranges, i.e., some uncertainties are affected by the test conditions used for the measurement. In some cases, the calibration method used also drastically affects the calculated uncertainties.

This summary presents numerical results for these uncertainties whenever possible, but we cannot emphasize too strongly that these values are *representative only*. Users of this report are responsible to determine whether (and to what extent) the test conditions of interest differ from the conditions used in determining these values. *If the conditions are significantly different, the applicable measurement uncertainties should be calculated from the relevant equations contained in this report.* Also, note that all results in this report represent one standard deviation of uncertainty values in accordance with standard industry practice for expressing measurement uncertainty.[2] Practical application of such results requires the user to determine the confidence level required for a specific application and to multiply these standard uncertainties by the appropriate factor (e.g., 2x for a desired 95% confidence level.)

Representative results are presented in Table 1 for a Maccor test channel with 10-V and 12.5-A full-scale measurement ranges, except where noted. For easy reference, Table 2 summarizes the analytical expressions used to compute the values in Table 1. Most of these example results are shown in the computerized worksheet provided on CD-ROM with this report. (See Appendix B for further information.)

Table 1. Representative measurement uncertainty results for a Maccor tester.

Parameter	**Uncertainty Expression (See Table 2)**	**Calculated Uncertainty *(ONE Standard Deviation)* (% F.S. = % of full scale, % Rdg = % of reading)**	**Conditions for Calculated Values**
Directly Measured Parameters			
Temperature	22, 23	±1.22°C (TC simulator)	New Maccor TC algorithm 0 to 100°C range
	22, 24	±0.58°C (end-to-end with TC oven)	
Current	27, 26	±0.278% full scale	12.5 A, full scale Keithley 195 A, 0.25% shunt
		±0.13% full scale	Same, except using actual resistance of a de-rated shunt
Voltage	30, 29	±0.081% full scale	10 V, full scale, Keithley 195 A, Dial-a-Source 56 A
Derived Parameters			
Power	53	±0.40% Rdg (I = 10; V = 4)	10 V, full scale; 12.5 A, full scale. V and I uncertainty, as above
		±3.49% Rdg (I = 1, V = 2.5)	
Capacity	55	±0.16% Rdg (I_{avg} = 10 A)	12.5 A, full scale, using actual shunt resistance, current error of 0.13% F.S.
		±0.35% Rdg (I_{avg} = 10 A)	12.5 A, full scale, using existing current error of 0.278% full scale.
		±3.46% Rdg (I_{avg} = 1 A)	12.5 A, full scale, using existing current error of 0.278% full scale.
Energy	56	±0.36% Rdg (I_{avg} = 10 A; V_{avg} = 7 V)	10 V, full scale; 12.5 A, full scale, V cal error 0.078%, full scale, I cal error 0.277% F.S. [from equations (26) and (29)]
		±3.47% Rdg (I_{avg}=1A, V_{avg} = 3.5 V)	
Source impedance	66	±0.29% Rd (ΔV=1V, ΔI = 10 A)	10 V, full scale; 12.5 A full scale, V & I calibration errors as above for Energy, V STD ≅ 0.0009% full scale (from test), I STD ≅ 0.0036% full scale (from test)
		±0.39% Rdg (ΔV=.05V, ΔI = 1 A)	
Efficiency	67	±0.56% Rdg (I_{avg} = 10A, V_{avg} = 4 V)	10 V, full scale; 12.5 A full scale; V & I calibration errors as above for Energy
		±4.92% Rdg (I_{avg} = 1A; V_{avg} = 2.5V)	
Self-discharge	76	±0.41% Rdg	10 V, full scale; 12.5 A, full scale- V & I calibration errors are as above for Energy; V_{avg} = 3.5V; capacity = 10 Ah; 7-day Self-discharge = 17%
		±3.47% Rdg	Same as above, except capacity = 1 Ah; 7-day self-discharge = 7%

Table 1. (continued).

Parameter	**Uncertainty Expression (See Table 2)**	**Calculated Uncertainty *(ONE Standard Deviation)* (% F.S. = % of full scale, % Rdg = % of reading)**	**Conditions for Calculated Values**
Self-Discharge	78	±0.29% Rdg	Calibration errors are as above but assumed to be all linearity. (Result is independent of voltage, current, or measurement ranges.)
Discharge power capability	84	±0.95% Rdg (average over all DOD values)	10 V, full scale; 12.5 A full scale; V & I calibration errors are as above. Calculated from actual low-current HPPC data for an ATD 0.9-A·h Generation, 1 Li ion cell.
Regen power capability	98	±2.41% Rdg (average over all DOD values)	10 V, full scale; 12.5 A, full scale; V & I calibration errors are as above. Calculated from actual low-current HPPC data for an ATD 0.9 Ah. Generation 1, Li ion cell.
Available energy	104	±3.87% Rdg	10 V full scale; 12.5 A full scale; V & I calibration errors are as above. Calculated from actual low-current HPPC and C/1 data for an ATD 0.9 Ah, Generation 1, Li ion cell.

Table 2. Expressions used for calculating measurement uncertainty.

Parameter	**Ref** [b]	**Expression**
Measured parameter (general)	18	$\%Perr_{TOT} = \sqrt{(\%Peq_{TOT})^2 + (\%err_{CAL})^2 + (\%err_{TD})^2}$ Includes equipment, calibration, and transducer errors
Equipment error (from specs)	19	$\%Peq_{TOT} = \sqrt{(\%err_{FE})^2 + (\%err_{QUAN})^2 + (\%err_{ALGOR})^2}$ Neglects time jitter and aliasing
Equipment error (from test)	17	$\%Peq_{TOT} = \sqrt{(\%Perr_{STD})^2 + (\%\overline{P}_{ERR})^2 - (\%err_{CAL})^2}$ Calibration error is usually set to zero (conservative)
Temperature	22	$\%err_{T} = \sqrt{(\%Teq_{TOT})^2 + (\%err_{TCAL})^2}$ Transducer error included in CAL term

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[b] Reference numbers in Table 2 are to the equation numbers in Volume 1 that give these results. Most of these equations are repeated in the text of this volume.

Table 2. (continued).

Parameter	Ref [b]	Expression
Temperature calibration	23	$\%err_{TCAL} = \frac{100}{F.S.}\sqrt{(STc)^2 + (Tc)^2}$ Calibration with thermocouple simulator
	24	$\%err_{TCAL} = \frac{100}{F.S.}(RT)$ End-to-end with calibration oven
Current	27	$\%err_I = \sqrt{(\%Ieq_{TOT})^2 + (\%err_{ICAL})^2}$
Current calibration	26	$\%err_{ICAL} = 100\sqrt{(err_{SHUNT})^2 + \left(\frac{DVMerr}{F.S.\ Cal.\ Shunt\ Voltage}\right)^2}$ DVM error in volts; shunt error in decimal fraction
Voltage	30	$\%err_V = \sqrt{(\%Veq_{TOT})^2 + (\%err_{VCAL})^2}$
Voltage calibration	29	$\%err_{VCAL} = 100\sqrt{\left(\frac{DVMerr}{Full\ Scale\ Voltage}\right)^2 + \left(\frac{VSerr}{Full\ Scale\ Voltage}\right)^2}$ DVM and source errors in volts
Power	53	$\%W = \left\{\left(\frac{I_{FS}}{I}\%err_I\right)^2 + \left(\frac{V_{FS}}{V}\%err_V\right)^2\right\}^{\frac{1}{2}}$ Result is percentage of reading (not range) and function of measured V and I
Capacity	55	$\%Q = \frac{I_{FS}\%err_{ICAL}}{\bar{I}}$ Result is a percentage of reading (not range)
Energy	56	$\%E = \frac{1}{E}\sqrt{\left(\left\{\int Idt\right\}V_{FS}\%err_{VCAL}\right)^2 + \left(\left\{\int Vdt\right\}I_{FS}\%err_{ICAL}\right)^2}$ Result is a percentage of reading (not range)
Source impedance	66	$\%R_S = \left[2\left(\frac{\%errV_{STD}}{V(t_1) - V(t_2)}V_{FS}\right)^2 + 2\left(\frac{\%errI_{STD}}{I(t_1) - I(t_2)}I_{FS}\right)^2 + (\%err_{VCAL})^2 + (\%err_{ICAL})^2\right]^{\frac{1}{2}}$ Result is a percentage of reading and a function of measured voltages and currents
Efficiency	67	$\%Eff = \left\{\begin{matrix}(V_{FS}\%err_{VCAL})^2\left(\left(\frac{\int I_A dt}{\int V_A I_A dt}\right)^2 + \left(\frac{\int I_B dt}{\int V_B I_B dt}\right)^2\right) + \\ (I_{FS}\%err_{ICAL})^2\left(\left(\frac{\int V_A dt}{\int V_A I_A dt}\right)^2 + \left(\frac{\int V_B dt}{\int V_B I_B dt}\right)^2\right)\end{matrix}\right\}^{\frac{1}{2}}$ Result is a percentage of reading and a function of measured voltages and currents

Table 2. (continued).

Parameter	Ref[b]	Expression
Self-discharge $\%SD$	76	$\frac{1}{7SD}\left[\left(V_{FS}\%err_{VCAL}\right)^2(Q_1-Q_A-Q_B)^2+\left(I_{FS}\%err_{ICAL}\right)^2\left\{\int_{\Delta t_1}Vdt-\int_{\Delta t_A}Vdt-\int_{\Delta t_B}Vdt\right\}^2\right]^{\frac{1}{2}}$ Calibration offset is dominant; result is a percentage of reading
	78	$\left(\left(\%err_{VCAL}\right)^2+\left(\%err_{ICAL}\right)^2\right)^{\frac{1}{2}}$ Calibration linearity dominant: result is a percentage of reading
Discharge pulse power capability $\%P_D$	84	$\left\{\left(\%err_{VCAL}\right)^2+\left(\%err_{ICAL}\right)^2+\frac{\%errV_{STD}^2V_{FS}^2}{(V_0-V_1)^2}+2\frac{\%errI_{STD}^2I_{FS}^2}{(I_0-I_1)^2}+\frac{(\%errV_{STD}^2V_{FS}^2+\%err_{VCAL}^2V_{FS}^2)(V_{MIN}-V_1)^2}{(V_0-V_1)^2(V_0-V_{MIN})^2}\right\}^{\frac{1}{2}}$ Result is a percentage of reading and a function of measured voltages and currents
Regen pulse power capability $\%P_R$	98	$\left\{\left(\%errV_{STD}\right)^2V_{FS}^2\left[\frac{2}{(V_2-V_3)^2}+\frac{Q_A^2+Q_B^2}{\left(V_{MAX}-OCV_{regen}\right)^2(Q_A+Q_B)^2}\right]+\left(\%err_{VCAL}\right)^2\left[1+\frac{(V_4-V_5)^2Q_A^2+V_{FS}^2Q_B^2}{\left(V_{MAX}-OCV_{regen}\right)^2(Q_A+Q_B)^2}\right]+\frac{2\left(\%errI_{STD}\right)^2I_{FS}^2}{(I_2-I_3)^2}+\left(\%err_{ICAL}\right)^2\left[1+I_{FS}^2\frac{(V_4-V_5)^2\left(T_A^2Q_B^2+T_B^2Q_A^2\right)}{\left(V_{MAX}-OCV_{regen}\right)^2(Q_A+Q_B)^4}\right]\right\}^{\frac{1}{2}}$ Result is a percent of reading and a function of measured currents and voltages
Available energy $\%AE$	104	$\frac{100}{AE}\left\{\left(\left[\int Idt\right]V_{FS}\frac{\%err_{VCAL}}{100}\right)^2+\left(\left[\int Vdt\right]I_{FS}\frac{\%err_{ICAL}}{100}\right)^2+\left(U_{D,P}(Q_D)\cdot\frac{dg}{dP}(P_D)\cdot\frac{dU_E}{dQ}(Q_D)\right)^2+\left(U_{R,P}(Q_R)\cdot\frac{dh}{dP}(P_R)\cdot\frac{dU_E}{dQ}(Q_R)\right)^2\right\}^{\frac{1}{2}}$ Result is a percentage of reading and a function of the uncertainties in energy, discharge pulse power capability, and regen pulse power capability (all expressed as functions of DOD)

2. EXAMPLE MEASUREMENT UNCERTAINTY RESULTS

2.1 Overview and Reference Instrument Information

The technical basis for the uncertainty analysis performed on the various battery test systems is presented in Sections 2 and 3 of Volume 1 of this report. This section applies the theory developed in Volume 1 to an INEEL Maccor battery test system. This is done both to illustrate the application of the results of Volume 1 and to show representative uncertainties for a real tester. The uncertainty numbers obtained are in the form of a standard deviation for an assumed normal distribution of the associated parameter error. If a desired confidence level for the error is required, then the standard deviation as given must be multiplied by the appropriate factor (e.g., 2 for a 95% confidence level and 3 for 99.7%). The measured parameters (temperature, voltage, and current) and the derived parameters (power, capacity, energy, source impedance, efficiency, self-discharge, discharge and regen pulse power capability, and available energy) will be considered. For the measured parameters, the manufacturer-specified equipment error will be used preferentially. When the equipment error involves multiple components, the root sum square [square root of the sum of the squares (RSS)] of the component errors will be used to obtain a total. When manufacturer specifications are not available or not clearly defined, test data will be used in its place.

Many of the results in this study are expressed as a percentage of the full-scale range (generally indicated as % F.S.) of the measurement channel. Strictly speaking, for bipolar measurement channels (i.e., those that measure both positive and negative values), *full scale* refers to the total span of the measurement, from minimum to maximum value. For example, a measurement channel whose range is ±5 V has a span of 10 V, not 5 V, and an uncertainty of 0.1% F.S. for this measurement would correspond to 0.01 V. This distinction is important, because uncertainties for some derived parameters must be computed using engineering units (volts or amperes) rather than percentages. The only bipolar measurement considered in this report is current, and current error specifications are shown as a percentage of the maximum value, for reasons explained in Section 2.2.2. Other approaches (including specifying values in units of the measured variables) are usable as long as they are used consistently and the resulting values agree with manufacturer's specifications.

Note that the potential error from signal aliasing was evaluated and tested for, but it is not included in the summary results for this equipment. In general, these battery test systems are not able to reject any aliasing errors caused from undersampling. Thus, we assume that all battery tests performed with these systems are properly designed so that the possibility of having an aliasing error source is nonexistent (i.e., the sample rate is always set much greater than the spectral content of the anticipated signal to be measured). Specific equipment evaluations for aliasing effects are discussed later in this report.

Testing performed to evaluate tester uncertainty made use of a number of reference measuring devices, both for tester calibration and for selected measurements during the testing itself. For convenience these devices and their manufacturer-specified uncertainties are listed in Table 3.

Table 3. Reference measurement devices used for testing and calibration.

Manufacturer and Model	Device Type	Specification[1]
Omega CL-730	Reference temperature oven	±0.3 °C
Omega CL-24	Hand-held thermocouple Simulator	±0.5 °C
Omega (various)	Type T thermocouple	±1 °C (assumed)
Keithley 195A	Digital voltmeter	Depends on range[2] (See Table 4)
Hewlett Packard 3456A	Digital voltmeter	±0.0054 mV on 100 mV range
Various	Current shunt	±0.25 % F.S.[3]
General Resistance Instruments DAS-56A Dial-a-Source	Precision DC voltage source	(Accuracy not used in results) Voltage stability 15 ppm
1. All uncertainty specifications are assumed to be one standard deviation confidence level. 2. A more accurate voltmeter has since been procured for calibration purposes, but it was not available when the original testing described in this report was performed. The potential effects of using the improved meter are considered in Section 2.2.3. 3. This nominal value can be reduced to a value of ~0.05% F.S., as described in Section 2.2.2.		

Table 4. Accuracy specification for the Keithley 195A Digital Voltmeter.

Range (volts)	Error (% of range)	Error (counts)	Combined Accuracy (volts)
0.020 (20 mV)	±0.025	±8	±7.44e-06
0.2 (200 mV)	±0.025	±8	±7.44e-05
2.0	±0.020	±8	±6.44e-04
20	±0.030	±6	±7.83e-03
200	±0.025	±8	±7.44e-02
1000	±0.025	±6	±3.41e-01

The INEEL uses several models of battery test systems that have different power levels, different numbers of data channels, and different numbers of batteries that can be concurrently tested.[c] For a battery under test, the test system records terminal voltage, terminal current, and several user-specified temperatures (typically measured with Type T thermocouples), all at user specified sample rates. (The maximum sampling rate for Maccor testers is 100 samples per second.) In addition, the user can program-specific battery-terminal current-time-step sequences to charge and discharge each device under test. In the following sections, the uncertainty of the data measured by a specific Maccor system is evaluated for voltage, current, and temperature along with various derived parameters that have as inputs the measured parameters.

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[c] These tester types are identified in Section 1.4.1 of Volume 1.

2.2 Example of Measured Parameter Uncertainty

For each of the uncertainties for the measured parameters, a numerical value for uncertainty was obtained for a typical full-scale measurement range provided by an example Maccor test system. In most cases, for a different full-scale range the uncertainty value would be slightly different.

2.2.1 Temperature Uncertainty

There are four different cases for consideration in Maccor temperature measurements. The original Maccor software used a two-point temperature calibration with straight-line interpolation, which gave a worst-case error of about 2.5°C due to the algorithm alone. At INEEL instigation, Maccor revised the software to incorporate a more accurate conversion algorithm, which renders the software error insignificant (i.e., <<1°C). The improved software is now in use for all Maccor testing; hence, Cases 1 and 2 below are treated only for historical use with previously acquired data.

In addition, temperature calibration was originally calibrated using a hand-held thermocouple simulator (Cases 1 and 3), because the Maccor calibration software made it very time consuming to do end-to-end calibrations. The revised software now allows multiple channels to be calibrated simultaneously using a reference temperature oven; this end-to-end approach compensates for the error of the thermocouples themselves (Cases 2 and 4).

