Office of Vehicle Technologies

Life Validation Testing Protocol Development

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This presentation does not contain any proprietary or confidential information

Outline

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Purpose, Barriers, and Approach

- **Purpose:**
  - Accurately estimate battery life with uncertainty bounds.
  - Develop, apply, and evaluate new accelerated aging protocols and analysis methodologies for Technology Life Verification Testing (TLVT).
- **Barriers:**
  - *Focus area:* Accurate Life Prediction
- **Approach:**
  - Verification testing with commercial cells
  - Life Model Development
  - Test Manual Development
    - Revisions from published version (February 2005)

Previous Reviewer Comments

- **Use NiMH data (with known life) to check the model's validity.**
  – Model was still under development in FY07.
- **Show methodology's application to existing Gen2 chemistries.**
  – Insufficient temperature spread in the Gen2 data for accurate life prediction (only two temperatures for calendar-life cells).
- **Factor in welding resistance to the testing error.**
  – The new error model includes a generic manufacturing effect, which would include welding resistance.
- **Provide methodology (with default models) to cell makers so that they can predict life of their technology.**
  – Model and methodology have been successfully used by some of the FreedomCAR developers in beta tests.

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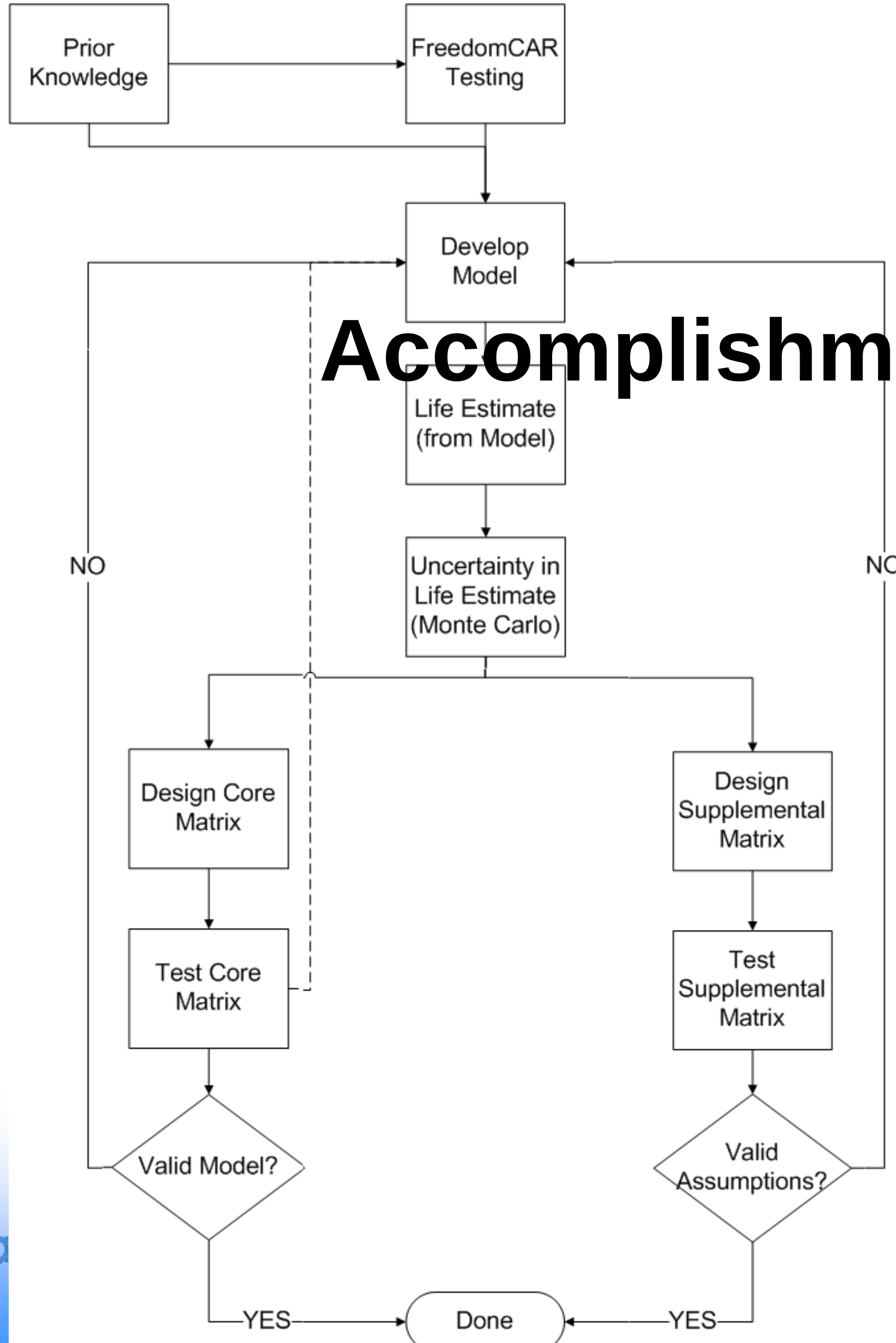
TLVT Accomplishments