Note that all temperature uncertainty calculations are performed, and results are specified here in units of the measured variable (i.e., °C). This is coincidentally equivalent to percent of range due to the specific temperature range evaluated (0 to 100°C). Most other calculations in this report are done in percentages, but either approach can be used, depending on the specifications and data available.

Case 1. Original software and assumed calibration of 0 to 100^oC, using the Omega hand-held calibrator.

$$\mathit{Error:}\quad \pm{}^0C = \sqrt{(\underbrace{2.5\ {}^0C}_{\substack{\mathit{Software}\\ \mathit{error}}})^2 + (\underbrace{1\ {}^0C}_{\mathit{Tc\ error}})^2 + (\underbrace{0.5\ {}^0C}_{\substack{\mathit{Calibrator}\\ \mathit{error}}})^2 + (\underbrace{0.5\ {}^0C}_{\substack{\mathit{Maccor}\\ \mathit{error}}})^2} = \pm 2.78\ {}^0C\ .$$

Case 2. Original software and assumed calibration of 0 to 100^oC, using the Omega reference temperature source for an end-to-end calibration.

$$\mathit{Error:}\quad \pm{}^0C = \sqrt{(\underbrace{2.5^0C}_{\substack{\mathit{Software}\\ \mathit{error}}})^2 + (\underbrace{0.3^0C}_{\substack{\mathit{Calibrator}\\ \mathit{error}}})^2 + (\underbrace{0.5^0C}_{\substack{\mathit{Maccor}\\ \mathit{error}}})^2} = \pm 2.57\ {}^0C\ .$$

Case 3. Revised software and assumed calibration of 0 to 100^oC, using the Omega hand held calibrator.

$$\mathit{Error:}\quad \pm{}^0C = \sqrt{(\underbrace{1^0C}_{\mathit{Tc\ error}})^2 + (\underbrace{0.5^0C}_{\substack{\mathit{Calibrator}\\ \mathit{error}}})^2 + (\underbrace{0.5^0C}_{\substack{\mathit{Maccor}\\ \mathit{error}}})^2} = \pm 1.22\ {}^0C\ .$$

Case 4. Revised software and assumed calibration of 0 to 100^oC, using the Omega temperature source for an end-to-end calibration.

$$Error:\quad \pm{}^0C = \sqrt{(\underbrace{0.3^0C}_{\substack{Calibrator\\error}})^2 + (\underbrace{0.5^0C}_{\substack{Maccor\\error}})^2} = \pm 0.58\ {}^0C \quad .$$

2.2.2 Current Uncertainty

Assume the calibration is done with a calibrated current shunt and the Keithley 195-A digital voltmeter (DVM). This will result in a calibration error of $\pm 0.277\% F.S.$ for a 12.5-A channel, based on the use of a 100-A/50-mV shunt.[d] The shunt portion of this error is $\pm 0.25\% F.S.$[e] Note that this error is not expressed with respect to the span of the current measurement channel, because the shunt specification really represents a linearity error. Thus, the maximum error (in amperes) is a percentage of the maximum current (12.5 A), not of the 25-A span of the channel. We believe the Maccor repeatability specification is also specified in this fashion, and thus all current uncertainty numbers are treated as a percentage of maximum current.

$$Error:\quad \pm\% F.S. = \sqrt{(\underbrace{0.277}_{\substack{Calibration\\error}})^2 + (\underbrace{0.02}_{\substack{Maccor\\error}})^2} = \pm 0.278\% F.S.$$

Because the shunt error dominates the current measurement uncertainty, a method has now been devised to significantly reduce this error. The method uses oversized current shunts (i.e., used only in the lower portion of their operating current range) to avoid self-heating effects. The actual resistances of these shunts (rather than their nominal values) are then used for the voltage-to-current conversion, allowing the shunt portion of the error to be reduced by approximately a factor of 5. Thus, a revised current uncertainty can be achieved as follows:

$$Case\ 2\ (Revised)\ Error:\ \pm\% F.S. = \sqrt{(\underbrace{0.129}_{\substack{Calibration\\error}})^2 + (\underbrace{0.02}_{\substack{Maccor\\error}})^2} = \pm 0.13\% F.S.$$

Note that, for this case, the error is dominated by the voltmeter used for calibration, not the shunt. Even further improvement is possible by using a higher-accuracy voltmeter. A voltmeter whose error is insignificant compared to the shunt error of ±0.05% F.S. used in this case could reduce the overall error to only slightly more than the shunt error itself.

2.2.3 Voltage Uncertainty

Assume that the calibration is done using a Keithley 195-A DVM and a Dial-A-Source DAS 56A. This will result in a calibration error of $\pm 0.078\% F.S.$ This assumes that the full-scale voltage is 10.0 V, with the Keithley used on the 20-V range.

$$Error:\quad \pm\% F.S. = \sqrt{(\underbrace{0.078}_{\substack{Calibration\\error}})^2 + (\underbrace{0.02}_{\substack{Maccor\\error}})^2} = \pm 0.081\% F.S.$$

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[d] Computed using Equation 26 in Volume 1, repeated in Table 2 for reference.

[e] If the full-scale current is other than the ±12.5 *A* value assumed, then the Keithley DVM error contribution may be slightly different, due to the use of a different measuring range.

As in the case of current discussed above, this uncertainty can be significantly improved through the use of a higher-accuracy voltmeter for calibration, with the extent of improvement depending on the specifications of the voltmeter. The new HP 3458A voltmeter acquired by the INEEL EST Laboratory for this purpose has a claimed accuracy 30 times better than the Keithley 195A. However, results are still limited by the inherent Maccor error and the stability of the voltage source used for calibration. Existing calibration procedures must also be modified to comply with various constraints required to achieve this improved meter accuracy. This evaluation is still in progress, and numerical results based on this higher accuracy meter are not included here, but it should ultimately be possible to limit the voltage uncertainty to the Maccor repeatability of 0.02% F.S.

2.3 Example of Derived Parameter Uncertainty

Derived parameters are defined as those parameters that are obtained from post-processing the time records of measured voltage and current data. Unlike the measured parameters, the derived parameters will not have a simple numerical value for uncertainty. This is because their uncertainty is typically a function of some combination of measured parameters, in some cases with time integrals of these parameters, and is usually expressed as a percent of reading. These uncertainties are, thus, often data-dependent because they vary with the specific test conditions. For each of the derived parameters, the formula developed above in this report is repeated, along with numerical values for typical calibration errors. Numerical uncertainty results for various representative values of the measured variables are presented in Table 1 in Section 1.4. The numerical calculations for these results are not shown in the body of this report; instead they have been generated using a computerized worksheet (Microsoft Excel spreadsheet), which is available on the CD-ROM accompanying this report. This worksheet, described in Appendix B, exemplifies the results shown in Table 1, but it can also be used to calculate uncertainties for other measurement channel characteristics and data sets.

The derived parameters are power, W; energy, E; capacity, Q; source impedance, R_S; efficiency, Eff; self-discharge, SD; discharge pulse power capability, P_D; regen pulse power capability, P_R; and available energy, AE. All of these derived parameters have as dependant variables some combination of voltage, V; current, I; time, t; or other derived parameters. (See Volume 1 of this report for more details, including the definition of all parameters used here.)

Power: $W = VI$

Energy: $E = \int VIdt$

Capacity: $Q = \int Idt$

Source Impedance: $R_S = \dfrac{V(t_1) - V(t_2)}{I(t_1) - I(t_2)}$

Efficiency: $Eff = 100\dfrac{E_{Discharge}}{E_{Charge}} = 100\dfrac{\int_{Discharge} V_A I_A dt}{\int_{Charge} V_B I_B dt}$

Self-discharge: $SD = \frac{(E_1 - E_A - E_B)}{7}$

Discharge pulse power capability: $P_D = \frac{V_{MIN}\ (OCV - V_{MIN})}{R_S}$

Regen pulse power capability: $P_R = \frac{V_{MAX}\ (V_{MAX} - OCV)}{R_S}$.

Available Energy, AE, is not shown here, because there is no analytical expression for calculating it. It is determined using a complex process, described in detail in Section 3.2.8 of Volume 1 of this report.

2.3.1 Power Uncertainty

The relationship for power uncertainty as a percent of reading is given by:

$$\%W = \left\{ \left(\frac{I_{FS}}{I} \%err_I \right)^2 + \left(\frac{V_{FS}}{V} \%err_V \right)^2 \right\}^{\frac{1}{2}}$$

where

I and V = measured current and voltage

I_{FS} = full-scale current (typically $12.5\,A$ for Maccor 8, 9, and 10)

V_{FS} = full-scale voltage (typically $10V$ for Maccor 8, 9, and 10)

$\%err_I$ = uncertainty of the current as a percentage of full scale, typically $\pm 0.278\% F.S.$. as calculated in Section 2.2.2

$\%err_V$ = the uncertainty of voltage as a percentage of full scale, typically $\pm 0.081\% F.S.$ as calculated in Section 2.2.3.

2.3.2 Energy Uncertainty

The relationship for energy uncertainty as a percentage of reading is given by

$$\%E = \frac{1}{E} \sqrt{\left(\left\{ \int Idt \right\} V_{FS} \%err_{VCAL} \right)^2 + \left(\left\{ \int Vdt \right\} I_{FS} \%err_{ICAL} \right)^2}$$

where

E = computed energy

I and V = measured current and voltage; they are integrated over the time interval for which the energy is determined

V_{FS} = full-scale voltage (typically $10V$ for Maccor 8, 9, and 10)

$\%err_{VCAL}$ = voltage calibration error as a percentage of full scale, typically $0.078\% F.S.$, as calculated in Section 2.2.3

I_{FS} = full-scale current (typically $12.5\,A$ for Maccor 8, 9, and 10)

$\%err_{ICAL}$ = current calibration error as a percentage of full scale, typically $0.277\% F.S.$ as calculated in Section 2.2.2.

2.3.3 Capacity Uncertainty

The relationship for capacity uncertainty as a percent of reading is given by

$$\%Q = \frac{I_{FS}\,\%err_{ICAL}}{\bar{I}}$$

where

$\%err_{ICAL}$ = current calibration error as a percentage of full scale, typically $0.277\% F.S.$, as calculated in Section 2.2.2

I_{FS} = full-scale current (typically $12.5\,A$ for Maccor 8, 9, and 10)

$\bar{I}$ = average current over the time interval where the capacity is determined.

2.3.4 Source Impedance Uncertainty

The relationship for source impedance uncertainty as a percent of reading is given by

$$\%R_S = \left[2\left(\frac{\%errV_{STD}}{V(t_1) - V(t_2)} V_{FS} \right)^2 + 2\left(\frac{\%errI_{STD}}{I(t_1) - I(t_2)} I_{FS} \right)^2 + \left(\%err_{VCAL}\right)^2 + \left(\%err_{ICAL}\right)^2 \right]^{\frac{1}{2}}$$

where

$\%errV_{STD}$ = standard deviation for voltage uncertainty (as % F.S.)

$\%errI_{STD}$ = standard deviation for current uncertainty (as % F.S.)

$V(t_1)$ *and* $V(t_2)$ = measured voltages at times t_1 and t_2 (typically immediately before and at the end of a prescribed current pulse)

$I(t_1)$ *and* $I(t_2)$ = measured currents at times t_1 and t_2

$\%err_{ICAL}$ = current calibration error expressed as a percentage of F.S., typically 0.277% F.S., as calculated in Section 2.2.2

$\%err_{VCAL}$ = voltage calibration error expressed as a percentage of F.S., typically 0.078% F.S., as calculated in Section 2.2.3.

2.3.5 Efficiency Uncertainty

The relationship of efficiency uncertainty as a percentage of the calculated efficiency is given by the following equation:

$$Eff\% = \left\{ \left(V_{FS}\,\%err_{VCAL}\right)^2 \left(\left(\frac{\int I_A dt}{\int V_A I_A dt} \right)^2 + \left(\frac{\int I_B dt}{\int V_B I_B dt} \right)^2 \right) + \left(I_{FS}\,\%err_{ICAL}\right)^2 \left(\left(\frac{\int V_A dt}{\int V_A I_A dt} \right)^2 + \left(\frac{\int V_B dt}{\int V_B I_B dt} \right)^2 \right) \right\}^{\frac{1}{2}}$$

where

I_{FS} and V_{FS} = full-scale current and voltage (typically 12.5 A and 10 V, respectively, for Maccor 8, 9, and 10)

$\%err_{ICAL}$ = current calibration error, expressed as a percentage of full scale, typically $0.277\%\,F.S.$, as calculated in Section 2.2.2

$\%err_{VCAL}$ = voltage calibration error expressed as a percentage of full scale, typically $0.078\%\,F.S.$ as calculated in Section 2.2.3.

The various integrals are of the measured current, measured voltage, and power (i.e., the product of current and voltage) over the two parts of the efficiency test. (Specifically, V_A, I_A, and $V_A I_A$ are integrated over the discharge portions of the test, while the *B*-subscripted terms are integrated over the charge portions, although the symmetry of the expression makes this somewhat academic.)

2.3.6 Self-discharge Uncertainty

The relationship for self-discharge uncertainty as a percentage of reading is given by the following equation, if the calibration error is due to offset errors:

$$\%SD = \frac{1}{7SD}\left[\left(V_{FS}\,\%err_{VCAL}\right)^2 (Q_1 - Q_A - Q_B)^2 + \left(I_{FS}\,\%err_{ICAL}\right)^2 \left\{ \int_{\Delta t_1} V\,dt - \int_{\Delta \mathrm{t}_{\mathrm{A}}} V\,dt - \int_{\Delta t_B} V\,dt \right\}^2 \right]^{\frac{1}{2}}$$

where

Integral terms are of the measured voltages over the three parts of the test

Q_1, Q_A, and Q_B = capacities (in ampere-hours) measured during the three parts of the test

Δt_1, Δt_A, and Δt_B = corresponding time intervals for the three parts of the test

V_{FS} and I_{FS} = full-scale voltage and current

$\%err_{VCAL}$, $\%err_{ICAL}$ = voltage and current calibration errors *as a percentage of full scale*, typically $0.078\%\,F.S.$ and $0.277\%\,F.S.$, respectively as calculated in Sections 2.2.3 and 2.2.2

SD = measured self-discharge (Wh/day), i.e., *7 SD* is the total energy loss over the stand time.

If the calibration error is due to linearity errors instead, the uncertainty in self-discharge as a percent of reading is

$$\%SD = \left((\%err_{VCAL})^2 + (\%err_{ICAL})^2 \right)^{\frac{1}{2}}$$

where $\%err_{VCAL}$ and $\%err_{ICAL}$ are the voltage and current calibration errors *as a percentage of reading*, also assumed to be typically $0.078\% F.S.$ and $0.277\% F.S.$, respectively.[f]

2.3.7 Discharge Pulse Power Capability Uncertainty

The relationship for discharge pulse power capability uncertainty as a percentage of reading is given by the following equation:

$$\%P_D = \left\{ \begin{array}{c} (\%err_{VCAL})^2 + (\%err_{ICAL})^2 + \dfrac{\%errV_{STD}^2 V_{FS}^2}{(V_0 - V_1)^2} + 2\dfrac{\%errI_{STD}^2 I_{FS}^2}{(I_0 - I_1)^2} \\ + \dfrac{(\%errV_{STD}^2 V_{FS}^2 + \%err_{VCAL}^2 V_{FS}^2)(V_{MIN} - V_1)^2}{(V_0 - V_1)^2 (V_0 - V_{MIN})^2} \end{array} \right\}^{\frac{1}{2}}$$

where

Various voltages and currents are values measured at specific points in the hybrid pulse power characterization test procedure.

$\%errV_{STD}$ = standard deviation for voltage uncertainty (as %FS)

$\%errI_{STD}$ = standard deviation for current uncertainty (as %FS)

V_{FS} = full-scale voltage (10 V for example results)

I_{FS} = full-scale current (12.5 A for example results)

$\%err_{ICAL}$ = current calibration error, typically $0.277\% F.S.$, as calculated in Section 2.2.2

$\%err_{VCAL}$ = voltage calibration error, typically $0.078\% F.S.$, as calculated in Section 2.2.3.

2.3.8 Regen Pulse Power Capability Uncertainty

The relationship for regen pulse power capability uncertainty as a percentage of reading is given by the following equation:

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[f] The derivations in Volume 1 generally assume that calibration errors are some combination of offset and linearity errors whose relative contribution is unknown, with the total expressed as a percentage of full-scale. If the error is all due to linearity, it can be properly expressed as a percentage of reading.

$$\%P_R = \left\{ \begin{array}{c} \left(\%errV_{STD}\right)^2 V_{FS}^2 \left[\dfrac{2}{\left(V_2 - V_3\right)^2} + \dfrac{Q_A^2 + Q_B^2}{\left(V_{MAX} - OCV_{regen}\right)^2 \left(Q_A + Q_B\right)^2} \right] \\ + \left(\%err_{VCAL}\right)^2 \left[1 + \dfrac{\left(V_4 - V_5\right)^2 Q_A^2 + V_{FS}^2 Q_B^2}{\left(V_{MAX} - OCV_{regen}\right)^2 \left(Q_A + Q_B\right)^2} \right] \\ + \dfrac{2\left(\%errI_{STD}\right)^2 I_{FS}^2}{\left(I_2 - I_3\right)^2} + \left(\%err_{ICAL}\right)^2 \left[1 + I_{FS}^2 \dfrac{\left(V_4 - V_5\right)^2 \left(T_A^2 Q_B^2 + T_B^2 Q_A^2\right)}{\left(V_{MAX} - OCV_{regen}\right)^2 \left(Q_A + Q_B\right)^4} \right] \end{array} \right\}^{\frac{1}{2}}$$

where

$\%errV_{STD}$, $\%errI_{STD}$, V_{FS}, I_{FS}, $\%err_{ICAL}$, and $\%err_{VCAL}$ are as defined in the previous section.

Various voltages and currents are values measured at specific points in the hybrid pulse power characterization (HCCP) test procedure

T_A and T_B = time intervals corresponding to (a) the discharge pulse and (b) the remainder of the nonzero steps in an HPPC pulse profile

Q_A and Q_B = integrated current (charge) quantities calculated during these time intervals. (See Reference 1 and Volume 1 of this report for more information.)

2.3.9 Available Energy Uncertainty

The relationship for available energy uncertainty as a percentage of reading is given by the following equation:

$$\%AE = \frac{100}{AE} \left\{ \begin{array}{c} \left(\left[\int Idt\right] V_{FS} \dfrac{\%err_{VCAL}}{100} \right)^2 + \left(\left[\int Vdt\right] I_{FS} \dfrac{\%err_{ICAL}}{100} \right)^2 + \\ \left(U_{D,P}(Q_D) \cdot \dfrac{dg}{dP}(P_D) \cdot \dfrac{dU_E}{dQ}(Q_D) \right)^2 + \\ \left(U_{R,P}(Q_R) \cdot \dfrac{dh}{dP}(P_R) \cdot \dfrac{dU_E}{dQ}(Q_R) \right)^2 \end{array} \right\}^{\frac{1}{2}} .$$

All terms in this expression are defined in a table presented in Volume 1; it is not reproduced here because of its length. Except for V_{FS}, I_{FS}, $\%err_{ICAL}$, and $\%err_{VCAL}$, which are defined as in the preceding sections, all terms are data-dependent and, thus, have to be calculated case-by-case. The Excel spreadsheet that accompanies this report on CD contains a set of worksheets showing how the various functions are extracted from the two data files (an HPPC test and a constant-current or constant-power test performed in conjunction with the HPPC test.) See Appendix B for more information on this worksheet.

2.4 Test Results for an Example Maccor Test Station

All of the various models of Maccor test systems use the same basic electronic instrumentation for data acquisition. Thus, testing performed on one type of Maccor generally will apply to any of them, although specific results may depend on channel measurement range. Tests were designed and conducted for each of the Maccor measured parameters. The purpose of this testing was generally to verify the manufacturer's claims for the inherent uncertainty (equipment uncertainty) of the primary measurements. This is critically important because subsequent calculations of uncertainty for derived parameters generally depend directly on one or more of these parameters.

Evaluation tests were developed and conducted for the measurements of temperature, voltage, and current. These evaluations were performed on several channels using a Maccor tester, and over the full range for these measurements. As an aid to future evaluations of other test stations, a simple test plan was defined for conducting this testing and is presented as Appendix C to this report. Note that this test plan was defined partly on the basis of the experience gained in conducting the testing described here; thus, this plan was not necessarily followed in all respects for the original testing.

In addition, a simple test was conducted to illustrate the phenomenon of aliasing. A rigorous test of the system's ability to reject aliasing noise was not considered useful, because the data system was designed as a data logger without serious attention to bandwidth limitations. As such, the spectral limitations necessary to reject aliasing for a selected sample rate must be enforced externally as part of the test design. Appendix A to this report includes some additional information on aliasing effects.

2.4.1 Temperature Tests

Maccor battery test systems have multiple signal channels available to measure temperature. The number of available channels varies with the model.[g] The Maccor testers use Type T thermocouples for temperature measurements. Each temperature channel includes an electronic ice point reference junction, and channels are typically calibrated from 0 to 100ºC.

During the course of the evaluation, the Maccor system software was upgraded to incorporate a high-accuracy polynomial algorithm to obtain temperature from the thermocouple voltage. The old algorithm (a straight line fit over 0 to 100ºC) resulted in a possible error of up to 2.5ºC. (See Appendix A to this report for further description of this error and the effects of correcting it.) The testing reported makes use of the upgraded software. The test was designed and conducted specifically to assess the temperature measurement uncertainty.

Eight temperature channels were end-to-end calibrated using a high-precision Omega model CL-730 temperature oven. The individual thermocouples were placed in the oven and the calibration was performed at 0 and 100ºC. The oven was then used as a signal source, and the temperature was stepped from 0 to 100ºC in 5ºC steps. At each step, the temperature was completely equilibrated (typically for about 10 minutes), and about 1000 data points were acquired for each of the eight channels. The acquired Maccor temperature data was post-processed with Matlab to determine the statistical results defined in Section 2.3 of Volume 1.

Table 5 summarizes the processed temperature data results. Figure 1 presents plots for each channel tested, showing the average error, over the 1000 points, relative to the Omega reference oven set point and at each step of temperature. Figure 2 presents plots for each channel, showing the standard deviation obtained over the 1000 points and at each step of temperature. The highest average error in Table 5 occurred for Channel 9 and is 0.55ºC with a STD of 0.03ºC. This agrees very well with the uncertainty of 0.58ºC (one standard deviation) calculated for Case 4 in Section 2.2.1, and the standard deviation of the data is comparable to the resolution of the Maccor data system analog-to-digital converter. Thus, while the claimed Maccor equipment repeatability of ±0.5ºC cannot be definitely

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[g] See Volume 1, Table 1, for a list of channels by tester.

confirmed by this testing (because it cannot be separated from the calibration error), the results appear quite consistent with the manufacturer's claims.

Table 5. Summary of Maccor temperature error for a 0 to 100ºC Range.

Channel Number	Peak Error (ºC)	Average Error (ºC)	Peak STD (ºC)
9	0.9	0.55	0.03
10	0.7	0.308	0.035
11	0.25	0.144	0.033
12	0.5	0.151	0.032
13	0.47	0.178	0.028
14	0.45	0.199	0.025
15	0.27	0.186	0.036
16	0.22	0.074	0.039
Overall average STD is 0.0219°C. Overall average error is 0.1876°C.			

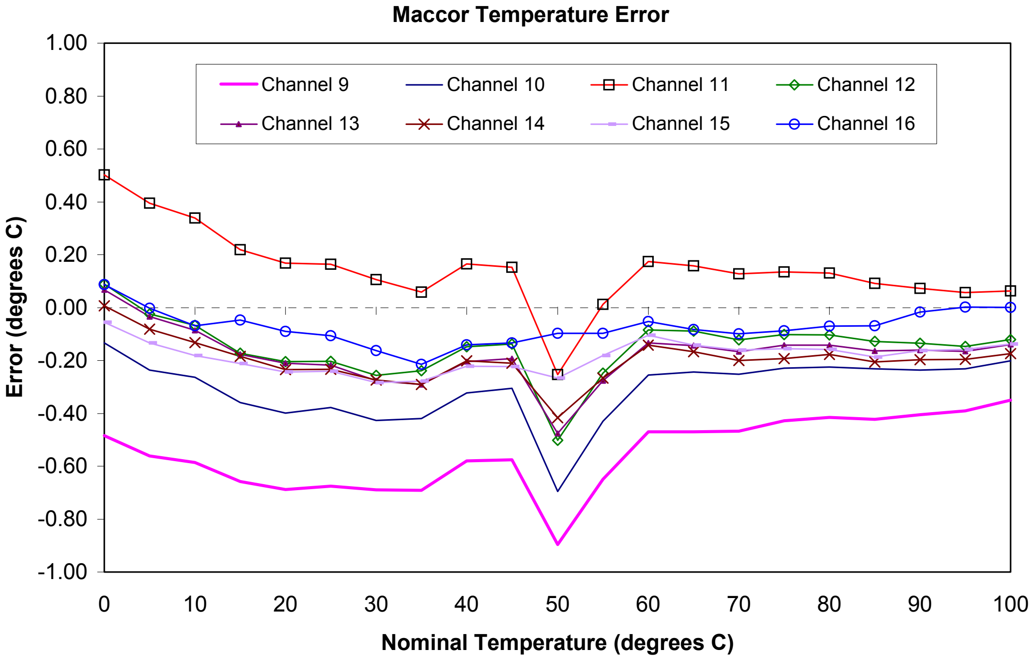

Figure 1. Maccor temperature error.

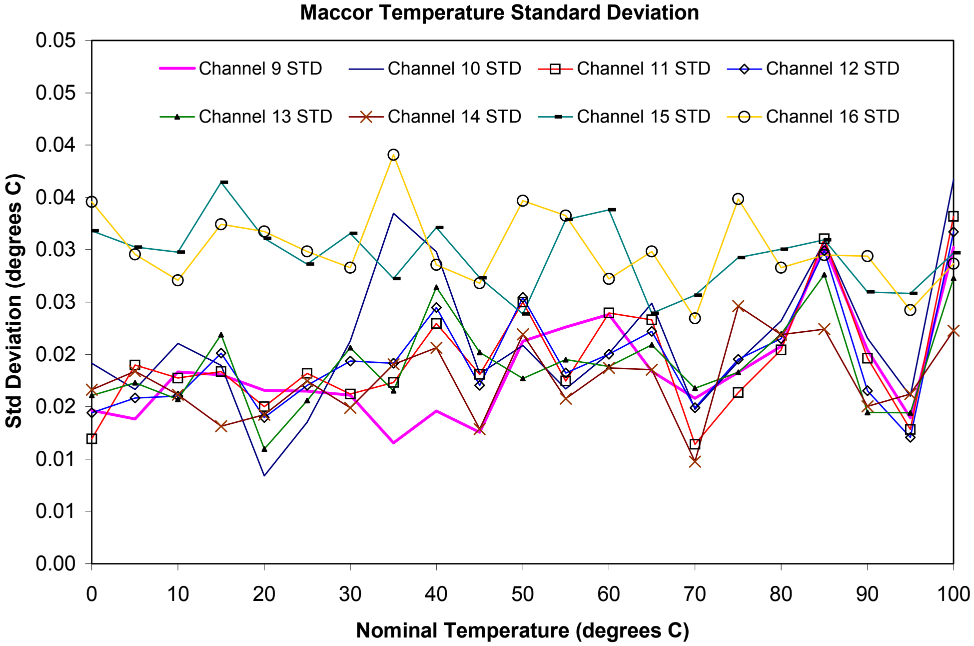

Figure 2. Maccor temperature standard deviation.

2.4.2 Current Tests

The Maccor battery testers supply a controlled current to charge or discharge the battery being tested. Each test channel in a system has an internal current shunt to measure the charge or discharge current. This measurement is used for both data acquisition and control. The number of available channels varies with the model.[h] To perform calibration on the current measurement, in the battery charge mode, the individual current channel is shorted through an external current shunt. A precision DVM measures the external shunt voltage, which is converted to a current value. The calibration external current measurements are then manually entered into the Maccor computer, which then calculates the calibration coefficients used in its data processing algorithms. In order to calibrate the discharge mode, a test battery or other power source is needed, because the Maccor can only supply energy in the charge mode. (It acts like a controlled load resistor to sink current for discharge modes.)

Because of availability and schedule limitations, testing of the Maccor current measurement was originally performed using only three 12.5-A DC channels and only in the charge mode. After the normal two-point calibration, the tester was kept in the charge current calibration configuration and was instructed to step through a range of charge current levels (0.5, 1.0, 2.0, 4.0, and 8.0 A). The tester output was held at each step level for about 2 hours, with 1000 data points acquired over this time interval. In addition, the voltage across the current shunt (50 mV/50 A) was recorded for each channel, using a precision DVM (Keithley 195A) at the beginning, 1-hour point, and at the end of the test interval for each step current level. The acquired Maccor current data were post-processed with Matlab to determine the error and standard deviation, as defined in Section 2.3 of Volume 1.

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[h] See Volume 1 for a summary of test channels for each tester.

Table 6 summarizes the measurements taken with the external shunt. It also shows the overall average error and standard deviation from all the data acquired during this initial test. Figure 3 presents plots for each channel tested, showing the average error over each group of 1000 points, relative to the average DVM measured current at each step of current. Figure 4 presents plots for each channel, showing the standard deviation obtained over each group of 1000 points taken at each step of current. A graph of the raw data for the 8-A test is presented in Appendix A.

Table 6. Summary of Maccor current (shunt) error for a 12.5-A range.

Channel Number.	Nominal Current (A)	Recorded (Start) (A)	Recorded (1 Hour) (A)	Recorded (End) (A)	Recorded (Average) (A)	Error (% full scale)
6	0.5	0.5001	0.4997	0.4991	0.499633	-2.936e-03
7	0.5	0.4999	0.5014	0.5026	0.501300	1.0400e-02
8	0.5	0.5023	0.4996	0.4987	0.500200	1.6000e-03
6	1	0.9995	0.9995	0.9993	0.999433	-4.5360e-03
7	1	1.0025	1.0043	1.0047	1.003833	3.0664e-02
8	1	1.0026	1.0013	1.0008	1.001566	1.2528e-02
6	2	1.9981	1.9978	1.9977	1.997866	-1.7075e-02
7	2	2.0102	2.0090	2.0076	2.008933	7.4164e-02
8	2	2.0018	2.0047	1.9983	2.001600	1.2749e-02
6	4A	3.9965	3.9961	3.9950	3.996033	-3.1736e-04
7	4A	4.0154	4.0199	4.0184	4.017900	1.1432e-01
8	4A	4.0089	4.0255	4.0048	4.013066	1.0411e-01
6	8A	7.9893	7.9917	7.9939	7.991633	-6.6936e-02
7	8A	8.0328	8.0337	8.0384	8.034966	2.7973e-01
8	8A	7.9996	8.0019	8.0479	8.016466	1.3173e-01

Overall average STD: 0.0011% F.S.

Overall average error: 0.0456% F.S.

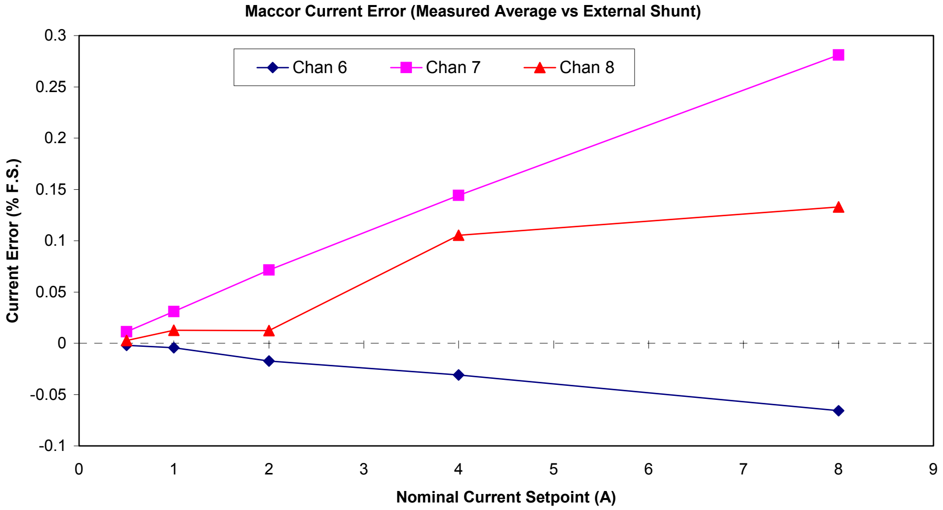

Figure 3. Maccor current error.

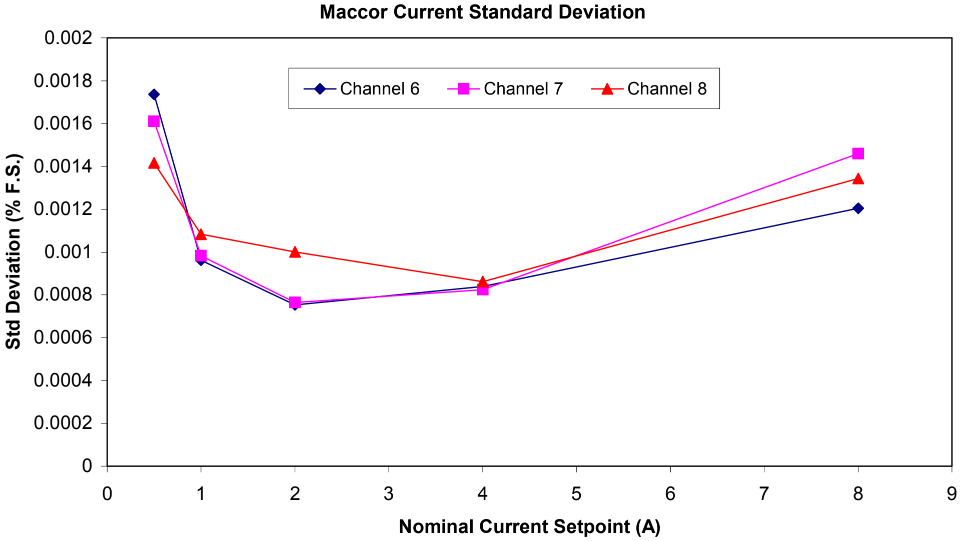

Figure 4. Maccor current standard deviation.

The overall standard deviation shown in Table 6 is comparable to the value of the least significant bit from the Maccor analog-to-digital converter, indicating excellent short-term stability under DC measurement conditions. The average error is only a fraction of the current uncertainty (0.278% F.S., one standard deviation) calculated in Section 2.2. This result is not entirely satisfactory, because the worst-case error in Figure 3 equals the uncertainty value, and the curves suggest that this value could be even greater at the full-scale current of 12.5A. This may have been due to the fact that there were two shunts involved in both the calibration and this testing, and the nominal value of the external shunt was effectively the reference for both processes. However, the same shunts were presumably used for both steps. Results could also have been affected by the fact that only three (manual) external measurements were made at each current level for each channel. These data at least suggest that the current calibration process might not be adequate to ensure that the expected uncertainty value is achieved.

As a result of this finding, some additional testing was performed later, as part of a review of Maccor calibration practices. Five channels on Maccor Tester 10 (full-scale range of ±12.5 A) were calibrated, then charge and discharge current data were collected at a total of 10 current values for each of the five channels. The calibration was performed, and the subsequent current data were acquired using a large battery connected to the channel under test. This allowed the Maccor to control the desired currents in both charge and discharge modes, thus avoiding the need for a precision current source. The calibration was later repeated, and additional data were collected on three of the five channels. All tests used the same external shunt, rated for 50 A at a 50-mV voltage drop, and all currents were measured and recorded externally using a Hewlett Packard 3456A voltmeter and a LabView data acquisition system. Table 7 summarizes the current errors and standard deviations measured for all eight cases in this testing, while Figures 5 and 6 show the current standard deviations and errors for each case at each current value.