- **Initial manual validation testing with 7 Ah Li-Ion cylindrical cells was completed in FY07.**
- **Lessons learned are being incorporated into a manual revision (to be published by August 2008).**
  - Testing protocols and requirements made more synergistic with FreedomCAR procedures.
  - Additional TLVT matrix designs were developed to accommodate resource limitations.
  - Improved life model and software tool.
  - Developed error model with lack of fit statistic and improved determination of measurement uncertainty.
- **Validation effort of the supplemental life matrices is planned for FY08.**

TLVT

Accomplishments



TLVT Accomplishments (cont.)

Manual Development

- **The goal of TLVT is to verify battery life capability at the target confidence level of 90% within one or two years of testing.**
  - Example: FreedomCAR requirement of 15-year, 150,000 miles.
- **Three stages of battery life verification:**
  - Stage 1 – Standardized testing with typical FreedomCAR procedures and requirements.
  - Stage 2 – Demonstrate a battery technology's readiness for transition to production (TLVT stage).
  - Stage 3 – Demonstrate a complete battery system will meet life target for the 90^{th} percentile customer.

TLVT Accomplishments (cont.)

Manual Development

- **Prerequisites to the second stage (i.e., TLVT stage):**
  - Life-limiting wearout mechanisms must be identified and characterized.
  - A life model (empirical or physics-based) that accurately reflects typical degradation over time.
  - An error model that accounts for both measurement uncertainty and manufacturing variability.
  - Sufficient supply of batteries, test channels, and temperature chambers for core and supplemental aging experiments.

TLVT Accomplishments (cont.)

Manual Development

- **Core Life Test Matrices**
  - Minimal – limited by cells, channels, or chambers
  - Medium – additional conditions with one or two stress factors
  - Full Factorial – complete stress factor interaction (e.g., Stage 3)
- **The core matrix is very flexible, and can be designed based on the customer needs and limitations. Some examples include:**
  - Calendar-life interactions between temperature and SOC.
  - Cycle-life interactions between temperature, SOC, throughput, and power ratings.
- **One significant criterion for the core matrix is that it includes at least one un-modeled test condition.**
  - This will help validate the model prior to making any life predictions.

TLVT Accomplishments (cont.)

Manual Development

- **Supplemental Life Testing (assess presence/absence of effects)**
  - Memory effects (i.e., path dependence)
    - Does future degradation depend only on current state-of-health and the future environment?
  - Effect of combined calendar and cycle life testing
  - Effect of additional stressors (e.g., throughput and power rating)
  - Effect of cold start operations on life
  - Effect of low temperature operation

- **Matrix design depends on core matrix assumptions and expected range of stress during operation.**

- **Model developed for core matrix conditions will also accurately predict supplemental conditions if assumptions are valid.**

TLVT Accomplishments (cont.)

Cell-Level Validation Effort

- **Validation testing with 7 Ah Li-Ion cylindrical cells:**

	Experiment Condition	Temperature (°C)	Profile	State of Charge (SOC)	Throughput Rate (Wh)	Pulse Power Rate (kW)	Actual Number of Cells
Calendar-Life (INL)	1	30	Daily Taper	SOC_{MAX}	-	-	3
	2	40	Daily Taper	SOC_{MAX} - 10%	-	-	3
	3	40	Daily Taper	SOC_{MAX} + 10%	-	-	3
	4	40	Daily Taper	SOC_{MAX}	-	-	3
	5	47.5	Daily Taper	SOC_{MAX} - 10%	-	-	3
	6	47.5	Daily Taper	SOC_{MAX} + 10%	-	-	3
	7	47.5	Daily Taper	SOC_{MAX}	-	-	3
	8	55	Daily Taper	SOC_{MAX} - 10%	-	-	3
	9	55	Daily Taper	SOC_{MAX} + 10%	-	-	3
	10	55	Daily Taper	SOC_{MAX}	-	-	3
Spare Cells	11	55	Daily Taper	SOC_{MAX} + 20%	-	-	3
	12	55	Daily Taper	SOC_{MIN}	-	-	3
Cycle-Life (ANL)	13	40	99^{th} Percentile	SOC_{MAX}	Standard	Standard	2
	14	40	99^{th} Percentile	SOC_{MAX}	Double	Double	2
	15	40	99^{th} Percentile	SOC_{MAX}	Standard	Double	1
	16	40	99^{th} Percentile	SOC_{MAX}	Double	Standard	1

TLVT Accomplishments (cont.)

Cell-Level Validation Effort

- **Calendar-Life Testing:**
  - Daily taper charge back to the designated life-test SOC
- **Cycle-Life Testing:**
  - 99th Percentile Profile at SOC_{MAX} with changes to throughput (pulse durations) and pulse power levels
- **Reference Performance Test:**
  - Minimum Pulse Power Characterization (only resistance data)
  - C/1 and L-HPPC test at specified intervals
- **Spare Cells:**
  - Original SOC range (±10%) did not show statistical performance differences
  - SOC window increase to SOC_{MAX}+20% and SOC_{MIN}

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TLVT Accomplishments (cont.)

Cell-Level Validation Results

	Temp (ºC)	SOC	HPPC		MPPC		RPTs Completed
			C/1 Capacity Fade (%)	Power Fade (%)	Dis. R Growth at SOC_{MAX} (%)	Dis. R Growth at SOC_{MIN} (%)	
Calendar-Life	30	MAX	1.46%	7.64%	10.81%	3.61%	12
	40	MAX, ±10%	2.06%	13.03%	16.60%	12.63%	11
	47.5	MAX, ±10%	3.92%	19.22%	21.61%	16.82%	11
	55	MAX, ±10%	5.75%	23.23%	30.59%	24.11%	8
Spare Cells	55	MIN	6.36%	16.71%	12.13%	32.95%	12
	55	MAX+20%	11.41%	26.90%	34.52%	26.36%	12

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TLVT Accomplishments (cont.)

TLVT Model Development

- **Models**
  - Degradation Model
  - Error Model
- **Parameter Estimation ("model fitting")**
- **Uncertainty of Parameter Estimates via Monte Carlo Simulations ("Bootstrap")**
  - Assessment of Model Quality ("lack-of-fit")
  - Uncertainty of Life Estimates
  - Assess viability of candidate life-verification experiments

TLVT Accomplishments (cont.)

Combined Model

Observed Degradation = Average Degradation (Population) + Error

$$Y_i(X;t) = \mu(X;t) + \gamma_i(X;t)$$

$$X = \text{stress condition}$$

$$t = \text{time}$$

$$Y_i(X;t) = \text{observed degradation level of } \mathrm{i}^{th} \text{ cell}$$

Based on a measure of state-of-health

$\mu(X;t) = $ average degradation level across population ← *Degradation Model*

$\gamma_i(X;t) = $ deviation (error) from average ← *Error Model*

1. We are most interested in estimating $\mu(X;t)$
2. $\gamma(X;t)$ is needed to assess uncertainty

TLVT Accomplishments (cont.)