Table 7. Maccor post-calibration current Errors and standard deviations (re-test)

Channel Number	Average Error (% FS) Discharge Mode	Average Error (% FS) Charge Mode	Average STD (% FS)
1 (first calibration)	0.0396	-0.0380	0.00266
2 (first calibration)	0.0479	-0.0490	0.00287
3 (first calibration)	0.0438	-0.0460	0.00298
8 (first calibration)	-0.0042	-0.0048	0.00513
13 (first calibration)	0.0152	-0.0112	0.00505
1 (second calibration)	0.0017	-0.0016	0.00341
2 (second calibration)	0.0017	-0.0017	0.00351
3 (second calibration)	0.0047	-0.0016	0.00355
Overall average STD: 0.00364 %FS. Overall average error: 0.0188 %FS discharge, -0.0192 %FS charge.			

The standard deviation results fall into three distinct groups, made up of the first three tests, the tests of channels 8 and 13, and the second calibrations of the first three channels. This clustering is even more apparent on the curves shown in Figure 5. It is very likely that this behavior is caused by the configuration of the HP digital voltmeter. The resolution of this instrument is 0.1 microvolt, corresponding to 0.1 mA of shunt current, or about 0.0008 % FS for the Maccor channels. However, this resolution is only meaningful if a number of constraints are observed in the use of the meter, including sample rate and power line cycle averaging. These were not clearly understood at the time of this testing, and the cases that have higher standard deviations at low currents are probably a result of sampling too fast for the meter configuration.

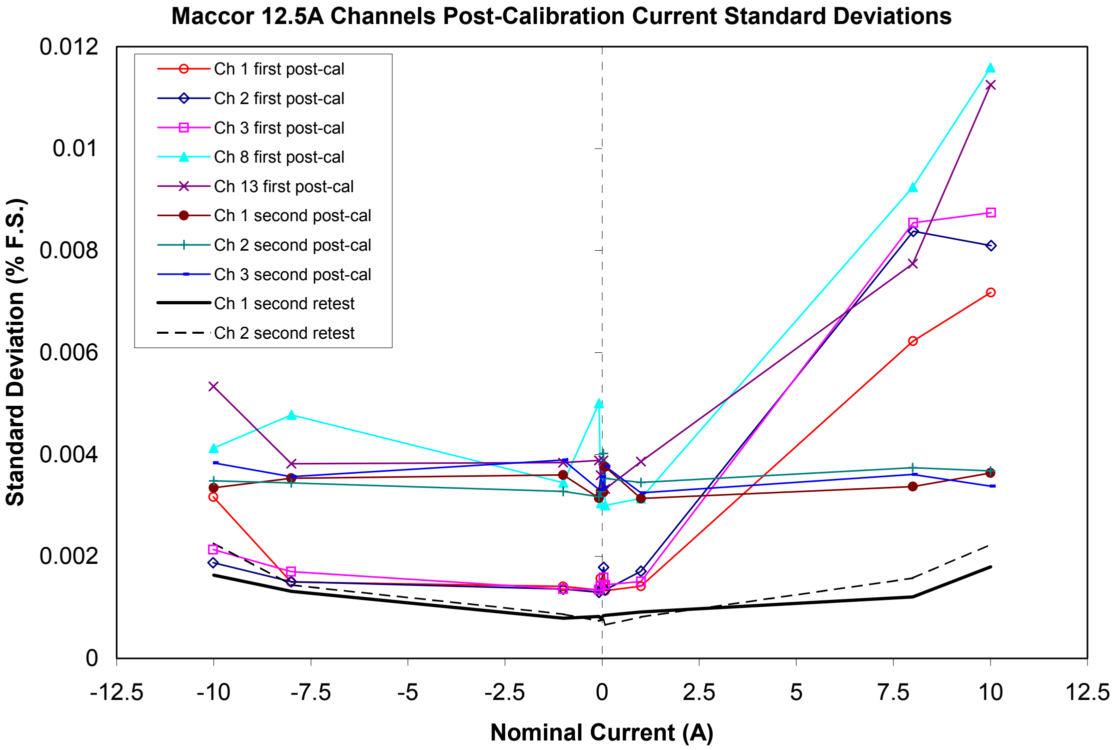

Figure 5. Maccor current standard deviations (re-test).

The higher standard deviations at high current values (8 and 10 A) are largely a result of sustaining these test currents long enough to acquire 1000 data samples (about 16 minutes). The Maccor internal current shunts apparently experience some self-heating effects when high currents are sustained for more than a few seconds. These heating effects can be either increased or reduced by the interaction between measurement times and the times used in the calibration procedure. The standard deviations are not as large at –8 and –10 A, because the test sequence: the shunts have been preheated by the preceding charge step in each case. This behavior is confirmed by analyzing only the last 500 of the 1000 data samples in each case; the resulting standard deviations are comparable to those at lower currents. The change in shunt resistance can also be detected in the time-based voltmeter data, which show a gradual increase in the actual currents, while the Maccor data show essentially no change. (The Maccor uses the same shunt for both measurement and control, and thus its data agree with its control values to a high degree of precision.) Figure 5 also shows the standard deviations calculated for two channels during a later test (labeled *second re-test*) about 3 months later without an intervening calibration. These values are lower and much more consistent, because the test intervals involved were short compared to the shunt heatup time constants, but the number of data points is too small (~100 points over ~50 s per current value) to give high confidence in the results.

The end result of testing these artifacts is that the true standard deviation of the Maccor current measurements cannot be definitely established on the basis of any of the testing performed, because it is masked by a combination of voltmeter characteristics and shunt heating effects. However, the maximum values computed are clearly less than the claimed measurement repeatability of 0.02% FS. The self-heating effects presumably did not manifest themselves in the original testing because of the very long times used (hours instead of minutes). The average standard deviation from the second set of tests in Table 7 has been used for the example calculations.

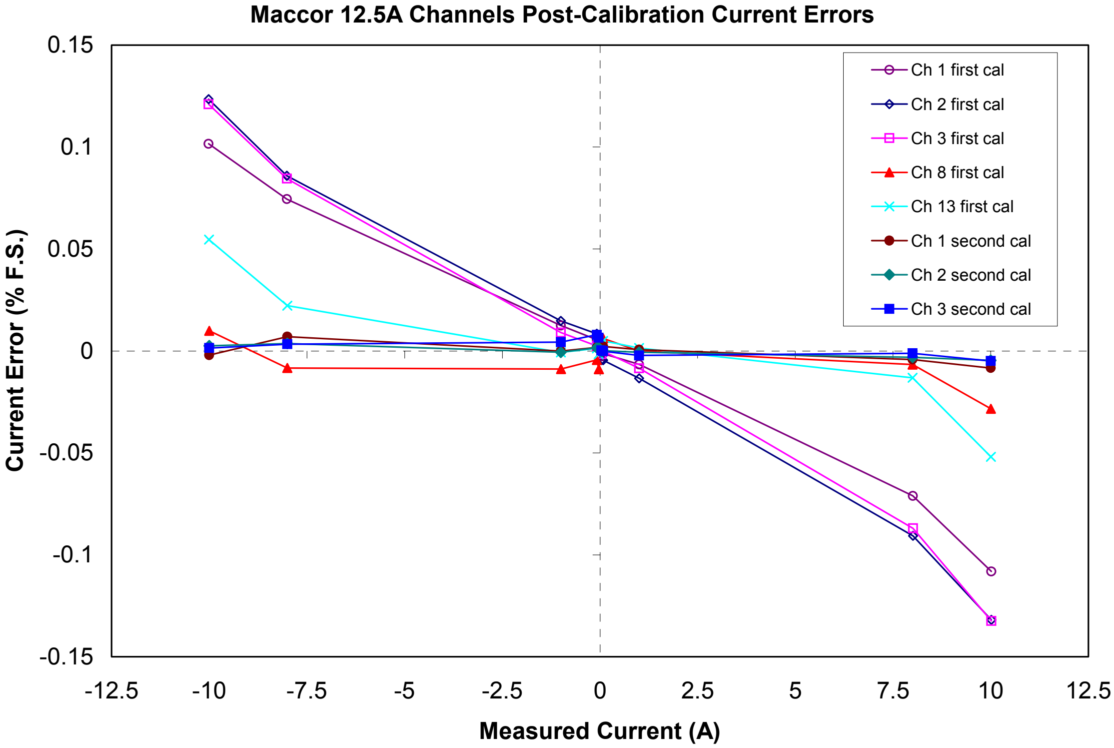

Figure 6. Maccor current errors (re-test).

The current errors shown in Figure 6 also fall into two distinct groups, with the first three tests having substantially higher errors than later tests. This is because the first calibration of channels 1, 2, and 3 was done using the nominal resistance value of the external shunt, which resulted in a linearity (slope) error in the channel calibration of about 0.1% F.S. Later tests used the actual resistance of the shunt, which largely eliminated this linearity error except at high currents, where self-heating introduces additional errors. Note that this linearity effect would be obscured in Table 7 if the errors were averaged over both positive and negative currents; instead, they are listed separately for charge and discharge modes. (The Maccor testers reverse their terminals to change from charge to discharge modes, so internal shunt errors have symmetric effects on the two modes.)

The resulting average errors are approximately equal to the Maccor repeatability of 0.02% F.S. The end result is that the combined equipment error indicated by the RSS combination of average error and average standard deviation is also barely within the 0.02% specification. However, it is clear that much of this error is actually due to calibration effects and may be subject to some improvement with improved calibration techniques. This testing reinforces the fact that seemingly minor variations in calibration practices can have clearly visible effects on measurement errors.

We recommend that this current testing be repeated using the actual calibration shunt resistance and the higher accuracy DVM now available in the EST Laboratory, so that the current calibration procedure can be optimized for best results. Also, the presence of Maccor shunt heating effects suggests that some current testing should be done on other test channel ranges, because the shunts are a critical element in the measurement chain, which are necessarily different for each distinct current range.

2.4.3 Voltage Tests

The Maccor battery test system has multiple signal channels available to measure voltage. The number of available channels and the full-scale range varies with the Maccor model.[i] For the 10 VDC full-scale channels used for testing, the calibration is performed with a precision voltage source and DVM (e.g., Dial-A-Source model DAS-56A and Keithley 195A). The five available voltage channels were subjected to a two-point calibration at zero volts and the full-scale value of 10 VDC. After calibration, all five channels were concurrently connected to the Dial-A-Source, which was then stepped from 0.5 VDC to 8.0 VDC in octave steps. At each step, the voltage was held at that level for 2 hours while the Maccor data system acquired 1000 samples of voltage data. DVM readings were not taken, and the set point of the Dial-A-Source was defined as the reference for data reduction. The acquired Maccor current data were post-processed with Matlab to determine the average error and standard deviation, as defined in section 2.3 of Volume 1.

Table 8 summarizes the voltage data results. Figure 7 presents plots for each channel tested, showing the average error over the 1000 points relative to the Dial-a-Source setting at each step of voltage. Figure 8 presents plots for each channel, showing the standard deviation obtained over the 1000 points and at each step of voltage. Table 8 also shows the overall voltage error and overall standard deviation averaged over the entire data set for all five channels tested at all five voltages. Appendix A presents a graph of the raw data obtained for the 4-V test condition during an earlier test.

Table 8. Summary of Maccor voltage error for a 10-V range.

Channel Number	Peak Error (V)	Peak STD (% full scale)
1	9.6e-04	9.5e-03
2	1.19e-03	1.2e-02
3	9.0e-04	9.0e-03
4	1.05e-03	1.05e-02
5	1.23e-03	1.2e-02
Overall average STD: 8.80e-04 %FS. Overall average error: 4.56e-03 %FS.		

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[i] See Table 1 for a summary of Maccor channel types.

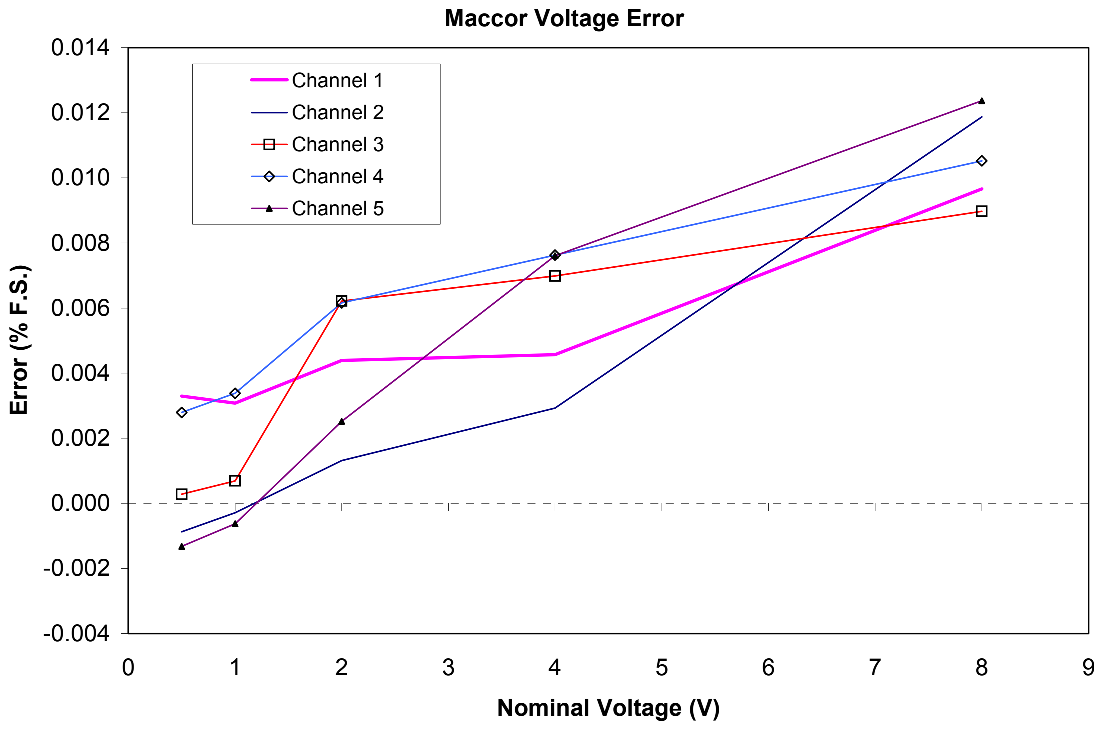


Figure 7. Maccor voltage error.

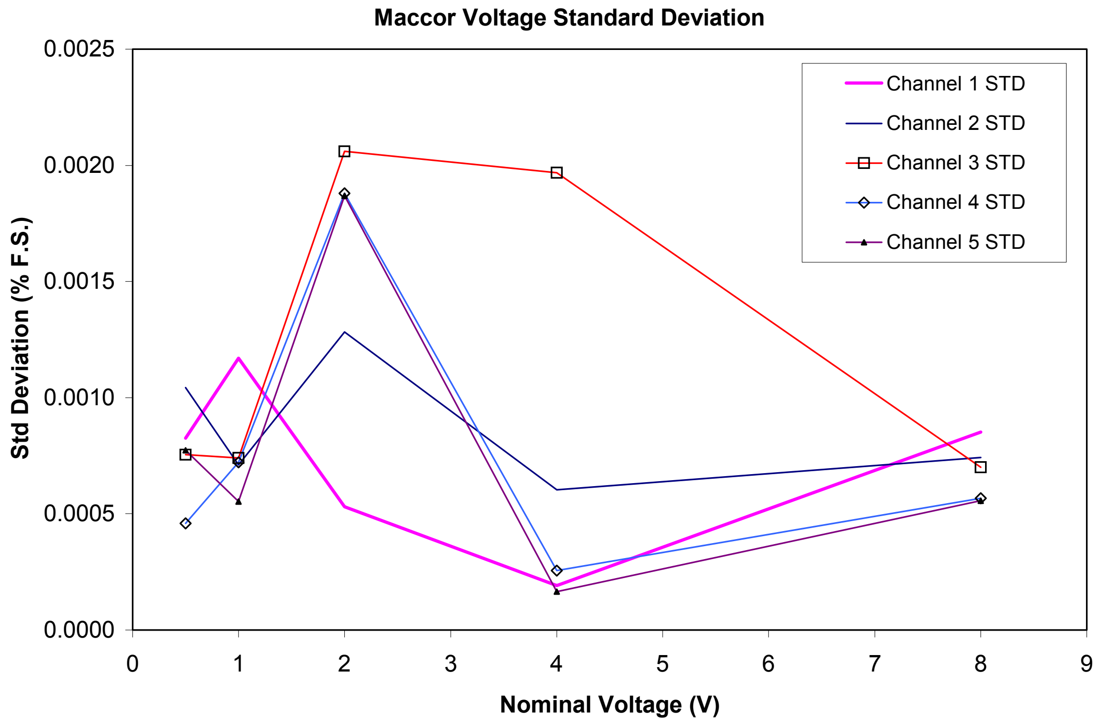


Figure 8. Maccor voltage standard deviation.

The standard deviations shown in Figure 8 are comparable to the least significant bit in the Maccor analog-to-digital converter, indicating excellent short-term measurement stability. The voltage errors shown in Figure 7 are all much less than the measurement uncertainty calculated in Section 2.2 (0.081% F.S., one standard deviation), which provides reasonable confidence that the equipment specifications are being met. However, note that these results include (but do not separately account for) the effects of the Dial-A-Source used for testing, since the errors shown are referenced to its setpoint. We recommend that this testing be repeated at some future date using a high-accuracy DVM as the reference.

2.4.4 Other Tests

Early in the conduct of this study, a brief series of tests was performed to examine the consistency of temperature control and measurement using a temperature chamber and a large number of Maccor temperature channels. Because there were multiple effects involved, including temperature chamber stability and uniformity, as well as significant calibration effects due to the use of now-obsolete software and calibration approaches, the results of this testing cannot reasonably be used to evaluate manufacturer's specifications. However, the data do provide some feel for the control consistency of a typical temperature chamber and for the stability of the Maccor temperature channels over a period of several hours. For this reason, selected data from this testing are presented in Appendix A to this report.

3. CONCLUSIONS AND RECOMMENDATIONS

The measurement uncertainty results documented in this volume build heavily on the analytical results previously published in Volume 1. Several significant results derive from the testing described in Section 2 of this volume. Some of these results led to (or can lead to) improvements in measurement uncertainty, specifically for Maccor testers, while others may have general applicability to INEEL EST Laboratory measurements. In addition, some areas may warrant additional testing and analysis to establish confidence in specific measurements.

3.1 Measurement Uncertainty Improvements

Changes made to the Maccor software during the conduct of this study result in potential improvement in temperature measurement uncertainty of about a factor of 5, from almost 3 to about 0.6°C. This change is due to two factors: (1) revision of the temperature conversion algorithm to eliminate the large error inherent in a linear approximation to the thermocouple response curve and (2) revision of the calibration software to allow multiple channels to be calibrated simultaneously using a high-accuracy reference oven. This second change permits end-to-end calibration, which is clearly superior to use of a thermocouple simulator, to be performed at acceptable cost.

Recognition that the accuracy of current measurement is severely limited by the uncertainty of the current shunts used for calibration led us to revise our process for calibrating current. This revision uses these shunts at a fraction of their rating (to avoid self-heating effects) and uses the actual (rather than nominal) shunt resistances. Together, these changes are an improvement of a factor of five in the uncertainty contribution of the calibration shunts, which results in a potential uncertainty improvement of a factor of two or more. However, subsequent testing has suggested that the shunt resistance may change enough over the calibration interval to negate some of this improvement, and higher accuracy shunts are being investigated. Additional improvements should also result from using a higher-accuracy voltmeter for calibration. Additional consideration should be given to transient heating effects in both the calibration shunts and the Maccor internal shunts to ensure that the calibration process gives the highest possible accuracy for conditions where current measurement accuracy is most important. If the calibration accuracy is optimized for steady-state measurements, it may not be optimal for the short-term transient measurements used for many of the derived parameters. It might be possible to improve this situation with improved thermal management of the shunts (e.g., improved heat sinking and temperature control), but the practicality of this has not yet been studied.

Voltage measurement uncertainty is found to be limited by the accuracy of the voltmeter used for calibration. The laboratory has acquired a higher-accuracy voltmeter. The improvement resulting from this calibration change will be evaluated when the needed changes to calibration procedures have been implemented, but a reduction of a factor of about four in voltage uncertainty (from about 0.08 to 0.02% F.S.) is anticipated.

In general, the recognition that current and voltage uncertainties are dominated by the assumed calibration errors suggests that a statistical evaluation of these in the EST Laboratory environment is needed. Such an effort could also account for the time-varying effects of calibration errors (i.e., drift), which have been neglected in this study.

Certain derived parameters (especially source impedance and pulse power capability) depend on measurements of current and voltage at very specific times during a test sequence. The uncertainty of voltage and current measurements at specific times (e.g., the 2-s point in a regen pulse) can be minimized by acquiring multiple samples at the fastest possible rate in a short interval around the desired time, and then averaging the sampled values. Such a high sample rate would be impractical due to data volume if used continuously, but it can be applied on a case basis at particular points to reduce the effects of random error.

3.2 Recommendations for Additional Testing and Analysis

Results from the testing of voltage and current performed earlier in this study generally suggest that the manufacturer's uncertainty specifications are capable of being met, provided that the calibration process is carefully controlled. Further testing of current should be performed to establish the true value of current uncertainty for the Maccor testers, particularly for test channels with different ranges than the example used here. Such testing can also quantify the improvement of using a higher-accuracy voltmeter in the process for calibrating current.

We also recommend that the voltage tests be repeated using the new higher-accuracy voltmeter when it becomes available. This will also have the beneficial side effect of eliminating any contribution to the results from the Dial-A-Source used for the testing, allowing a better estimate of the true voltage measurement uncertainty.

We anticipate that similar testing and analysis will be conducted for other types of INEEL battery test stations. The uncertainty results for these testers will be published either as supplements to Volume 2 of this report or as additional volumes.

4. REFERENCES

1. *PNGV Battery Testing Manual*, Revision 3, U.S. Department of Energy, DOE/ID-10597, February 2001.

2. Barry N. Taylor and Chris E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*,"* NIST Technical Note 1297, National Institute of Standards and Technology, 1994.

Appendix A

Aliasing Effects and Supplemental Test Data

Aliasing Effects and Supplemental Test Data

A.1 Maccor Aliasing Error Effects

The Maccor measurement channels possess only the most rudimentary provisions for noise filtering, in the form of a passive first order (single pole) filter having a 3-dB bandwidth of $[2]^{1/2}$ or ~1.4 Hz for temperature and ~1000 Hz for current and voltage channels; the corresponding maximum sampling rates for these channels are 10 samples per second (sps) for temperature and 100 sps for current and voltage.

An elementary analysis performed for a temperature channel suffices to show that such filtering is not adequate to defend against any significant noise content introduced into the channel. The convention used is to assume that the signal is "white noise" (equal energy per unit frequency), in which case the signal spectrum is equal to the filter transfer function. Applying the relationships of Equations (9), (10) and (11) of Volume 1 of this report,

$$Signal\ Power = \int_{0}^{fs/2} H(f)H^*(f)df \qquad Noise\ Power = \int_{fs/2}^{\infty} H(f)H^*(f)df$$

$$\sigma_{\%error} = 100\sqrt{\frac{noise\ power}{signal\ power}}$$

where f_s = 10 Hz (i.e., the Nyquist frequency $f_s/2$ is 5 Hz).

The Maccor filter signal power spectral density is $H(f)H^*(f) = \dfrac{2}{f^2 + (\sqrt{2})^2}$.

Using the relationship $\int \dfrac{df}{f^2 + a^2} = \dfrac{1}{a}\tan^{-1}\dfrac{f}{a} + C$ and substituting in the Signal Power and Noise Power equations above, it can be shown that the resulting error (in volts/volt) is $\sqrt{\dfrac{0.39}{1.83}} = 0.46 = 46\%$.

This result obviously takes no credit for constraints on the signal spectrum due to the thermal mass of the devices or areas whose temperatures are being measured (or the sensors themselves). In actual laboratory practice, large errors due to temperature dynamics have not been noted, which strongly suggests that the inherent filtering of the typical battery testing process results in negligible spectral content beyond the Nyquist frequency of 5 Hz. This behavior is fortunate, but the possibility of such errors must not be ignored in future testing. Low-frequency electrical noise is of particular concern because the passive first-order filter has such a gradual effect; even 60 Hz noise is only 5+ octaves above the filter cutoff frequency, and the signal input for these channels is only a few millivolts.

The first order filter in the current and voltage measurement channels is of no practical significance for aliasing because its -3 dB corner frequency of 1000 Hz is a factor of 20 (more than 4 octaves) above the Nyquist frequency (50 Hz) corresponding to the maximum sampling rate for these channels. Thus, any noise components between 50 and 1000 Hz (or greater, because the filter is so gradual) can be aliased into the measurement channel without being attenuated at all by the filter.

An example of such aliasing is illustrated by Figure A-1, which shows the result of sampling a 100-Hz sine wave input (2 V peak-to-peak with a 2-V DC offset) at 100 samples per second. The data appear to show a 2-V peak-to-peak sinusoidal input at about 1/720 Hz. In actuality, this “waveform” results from a slight difference between the sampling frequency and the frequency of the sine wave oscillator; almost any desired (low) frequency content could be produced in the data by suitably adjusting the oscillator.

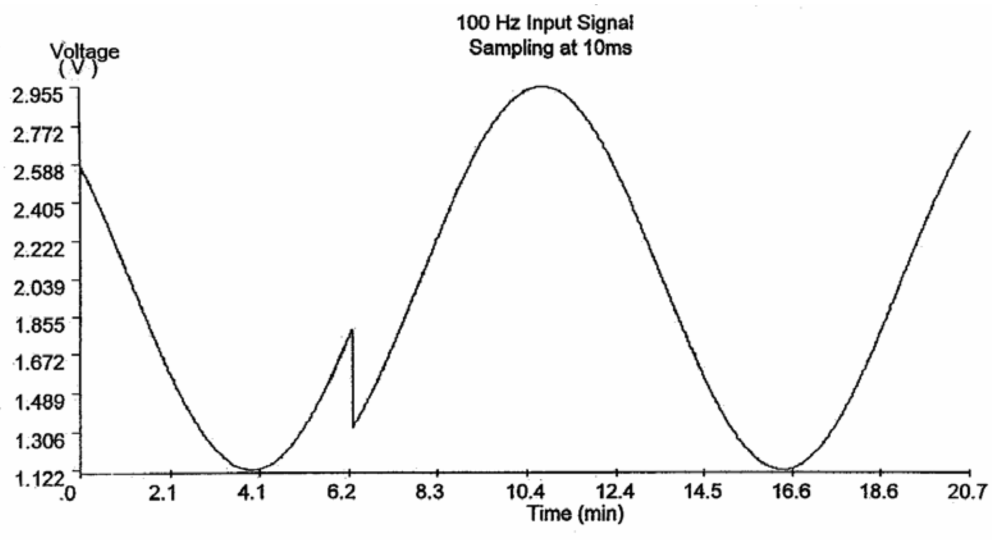


Figure A-1. Aliased data from 100-Hz sine wave input.

During the early stages of this study, a Maccor representative noted that the data acquisition software performs digital filtering on the sampled data. The characteristics of this filtering, which are performed internally and are not controllable by the user, have not been disclosed. However, post-sampling digital filtering cannot remove the effects of aliasing, as the preceding figure shows all too clearly. This is because the effect of aliasing is to reflect undesired spectral content into the same frequency region as the desired data. Once this happens, there is no way of removing the unwanted noise without also removing part of the signal being measured.

One possibly significant effect of this digital filtering is to create a certain amount of distortion of the input signal, due to the dynamics of the filter response. This can be seen by noting the increasing waveform distortion in Figure A-2 as the frequency of a sinusoidal input signal is raised from 1 to 8 Hz. The digital filtering begins to distort the waveform noticeably, even at frequencies that are low enough that little attenuation of the signal amplitude is taking place.

This waveform distortion effect is also illustrated in Figure A-3, which shows the results of sampling square waves having fundamental frequencies from 1 to 8 Hz at a sampling rate of 100 sps. The first visible effect of the digital filtering as the frequency is increased is an apparent overshoot on the leading and trailing edges of the pulse waveforms; gross waveform distortion results as the frequency is increased still further. In both of these examples, the highest (fundamental) frequency used is much less than the Nyquist frequency for a 100-Hz sampling frequency. This indicates that input spectral content should be limited to approximately 1 Hz or less (even at the highest sampling rate) if an accurate representation of the input waveform is to be obtained.

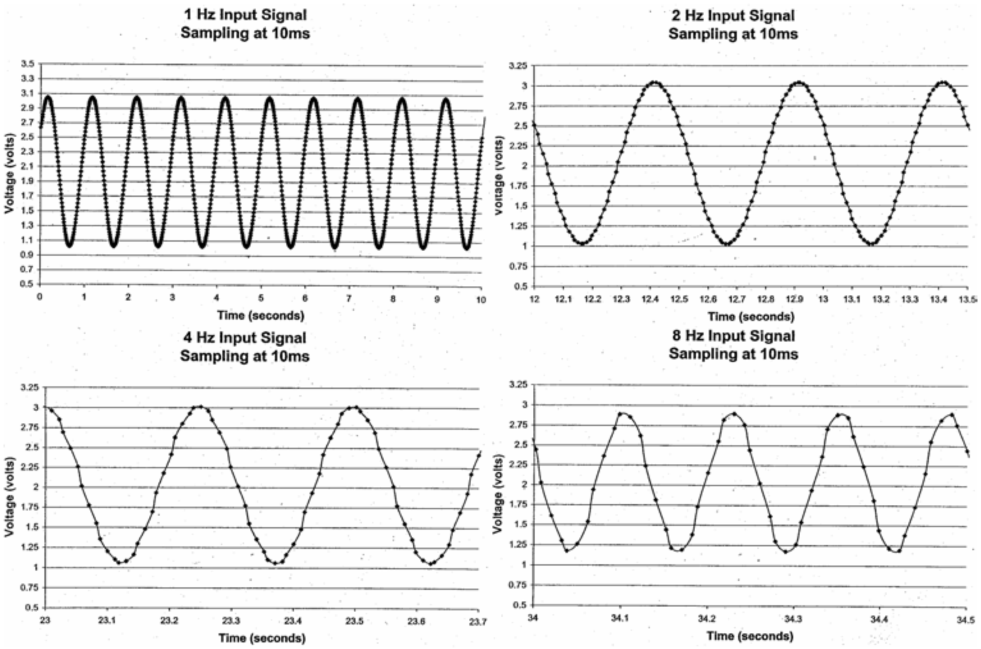


Figure A-2. Waveform distortion from digital filtering (sine wave inputs).

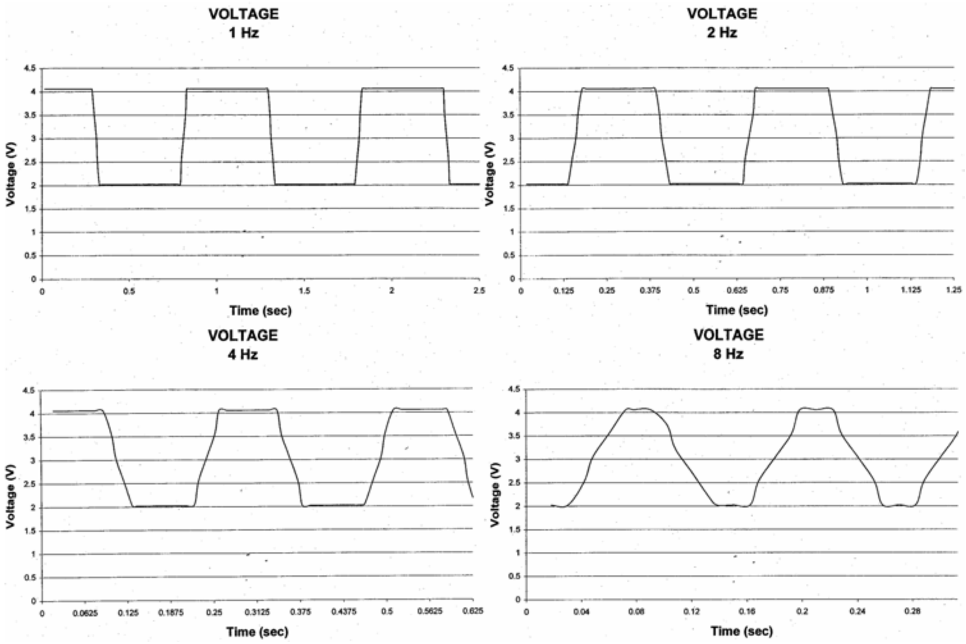


Figure A-3. Waveform distortion from digital filtering (square wave inputs).

A.2 Maccor Temperature Algorithm Error

The Maccor temperature conversion algorithm (which converts the millivolt signal measured by the data system to engineering units of degrees Celsius) was originally based on a two-point straight-line approximation, with the nominal calibration points at 0 and 100°C. However, the output of a thermocouple is not a very linear function of temperature, even over this relatively restricted interval. For the Type T thermocouples commonly used in the EST Laboratory, this nonlinear thermocouple output resulted in a deterministic error whose worst-case value was almost 2.5°C. This error is illustrated in Figure A-4, which shows the difference between the voltage output of a Type T thermocouple and a straight line between its 0 and 100°C output values.

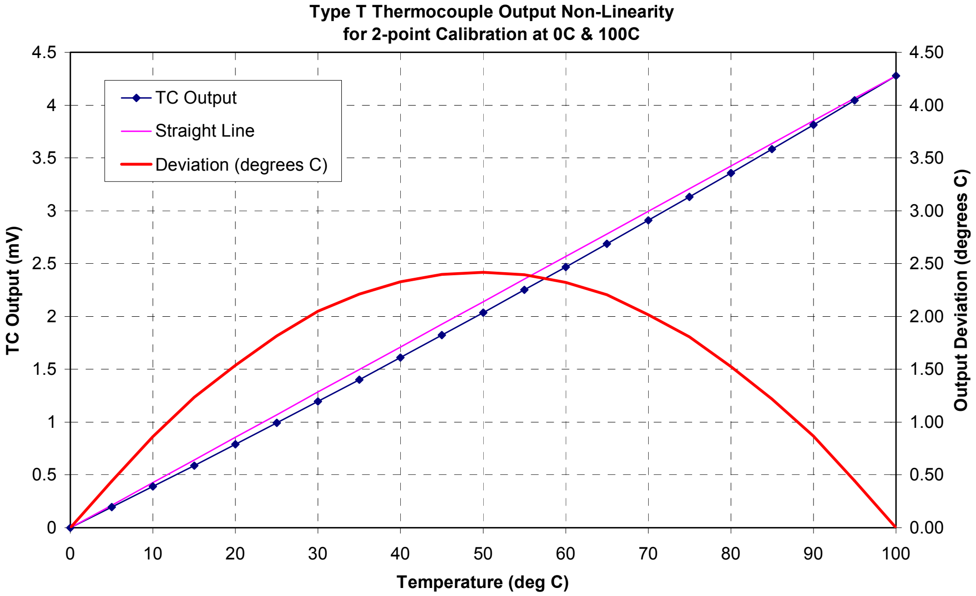


Figure A-4. Thermocouple linearity error (theoretical).

The error shown in Figure A-4 represents the theoretical value for an ideal thermocouple. The temperature step testing from 0 to 100°C described in Section 2.4.1 was originally performed before the Maccor temperature conversion software was modified. (It was repeated later using the corrected software.) These original data clearly illustrate the effects of the thermocouple nonlinearity. Figure A-5 shows the actual temperature ramp from 0 to 100°C in the left graph, where the upper curve is the setpoint of the reference temperature oven and the lower curve is the measured temperature; the deviation between these two curves is much larger in the middle of the temperature range than it is near the calibration points of 0 and 100°C. The right graph in Figure A-5 shows this deviation in more detail, where the upper curve is the difference between the temperature setpoint and the measured temperature and the lower curve results from subtracting the theoretical error curve in Figure A-4 from the measured data. As expected, this correction reduces the maximum temperature error to less than 1°C.