Degradation Model: $\mu\,(X;t)$

- **Can be empirical, chemistry/physics-based, or some combination of both**
- **Needs to accurately reflect state-of-health**
- **A generalized empirical degradation model is being developed, and can be applied to a set of data in the absence of a manufacturer's mechanistic model**

$$\mu(X;t) = 1 + \exp\{\beta_0 + \beta_1 \cdot f_1(X_1) + \ldots + \beta_q \cdot f_q(X_q)\} \cdot t^{\rho}$$

$$\mu(X;0) = 1,\ \mu(X;t) > 1 \text{ for } t > 0$$

$$Examples: \mu(X;t) \equiv \frac{\text{Impedance}(t)}{\text{Impedance}(0)}$$

$$\mu(X;t) \equiv \frac{\text{Available Power}(0)}{\text{Available Power}(t)}$$

TLVT Accomplishments (cont.)

Error Model: $\gamma(X;t)$

- **Needed in order to understand uncertainty and gauge lack-of-fit**
- **The error model accounts for both manufacturing variability from cell to cell as well as the measurement uncertainty**
  - Uses data from the degradation experiment
  - Alternatively, the INL uncertainty methodology can be used to directly determine measurement error
- **Default Model form:**

$$\gamma_i(X;t) = \delta_i \cdot (\mu(X;t) - 1) + \pi_i(t)$$

$$\delta_i = \text{random effect of } i^{th} \text{ cell}$$

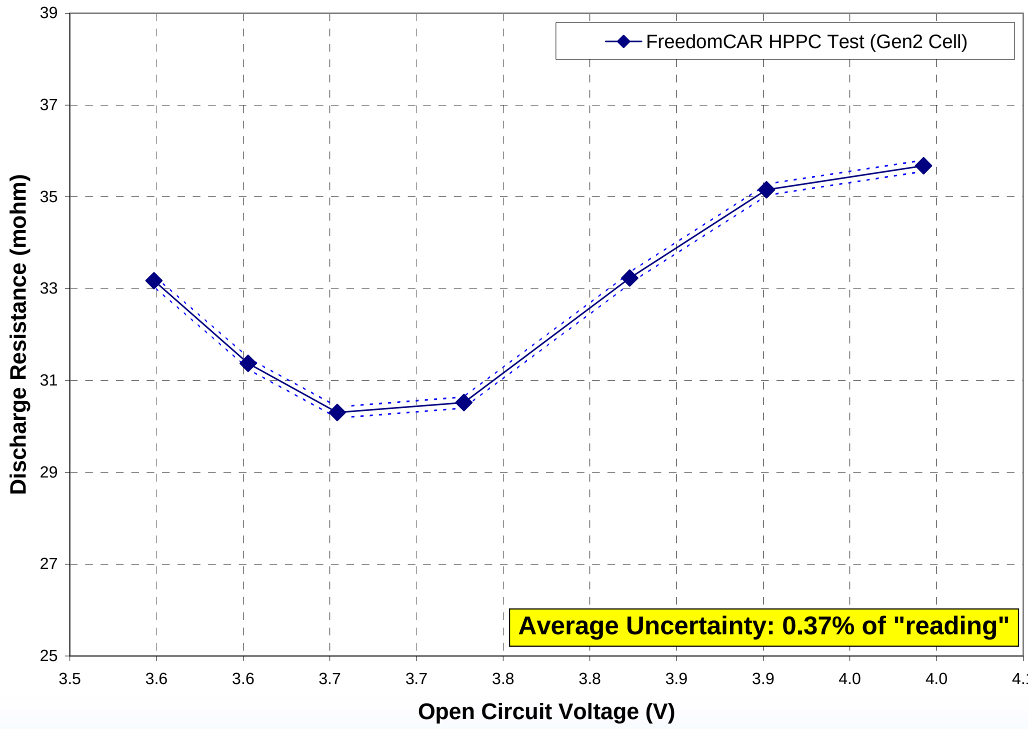
$$\pi_i(t) = \text{random effect due to measurement error } (i^{th} \text{ cell, time } t)$$

Note: Cell-to-cell variation in performance increases as the level of degradation (i.e., "μ(X; t) – 1") increases as observed in actual cell data.

TLVT Accomplishments (cont.)

INL Measurement Uncertainty

- **The INL Uncertainty Analysis Methodology enables the quantification of confidence levels for battery test data.**
- **Measured Parameters:**
  - Current
  - Voltage
- **Derived Parameters:**
  - Capacity
  - Energy
  - Resistance
  - Power



TLVT Accomplishments (cont.)