In principle this error could have been compensated by applying a posttest correction to the acquired temperature data, as was done for this special test. However, the logistics of performing such correction for large numbers of data files and maintaining records as to which data had been corrected rendered this infeasible. This was particularly true because the Maccor calibration was often performed over test-specific temperature ranges in order to reduce the effect of thermocouple non-linearity. During the course of this study, Maccor modified the tester software to apply a polynomial algorithm to the acquired data, which reduced this component of temperature measurement uncertainty to an apparently negligible amount (a fraction of a degree). The modified software also permits multiple channels to be calibrated simultaneously, which allows the practical use of a reference oven for end-to-end calibration. (This corresponds to Case 4 in the temperature uncertainty determination in Section 2.2.1.)

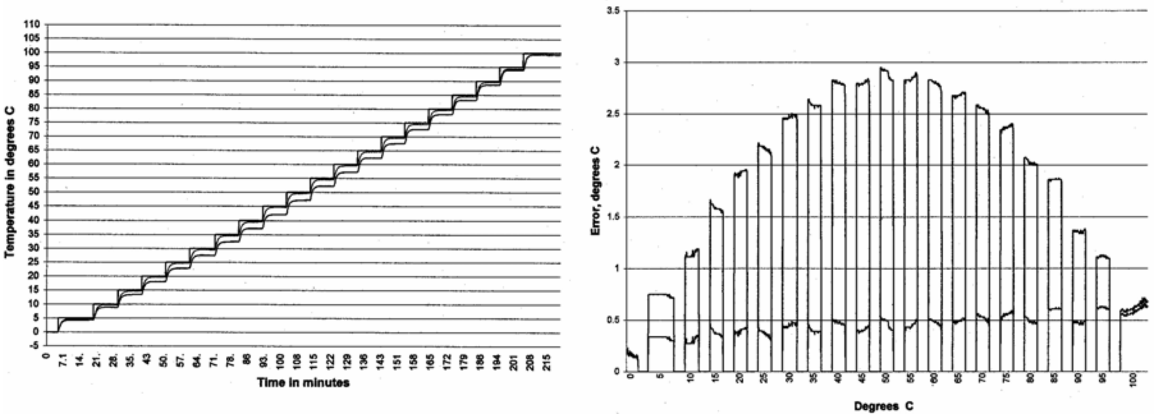


Figure A-5. Thermocouple linearity error (measured).

A.3 Temperature Chamber and Channel Consistency Test

As part of some scoping efforts performed early in this study, a repeatability test was performed using a temperature chamber and 32 Maccor temperature channels. Seven cells were placed at various locations in the chamber with four closely spaced thermocouples on each cell. Two additional groups of two thermocouples were used to monitor ambient chamber temperature at two locations. Data was acquired for three days at 50°C and one day at 5°C, with the intention of evaluating both channel-to-channel consistency for measurements and the control consistency of the temperature chamber. This was found to be impractical due to the number of experimental factors involved, but some representative samples of the resulting data are included here for information.

Figure A-6 illustrates the response at 50 and 5°C of (the same) four temperature channels attached to one of the cells. (A constant value of 45 has been subtracted from the data at 50°C to expand the graph scale in this Matlab-generated plot.) The spread between the four channels is generally within 0.25°C over the entire test at both temperatures.

Figure A-7 illustrates the temperature chamber response at 50 and 5°C, using two of the other Maccor channels measuring ambient air temperature. (A constant value of 45 has been subtracted from the data at 50°C to expand the graph scale in this Matlab-generated plot.) The spread between the two channels is within about 0.25°C over the entire test at both temperatures. The temperature chamber itself shows somewhat higher variability at 50°C than it does at 5°C (about 0.6 versus 0.1 degrees.) This could reflect some different chamber control behavior at high and low temperatures. However, it is more likely to be due simply to the fact that the 5°C data set (which occupies about a day compared to 3 days at 50°C) was taken at a different time, since the stable intervals in the 50°C data are also about one day long.

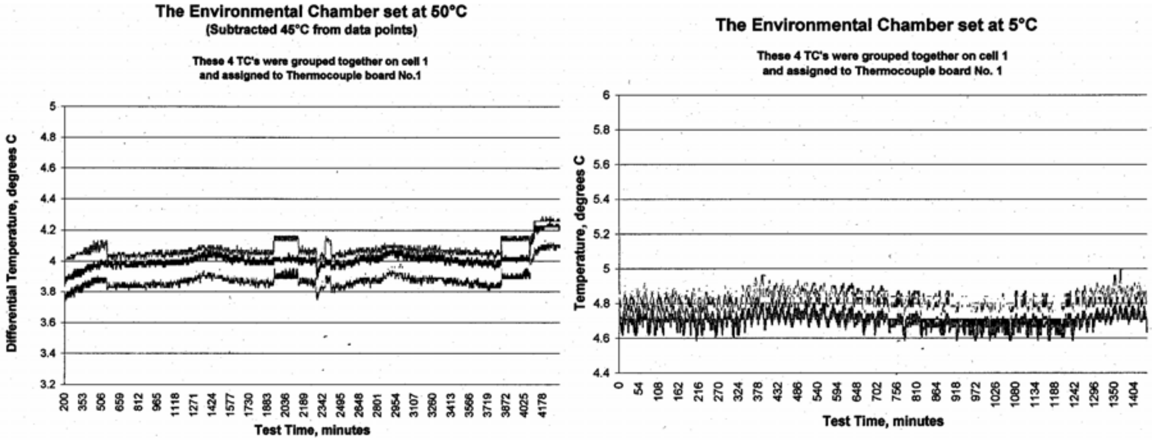


Figure A-6. Response of four Maccor temperature channels at 50 and 5°C.

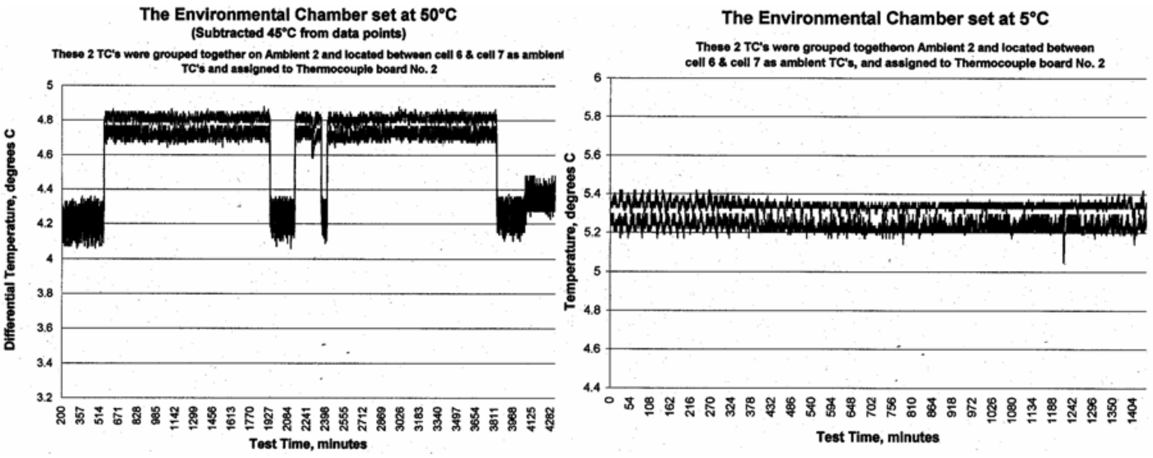


Figure A-7. Temperature chamber response at 50 and 5°C.

A.4 Consistency of Current and Voltage Test Raw Data

Sections 2.4.2 and 2.4.3 of Volume 2 of this report summarize the results of the steady-state testing performed on Maccor current and voltage channels, respectively. This generally involved the collection of about 1000 data points at each of several input values over the range of the measurement channels. A plot of one of the raw data sets for the current test is included here for information. Figure A-8 shows the 8-A data for three ±12.5-A current measurement channels. More than 90% of the data points have only one of two values, representing a variation of one least-significant bit (LSB) in the Maccor analog-to-digital converter. Only a tiny fraction of these 3000 data points differ from these two values by two LSBs, indicating the high degree of channel-to-channel consistency achieved by Maccor test channels. The total range of variation here is about 1 mA, which compares favorably to the Maccor repeatability specification of ±0.02% F.S. or ±2.5 mA for each of these channels.

Note that Figure A-8 says nothing about the actual errors associated with the current channels, because these values are taken with the Maccor data system and are thus relative to the channel calibration. Second-by-second reference data using the external voltmeter were not acquired during the original testing performed for this report. For comparison, Figure A-9 shows second-by-second data for five channels during a later series of tests described in Section 2.4.2. The total spread between the five channels is about 4 mA, or 0.032% F.S. This figure also illustrates the shunt heatup effect discussed in the text. (Only a few data points were acquired for Channel 8 due to data acquisition problems.)

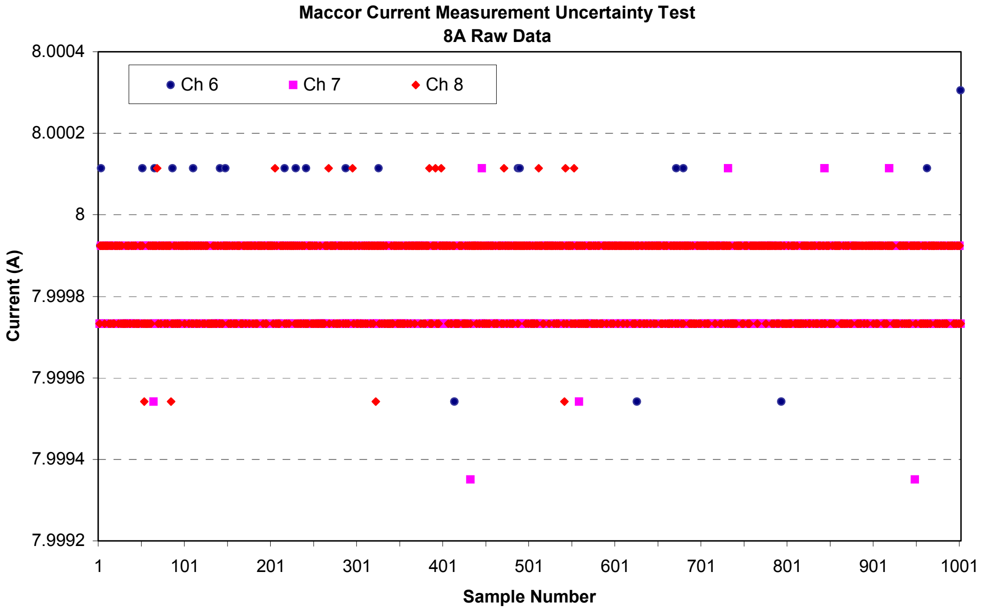


Figure A-8. Response of three Maccor current channels at 8-A DC.

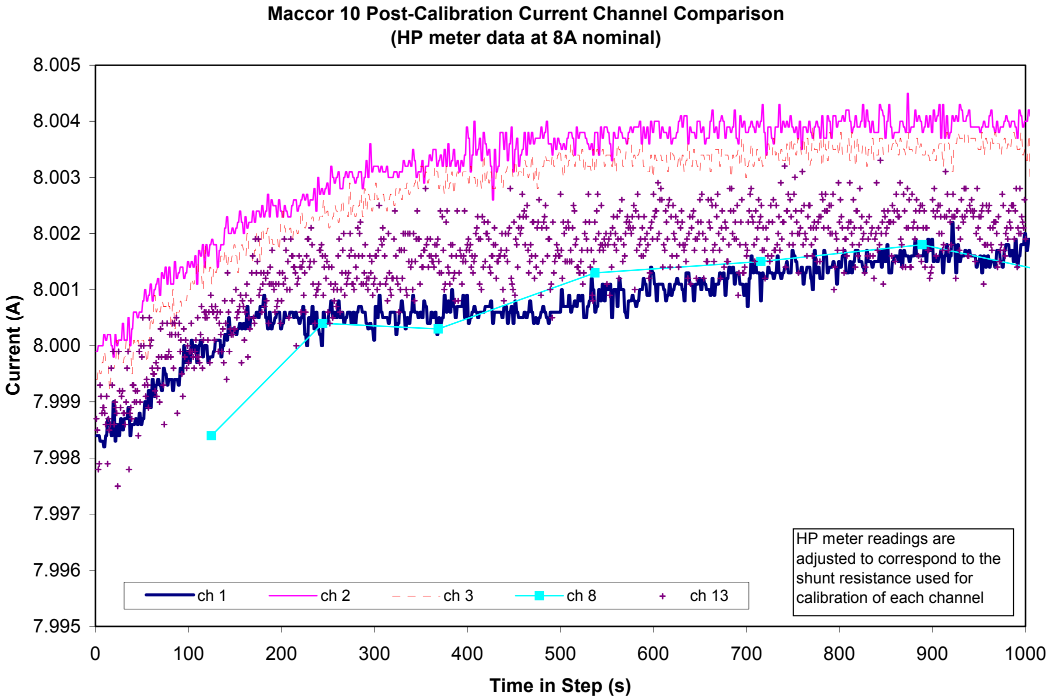


Figure A-9. Maccor channel-to-channel comparison at 8-A DC.

Figure A-10 illustrates comparable behavior for twelve 10-V voltage measurement channels, using a constant input of 4 volts from a Dial-A-Source voltage reference. These data were acquired during an early test conducted over a period of about 2 days, and it shows excellent medium-term stability of both the voltage source and the measurement channels. (The total variation observed over all 12 channels is about 11 LSBs, or 1.7 mV, compared to the Maccor specification of ±0.02%, or ±2 mV for any given channel.)

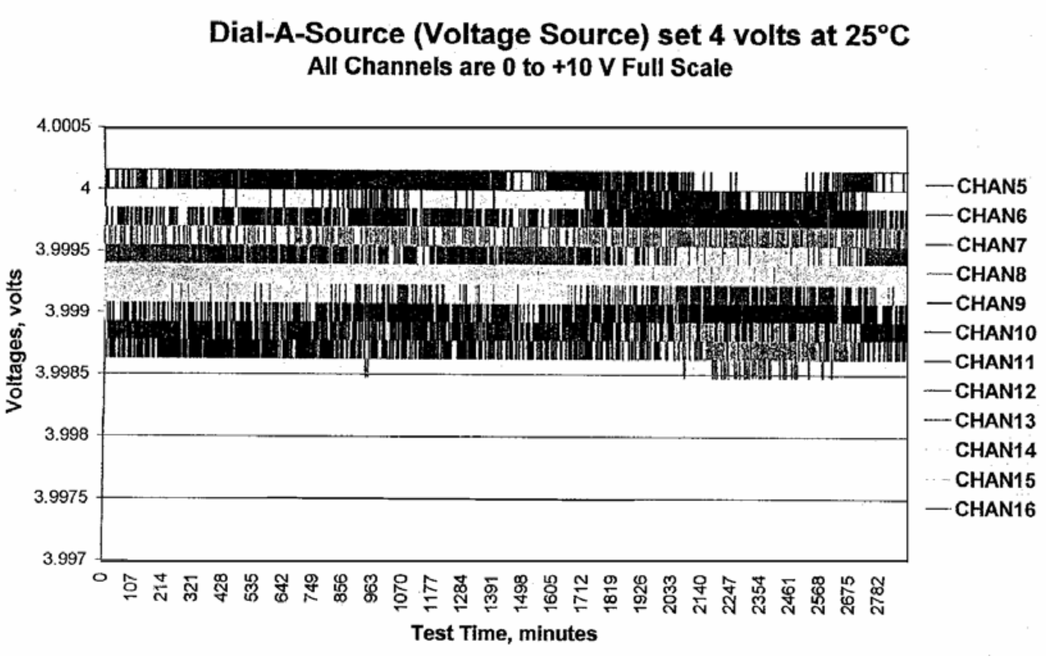


Figure A-10. Response of 12 Maccor voltage channels at 4-V DC.

Appendix B

Using the Uncertainty Calculation Spreadsheet

Using the Uncertainty Calculation Spreadsheet

B.1 Background

Calculating uncertainties manually for many of the derived parameters using the relationships developed in this report is difficult and error-prone because of the complexity of the expressions. In addition, most of these uncertainties depend on the measured values of current and voltage used to calculate the parameters, i.e., they are data-dependent. As a result, they may need to be recalculated often if a wide range of devices is tested under varying test conditions, as is the case in the INEEL EST Laboratory. To support this need, a computerized worksheet has been prepared to perform the calculations in a semiautomated fashion. This worksheet is implemented as a Microsoft Excel spreadsheet and is included on the CD-ROM that accompanies this report. The worksheet can be used to calculate uncertainties for any of the derived parameters treated in the report, provided that certain basic information about equipment and calibration errors for both current and voltage measurements is known.

Potential users of this worksheet should note two cautions regarding its use: (1) the calculations have not been independently verified to agree with the uncertainty expressions or to work over all likely ranges of data—only limited testing has been done to date with sample cases; (2) the worksheet is not intended for the casual user. The input data needed may require substantial testing, and review of equipment design may be necessary to ensure that various assumptions are satisfied. This is particularly true with respect to application of the calibration error components. For example, Volume 1 notes that the specific form of the expression derived for energy efficiency uncertainty (shown in Section 2.3.5 of this report) is valid only when the calibration errors for the discharge and charge portions of the efficiency test are independent. We discovered that the different calibration schemes used for the four types of testers in the EST Laboratory are such that this assumption is satisfied for some and probably not satisfied for others. In any event, this appendix only briefly describes how the worksheet is used. Only a modest level of expertise with Microsoft Excel is required, but the underlying calculations should be approached with care.

B.2 Description of the Spreadsheet

The spreadsheet, called UncertaintyCalculationExamples.xls, consists of 11data worksheets and a number of automatically generated graphs derived from them. The graphs are for information only and generally are not further described here. All numerical results appear on the data worksheets, typically in tan-colored cells. The data worksheets are as follows:

Name (worksheet name tab)	**Parameter Calculated**
Inputs	Total measurement uncertainty for voltage and current
Power	Power (conventional) uncertainty
Capacity	Capacity (charge) uncertainty
Energy	Energy (conventional) uncertainty
Rs	Source impedance uncertainty
Efficiency	Energy efficiency uncertainty
Self Dischg	Self-discharge uncertainty
Pdis data	Discharge pulse-power capability uncertainty

Preg data	Regen pulse-power capability uncertainty
AE data	Available energy uncertainty
CC_CP_data	None (provides inputs to available energy calculations)

Some of the worksheets are linked, so that results on one sheet depend on values entered on another sheet. These links are as follows:

- The Inputs worksheet contains the basic equipment and calibration uncertainties for current and voltage measurements. These values are used on almost every other worksheet. Changes to these values will automatically propagate to all the derived parameter calculations.
- Power, Capacity, Energy, Rs, Efficiency, and Self Dischg are not linked to each other or to any other sheets except Inputs.
- The Pdis and Preg worksheets perform their calculations independently of each other, although both are used to generate the associated graph of Discharge and Regen Pulse Power Capability and Uncertainty.
- The AE (available energy) worksheet depends on the results calculated on the Pdis, Preg, and CC_CP_data sheets. It will not give meaningful results until the appropriate data are placed on all three of the other sheets.
- The CC_CP_data worksheet does not use inputs from any other worksheet and does not calculate any uncertainty values. However, it generates results used in the available energy calculations.

In general, yellow cells on the various data worksheets indicate values to be supplied by the user. Only these places in the spreadsheet need to be modified. Note that none of the worksheet cells are locked in this version. The user should be careful not to inadvertently change other cells.

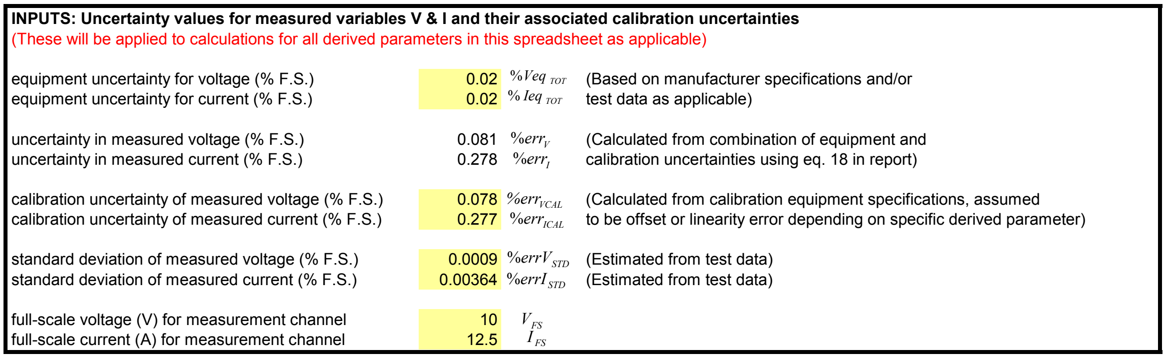
B.3 Using the Spreadsheet

Actual use of the spreadsheet is rather simple if the needed input values are available. The process can be summarized in the two steps discussed below. All illustrations here are extracted directly from the example spreadsheet. The references to colored cells in various areas may not be visible in a printed version of this report, but they should be obvious in the electronic version.

1. Enter the general values for equipment and calibration uncertainty for both voltage and current measurements on the Inputs worksheet. These must all be entered as a percentage (not a fraction) of the full-scale values of the measured variables, as shown in Figure B-1. The full-scale measurement ranges for current and voltage are also entered on this sheet. The discussion regarding the meaning of *full scale* for bipolar measurements in Sections 2.1 and 2.2.2 should be reviewed to see if uncertainties are expressed as a percentage of the measurement span or the full-scale value. For the examples in this spreadsheet, current uncertainties are expressed as a percentage of the full-scale current value (i.e., 12.5 A) rather than the measurement span (±12.5 A, or 25 A total). This can be done either way, as long as the full scale values and the % F.S. values are on the same basis.

2. Enter specific data values on the worksheet(s) for the derived parameter(s) whose uncertainty is desired. Eight of the nine derived parameters can be calculated independently of the others, so data values need only be entered on the worksheets of interest. The example worksheet for Source Resistance is shown in Figure B-2. Note that many of the worksheets include two example calculations, one labeled “good case,” the other labeled “poor case.” These examples

are intended to illustrate a range of effects of the measured variables on the uncertainty. They perform the same calculation, and new values can be entered into either case with the same result.

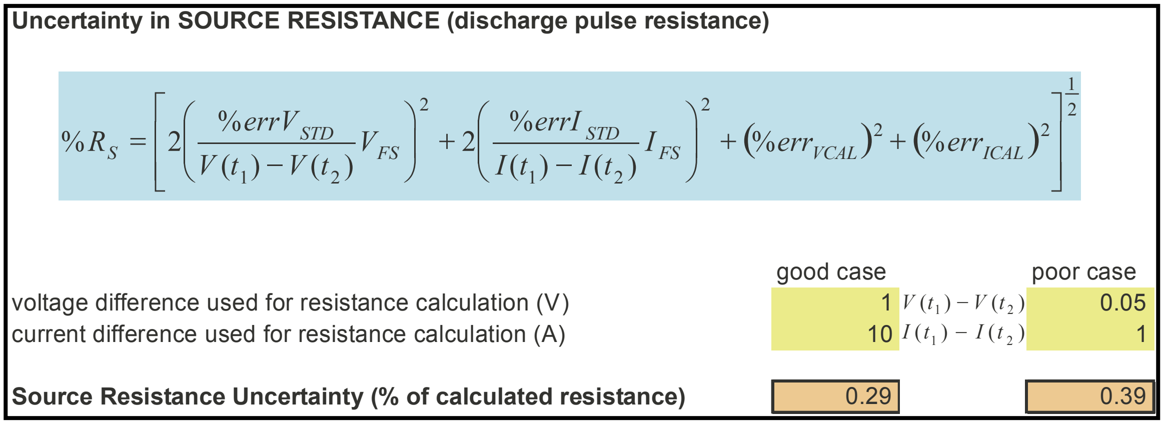


INPUTS: Uncertainty values for measured variables V & I and their associated calibration uncertainties

(These will be applied to calculations for all derived parameters in this spreadsheet as applicable)

equipment uncertainty for voltage (% F.S.)	0.02	$\%Veq_{TOT}$	(Based on manufacturer specifications and/or
equipment uncertainty for current (% F.S.)	0.02	$\%Ieq_{TOT}$	test data as applicable)
uncertainty in measured voltage (% F.S.)	0.081	$\%err_V$	(Calculated from combination of equipment and
uncertainty in measured current (% F.S.)	0.278	$\%err_I$	calibration uncertainties using eq. 18 in report)
calibration uncertainty of measured voltage (% F.S.)	0.078	$\%err_{VCAL}$	(Calculated from calibration equipment specifications, assumed
calibration uncertainty of measured current (% F.S.)	0.277	$\%err_{ICAL}$	to be offset or linearity error depending on specific derived parameter)
standard deviation of measured voltage (% F.S.)	0.0009	$\%errV_{STD}$	(Estimated from test data)
standard deviation of measured current (% F.S.)	0.00364	$\%errI_{STD}$	(Estimated from test data)
full-scale voltage (V) for measurement channel	10	V_{FS}	
full-scale current (A) for measurement channel	12.5	I_{FS}	

Figure B-1. Uncertainty Inputs Worksheet.



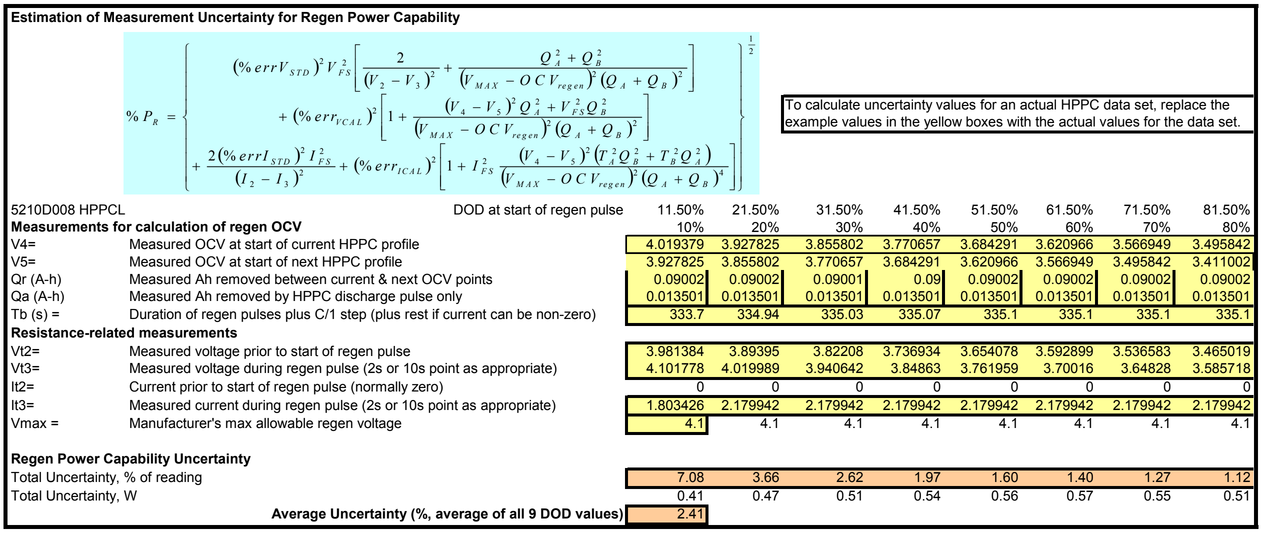
Uncertainty in SOURCE RESISTANCE (discharge pulse resistance)

$$\%R_S = \left[2\left(\frac{\%errV_{STD}}{V(t_1) - V(t_2)} V_{FS} \right)^2 + 2\left(\frac{\%errI_{STD}}{I(t_1) - I(t_2)} I_{FS} \right)^2 + \left(\%err_{VCAL}\right)^2 + \left(\%err_{ICAL}\right)^2 \right]^{\frac{1}{2}}$$

	good case		poor case
voltage difference used for resistance calculation (V)	1	$V(t_1) - V(t_2)$	0.05
current difference used for resistance calculation (A)	10	$I(t_1) - I(t_2)$	1
Source Resistance Uncertainty (% of calculated resistance)	0.29		0.39

Figure B-2. Source Resistance Uncertainty Worksheet.

Calculation of available energy uncertainty requires that data be entered on all four of the related worksheets (Pdis, Preg, AE_data, and CC_CP_data). Except for the CC_CP data worksheet, only selected data values are needed, and these can be entered by hand. Figure B-3 shows the data values required for the calculation of regen power capability uncertainty.



Estimation of Measurement Uncertainty for Regen Power Capability

$$\% P_R = \left\{ \begin{aligned} & (\% errV_{STD})^2 V_{FS}^2 \left[\frac{2}{(V_2 - V_3)^2} + \frac{Q_A^2 + Q_B^2}{(V_{MAX} - OCV_{regen})^2 (Q_A + Q_B)^2} \right] \\ & + (\% err_{VCAL})^2 \left[1 + \frac{(V_4 - V_5)^2 Q_A^2 + V_{FS}^2 Q_B^2}{(V_{MAX} - OCV_{regen})^2 (Q_A + Q_B)^2} \right] \\ & + \frac{2 (\% errI_{STD})^2 I_{FS}^2}{(I_2 - I_3)^2} + (\% err_{ICAL})^2 \left[1 + I_{FS}^2 \frac{(V_4 - V_5)^2 (T_A^2 Q_B^2 + T_B^2 Q_A^2)}{(V_{MAX} - OCV_{regen})^2 (Q_A + Q_B)^4} \right] \end{aligned} \right\}^{\frac{1}{2}}$$

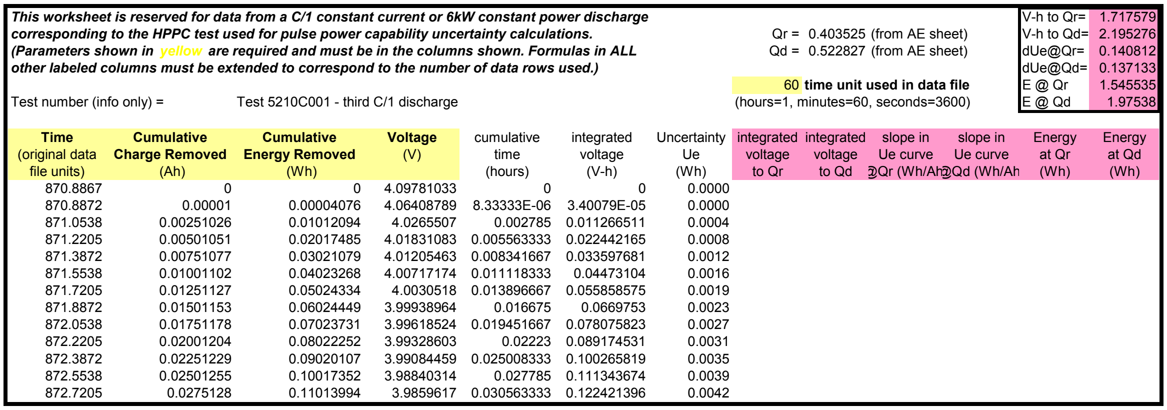
To calculate uncertainty values for an actual HPPC data set, replace the example values in the yellow boxes with the actual values for the data set.

5210D008 HPPCL	DOD at start of regen pulse	11.50%	21.50%	31.50%	41.50%	51.50%	61.50%	71.50%	81.50%
Measurements for calculation of regen OCV		10%	20%	30%	40%	50%	60%	70%	80%
V4=	Measured OCV at start of current HPPC profile	4.019379	3.927825	3.855802	3.770657	3.684291	3.620966	3.566949	3.495842
V5=	Measured OCV at start of next HPPC profile	3.927825	3.855802	3.770657	3.684291	3.620966	3.566949	3.495842	3.411002
Qr (A-h)	Measured Ah removed between current & next OCV points	0.09002	0.09002	0.09001	0.09	0.09002	0.09002	0.09002	0.09002
Qa (A-h)	Measured Ah removed by HPPC discharge pulse only	0.013501	0.013501	0.013501	0.013501	0.013501	0.013501	0.013501	0.013501
Tb (s) =	Duration of regen pulses plus C/1 step (plus rest if current can be non-zero)	333.7	334.94	335.03	335.07	335.1	335.1	335.1	335.1
Resistance-related measurements									
Vt2=	Measured voltage prior to start of regen pulse	3.981384	3.89395	3.82208	3.736934	3.654078	3.592899	3.536583	3.465019
Vt3=	Measured voltage during regen pulse (2s or 10s point as appropriate)	4.101778	4.019989	3.940642	3.84863	3.761959	3.70016	3.64828	3.585718
It2=	Current prior to start of regen pulse (normally zero)	0	0	0	0	0	0	0	0
It3=	Measured current during regen pulse (2s or 10s point as appropriate)	1.803426	2.179942	2.179942	2.179942	2.179942	2.179942	2.179942	2.179942
Vmax =	Manufacturer's max allowable regen voltage	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Regen Power Capability Uncertainty									
Total Uncertainty, % of reading		7.08	3.66	2.62	1.97	1.60	1.40	1.27	1.12
Total Uncertainty, W		0.41	0.47	0.51	0.54	0.56	0.57	0.55	0.51
	Average Uncertainty (%, average of all 9 DOD values)	2.41							

Figure B-3. Regen Power Capability Uncertainty Worksheet.

For this more complex calculation, the descriptions in the second column of the worksheet identify the specific item required. For example, the first row of entries (yellow cells) contains the measured open-circuit voltages just before each HPPC pulse profile begins. Many of these data values are the same data required for the calculation of the pulse power capability itself. In fact, the pulse power capability at the various DOD values is calculated on the worksheet, along with battery resistances and various other quantities used in the calculations. Most of these intermediate calculations are done in hidden rows. These can be revealed if the user wishes to inspect the details of the calculations. As a general rule, data values should be entered at the full resolution of the data; rounding off data values may seriously affect the calculations in some cases.

The CC_CP_data worksheet requires an entire data set from a C/1 constant current or a scaled 6-kW constant power discharge, and, thus, its data entry is more complicated. Part of this worksheet is illustrated in Figure B-4. The Excel column labels (A, B, C, etc.) mentioned in the text are not shown in the figure but are visible in Excel when the worksheet is loaded.



This worksheet is reserved for data from a C/1 constant current or 6kW constant power discharge corresponding to the HPPC test used for pulse power capability uncertainty calculations. (Parameters shown in yellow are required and must be in the columns shown. Formulas in ALL other labeled columns must be extended to correspond to the number of data rows used.)

Qr = 0.403525 (from AE sheet)
Qd = 0.522827 (from AE sheet)

60 **time unit used in data file**
(hours=1, minutes=60, seconds=3600)

Test number (info only) = Test 5210C001 - third C/1 discharge

V-h to Qr=	1.717579
V-h to Qd=	2.195276
dUe@Qr=	0.140812
dUe@Qd=	0.137133
E @ Qr	1.545535
E @ Qd	1.97538

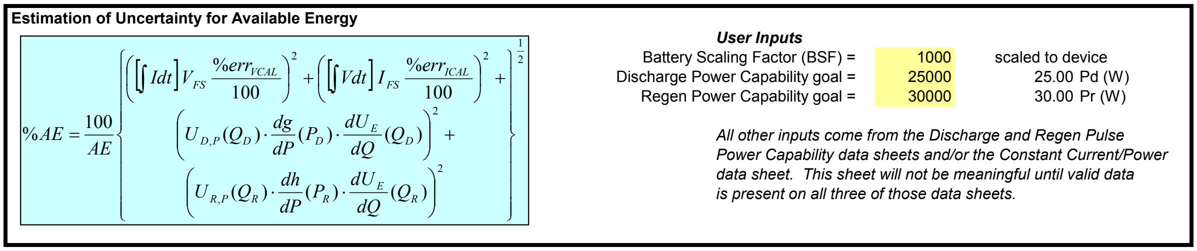
Time (original data file units)	**Cumulative Charge Removed** (Ah)	**Cumulative Energy Removed** (Wh)	**Voltage** (V)	cumulative time (hours)	integrated voltage (V-h)	Uncertainty Ue (Wh)	integrated voltage to Qr	integrated voltage to Qd	slope in Ue curve @Qr (Wh/Ah	slope in Ue curve @Qd (Wh/Ah	Energy at Qr (Wh)	Energy at Qd (Wh)
870.8867	0	0	4.09781033	0	0	0.0000						
870.8872	0.00001	0.00004076	4.06408789	8.33333E-06	3.40079E-05	0.0000						
871.0538	0.00251026	0.01012094	4.0265507	0.002785	0.011266511	0.0004						
871.2205	0.00501051	0.02017485	4.01831083	0.005563333	0.022442165	0.0008						
871.3872	0.00751077	0.03021079	4.01205463	0.008341667	0.033597681	0.0012						
871.5538	0.01001102	0.04023268	4.00717174	0.011118333	0.04473104	0.0016						
871.7205	0.01251127	0.05024334	4.0030518	0.013896667	0.055858575	0.0019						
871.8872	0.01501153	0.06024449	3.99938964	0.016675	0.0669753	0.0023						
872.0538	0.01751178	0.07023731	3.99618524	0.019451667	0.078075823	0.0027						
872.2205	0.02001204	0.08022252	3.99328603	0.02223	0.089174531	0.0031						
872.3872	0.02251229	0.09020107	3.99084459	0.025008333	0.100265819	0.0035						
872.5538	0.02501255	0.10017352	3.98840314	0.027785	0.111343674	0.0039						
872.7205	0.0275128	0.11013994	3.9859617	0.030563333	0.122421396	0.0042						

Figure B-4. Constant Current/Power Worksheet Inputs

- The Time, Ah, Wh, and Voltage data values for the complete discharge must be pasted into the appropriate (yellow-labeled) Columns A, B, C, and D in this worksheet. (Only a few rows are shown in Figure B-4.)

  - If the new data set has fewer samples (data rows) than the example data already on the worksheet, the leftover 'old' rows at the bottom of the sheet should be deleted.
  - If the new data set has more samples (data rows) than the example, the formulas in the six pink-labeled columns at the right side of the sheet (H, I, J, K, L, M) must be copied and pasted into the new rows for all these columns.
- The formulas in the six pink-labeled cells at the top of Column M must be adjusted so that the cell ranges in them correspond exactly to the data rows entered in the step above.
- A number representing the time units used in the data time column must be entered into the yellow cell H5. If the time data are expressed in hours, this value is one; it is 60 for time in minutes (as in the example) or 3600 for time in seconds. (All calculations in this worksheet use hours.)

The only entries required on the AE_data (available energy) worksheet are the power and energy goals for the battery under test and the associated battery size factor (BSF), as shown in Figure B-5. These quantities are not measured data. They are the discharge and regen power capability goals applicable to the device under test and the number of such devices that the manufacturer determines are necessary to meet these and other goals. See Reference 1 for an explanation of these quantities.



Estimation of Uncertainty for Available Energy

$$\%AE = \frac{100}{AE}\left\{ \begin{array}{c} \left(\left[\int Idt\right]V_{FS}\frac{\%err_{VCAL}}{100}\right)^2 + \left(\left[\int Vdt\right]I_{FS}\frac{\%err_{ICAL}}{100}\right)^2 + \\ \left(U_{D,P}(Q_D)\cdot\frac{dg}{dP}(P_D)\cdot\frac{dU_E}{dQ}(Q_D)\right)^2 + \\ \left(U_{R,P}(Q_R)\cdot\frac{dh}{dP}(P_R)\cdot\frac{dU_E}{dQ}(Q_R)\right)^2 \end{array} \right\}^{\frac{1}{2}}$$

User Inputs

Battery Scaling Factor (BSF) = 1000 scaled to device
Discharge Power Capability goal = 25000 25.00 Pd (W)
Regen Power Capability goal = 30000 30.00 Pr (W)

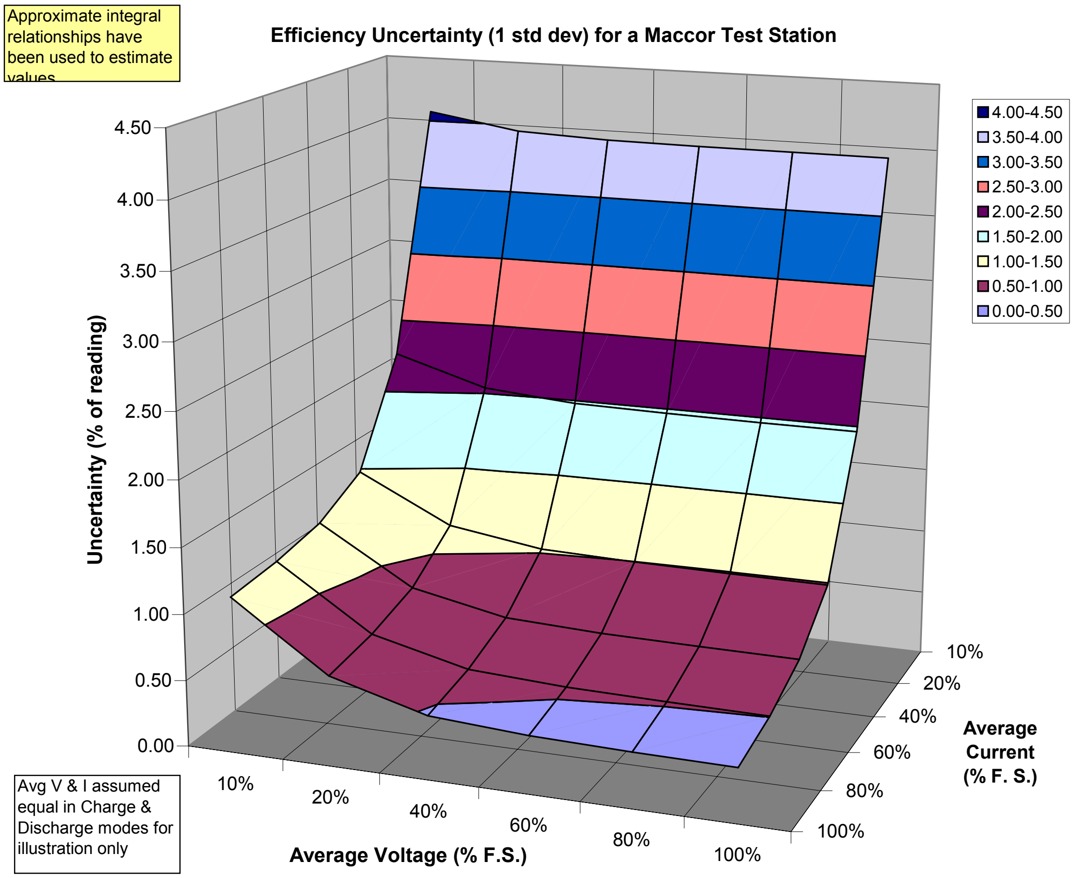
All other inputs come from the Discharge and Regen Pulse Power Capability data sheets and/or the Constant Current/Power data sheet. This sheet will not be meaningful until valid data is present on all three of those data sheets.

Figure B-5. Input Portion of Available Energy Worksheet.

Once the required measurement uncertainties and data values are entered, the associated uncertainties of the derived parameters (in percentage of reading, i.e., a percentage of the calculated value of the derived parameter) are displayed in the tan-colored cells on the appropriate worksheet(s). In some cases, uncertainties are also calculated and displayed in units of the parameter. For example, the available energy worksheet displays the resulting uncertainty as a percentage of the calculated available energy as well as in units of energy (Wh) and energy scaled to the full-size battery system level (also in Wh). In almost all cases, the results depend on the magnitude of measured data values as well as the channel measurement uncertainties, so the results should not be treated as generally applicable, even to a particular tester.

In addition to the results calculated from the specific data values entered by the user, some of the worksheets for simpler derived parameters include tables that calculate uncertainty of that parameter for various fractions of the current and voltage measurement ranges. These tables are then presented in graphs. The graphs can be used for a quick estimate of the uncertainty likely to result for that parameter. Note that some of the calculations rely on approximations, which are stated on the worksheets. Users should be cautious in making use of these approximate calculations. However, the graphs resulting from them (which are not affected by the specific data the user enters on the worksheet) illustrate the general behavior of the uncertainty for these derived parameters. Figure B-6 shows a example graph for energy efficiency.

The graph of uncertainty bounds for discharge and regen power capability uncertainty (on worksheet tab Pdis&Preg_(W) is generated from the user-entered data and is thus specific to the actual data on these worksheets.



Approximate integral relationships have been used to estimate values

Avg V & I assumed equal in Charge & Discharge modes for illustration only

Figure B-6. Generic Energy Efficiency Uncertainty Graph.

Appendix C

INEEL Measurement Uncertainty Test Plan

INEEL Measurement Uncertainty Test Plan

C.1 Background

The intent of this test plan is to acquire data for the calculation of measurement uncertainty for a battery test station. We intend such testing to be done on each type or design of test station. It need not necessarily be performed on each instance of an identical test station, although this may be desirable for obtaining additional channel data. Data are normally acquired for measurements of temperature, current, and voltage. To be usable for these measurements, the data must satisfy the following conditions: (a) the tester data acquisition system must be properly calibrated; (b) a statistically significant number of data points must be collected at each measurement value; and (c) the measurement values used must be distributed over the range of each measurement channel. In addition, multiple measurement channels should be used when they exist.

The general form of the measurement uncertainty expression to be used for a measured parameter is given by the following equation:[j]

$$\%Perr_{TOT} = \sqrt{\left(\%err_{CAL}\right)^2 + \left(\%Peq_{TOT}\right)^2} \quad .$$

This equation indicates that the measurement error for a parameter can be computed as the root sum square (RSS) of the calibration and equipment errors, provided that any external transducer error is either neglected or combined with the calibration error. The equipment error term can be computed based on test data using the equation [k]

$$\%Peq_{TOT} = \sqrt{\left(\%Perr_{STD}\right)^2 + \left(\%\overline{P}_{ERR}\right)^2 - \left(\%err_{CAL}\right)^2}$$

where the first two terms represent the standard deviation and average errors obtained from a set of test data acquired under the conditions described above. The third term involving calibration error is generally set to zero for conservatism in this calculation. To avoid excessive conservatism, the calibration should use the same external measurement equipment used for the actual testing.

C.2 Equipment Required

Table C-1 is a list of equipment based on the characteristics of INEEL battery test systems and may need to be modified for other types of test and measurement systems.

C.3 Procedure

The following general procedure is used for each of the three measured parameters (temperature, current and voltage). Note that data for each measured parameter must be acquired separately due to the required test configuration. This provides the ability to calibrate and acquire data for each parameter at different times if this is desirable or necessary due to equipment availability.

---

[j] This is the generic form of Equations (22), (27), and (30) in Volume 1 of the uncertainty report. See Section 2.4 of Volume 1 for more information on the derivation of this relationship.

[k] This is Equation (17) in Volume 1 of the uncertainty report.

Table C-1. A list of equipment based on the characteristics of INEEL battery test systems.

Description	Specifications	Parameter(s) Measured
High-precision temperature reference oven	Omega CL-730 (or equivalent)	Temperature
High-precision digital voltmeter	HP 3458A (or equivalent)	Voltage, Current
Current shunt	Rated accuracy 0.25% or better, current rating at least 4 times the maximum test channel current	Current
High-stability adjustable voltage source	DAS-56A Dial-a-Source or equivalent	Voltage
External power/energy source	Battery or other source able to source or sink required current for time needed for test	Current

Procedure

A. For each measurement channel to be used, calibrate the channel using the normal calibration procedure (with the additional provisions noted in Section C.6, Calibration Requirements).

B. At each value over the range of the measured parameter, perform the following steps:

  1. Provide a reference input value. (See Section C.4, Choosing Test Input Values, for more information.)
  2. Allow time for this input to stabilize
  3. Acquire a large number of measurements (~1000) of the stable input value using the tester data acquisition channel. (See Section C.5, Data Acquisition Considerations, for more information.)
  4. For current and voltage measurements only, acquire a similar number of reference measurements at the same time, using the external digital voltmeter (and shunt, for current) used for calibration. (See Section C.5, Data Acquisition Considerations, for specific requirements regarding these measurements.) For temperature testing, the temperature oven setpoint is used as the reference value, so no external measurements are required.

C. Repeat (B) for each input value over the measurement range.

D. Repeat (A) through (C) for each measurement channel to be used.

E. Repeat (D) for each measurement parameter to be tested.

C.4 Choosing Test Input Values

The input values chosen for each parameter should cover most of the measurement range. A minimum of five different values should be used; six to eight would be preferable. These can be (but need not be) evenly spaced over the range. For current and voltage, we recommend that values between 2 and 90% of the full-scale measurement value be chosen; for example, a minimum set of values could be

3,10,20,40, and 80% of the maximum value. The exact values to be used are not critical, because all results will be compared to the reference inputs.

Current is normally a bidirectional measurement parameter whose behavior cannot be assumed to be symmetric about zero. Consequently, data for the charge and discharge modes must generally be acquired separately.[l]

C.5 Data Acquisition Considerations

For temperature measurements, multiple channels can be tested simultaneously because no external reference measurements are required. (Depending on tester software, it may or may not be possible to calibrate multiple temperature channels simultaneously.) A thermocouple for each measurement channel to be tested is placed in the reference oven just as is done during calibration. At each temperature value, the reference oven must be allowed to stabilize before measurements are made. The tester measurement channels at any convenient rate can then acquire the required number of temperature data points. This generally requires the use of a dummy test program whose only purpose is to allow the data to be acquired; the tester need not have a load connected unless it cannot acquire data without one.

For current and voltage measurements, typically only one channel can be tested at a time because the same external voltmeter (and shunt) is used for all external reference measurements. Voltage measurements are made by connecting the external voltage source to both the test channel input and the external voltmeter. After each voltage input value is stabilized, data points can be acquired at a rate that is generally limited by the external voltmeter. (See Section C.6, Calibration Requirements, for more information.) Again, the tester program is only required to measure the voltage; no actual load evolutions are needed.

Current measurements require the tester to either source or sink the actual current being measured, which normally requires the presence of an external power/energy source (battery or another tester) for proper operation. The tester itself is used to control the current being measured.[m] Hence, for current measurements a test program containing constant current steps is used for data acquisition. A sequence of such steps can be programmed so that the entire range of measurement values is acquired in one test, provided that the steps are separated by suitable rest intervals. To minimize the effects of shunt self-heating on the results, the sequence of current steps should be ordered from the smallest to the largest value; any return to lower current values should be after a rest of at least one hour.

Also, the data acquired during the first several minutes at high-current values cannot be used for statistical purposes, because the progressive shunt heatup skews the resulting standard deviation values. These steps must be longer than would otherwise be needed so that the desired number of points is still available. (Earlier testing required more than 12 minutes for the shunts in a Maccor 12.5A channel to stabilize at 8-A and 10-A currents.) It may be desirable for the high-current steps (i.e., 50% or more of full-scale current) to be programmed as two steps at the same current; the first of these can acquire data at

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[l] If the design of the tester measurement channel is such that the same measuring circuitry is used for both charge and discharge modes, with current passing through an internal shunt in the same direction in both modes, and if only one set of calibration coefficients is used for both modes, then only one mode needs to be tested. The Maccor testers satisfy the first of these conditions but not the second.

[m] This approach is used in preference to an external precision current source because it is much simpler to implement, and in practice the testers are always used this way. This does introduce some additional random variability in the data due to the tester's control precision, but most INEEL testers are very good at controlling constant currents.

a lower rate if desired.[n] The reference measurements of current are determined by converting the external voltmeter readings using the actual value of the external current shunt, which must be used at less than 25% of its rated current to avoid self-heating.

C.6 Calibration Requirements

For temperature measurement channels, there are no special calibration issues other than making sure that both the reference temperature oven and the thermocouples in it are stabilized at the temperature being used.

For current measurement channels, special care must be taken to avoid test artifacts resulting from shunt effects, especially shunt self-heating. For this special testing only, current calibration at high current levels should be based on the measured value after several minutes of sustained current.[o] Also, the same external current shunt must be used for both calibration and the later acquisition of the measured data points, because use of different shunts will create an artificial error component in the averaged results. The actual resistance of this shunt (as supplied by the Calibration and Standards Laboratory) must be used for determining current in both the calibration and data acquisition phases of this testing, and the current applied to this shunt must not exceed 25% of its rated current, in either case. (This restriction is to ensure that no significant self-heating occurs in the external shunt.)

For both calibration and use of voltage and current measurement channels, meaningful results critically depend on proper setting of the high-precision digital voltmeter. The meter must be set so that it acquires data with its highest possible accuracy. Among other considerations, this generally requires the longest power line averaging interval possible. This greatly restricts the maximum allowable data rate. Data acquisition intervals of more than 1 second will be required. Sample data must be reviewed carefully to be sure that all samples are independent. If the sampling rate is too fast for the other meter settings, the meter will return the contents of its data buffer multiple times with no warning of a problem.

C.7 Test Conditions

For each type or model of tester for which data are to be acquired, the specific test conditions to be used should be defined using a table similar to the one on the following page:

---

[n] For simplicity this additional "shunt stabilization" step can be used for all current levels if desired.

[o] This calibration approach is not desirable for normal testing because sustained high currents (i.e., at a large fraction of the channel range) are the exception in most INEEL battery testing. In this particular case, the need to acquire a high number of data points at each sustained current value make it necessary to do the calibration under similar conditions, because some self-heating will necessarily take place in the tester's internal shunt(s).

Tester Name: ________________________________							
Temperature (Range ____ to ____ºC)							
Channel Number	Values of Measured Parameter to be Used for Test						
Current (Range _____ to _____A)							
Voltage (Range _____ to _____V)							