Monte Carlo Simulations

- **Use test duration, experimental conditions, number of cells per condition from actual experiment**
- **Simulate large number of independent trials of complete experiment assuming fitted degradation and error models**
  1. **Generate simulated experimental data**
  2. **Estimate model parameters from simulated data**
  3. **Estimate *average cell life* at 30C using estimates parameters**
     - Requires end-of-life target (e.g., when ASI increases 30%)
  4. **Compute lack-of-fit statistic**
- **Distribution of estimated average cell life provides a notion of the statistical uncertainty of life estimated from actual experiment**
- **Compare lack-of-fit statistic from actual experimental data with distribution of lack-of-fit statistics from simulation to assess lack-of-fit**

TLVT Accomplishments (cont.)

Methodology Applied to TLVT Data

$$\hat{Y} = 1 + \exp\left\{\hat{\beta}_0 + \hat{\beta}_1 \cdot \frac{1}{T}\right\} \cdot t^{0.5}$$

$t =$ time (years)

$T =$ temperature (K)

$\hat{\beta}_0 = 18.11\,(1.1)$

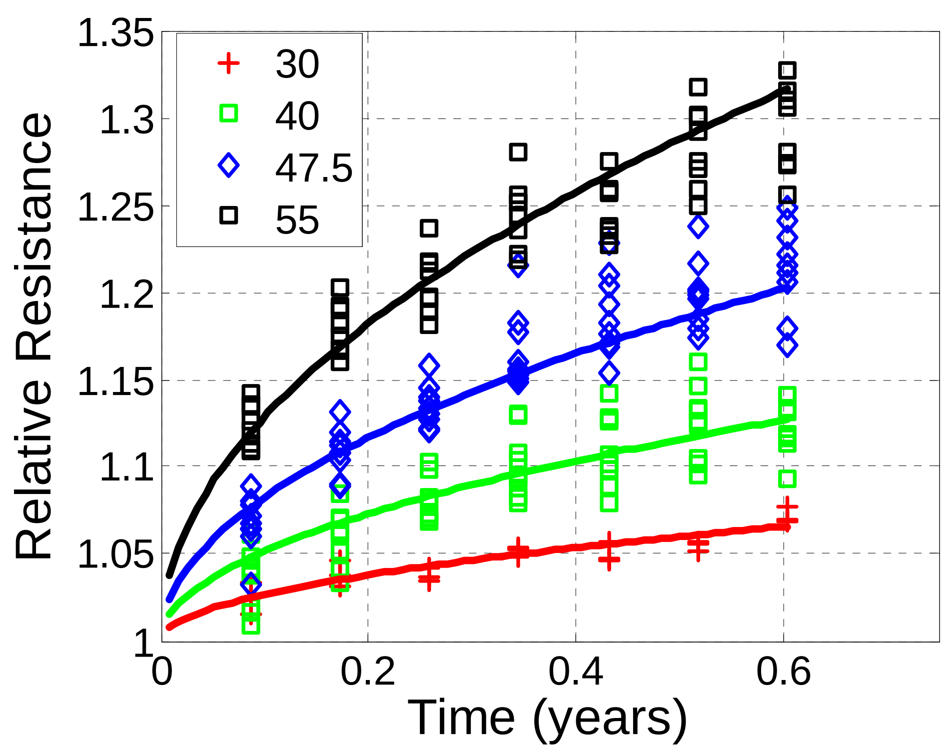
$\hat{\beta}_1 = -6236\,(360)$

Estimated Life $= 12.6\,(1.9)$ years

$$V\hat{a}r\left(Y_i(T;t)\right) = \hat{\sigma}_\delta^2 \cdot \left(\hat{Y}(T;t) - 1\right)^2 + 2 \cdot \hat{\sigma}_\varepsilon^2$$

$\hat{\sigma}_\delta = .056$

$\hat{\sigma}_\varepsilon = .011$



Model Quality: LOF-statistic* = 52

*Under Assumption of no lack-of-fit
Prob {LOF-statistic > 52} <.01

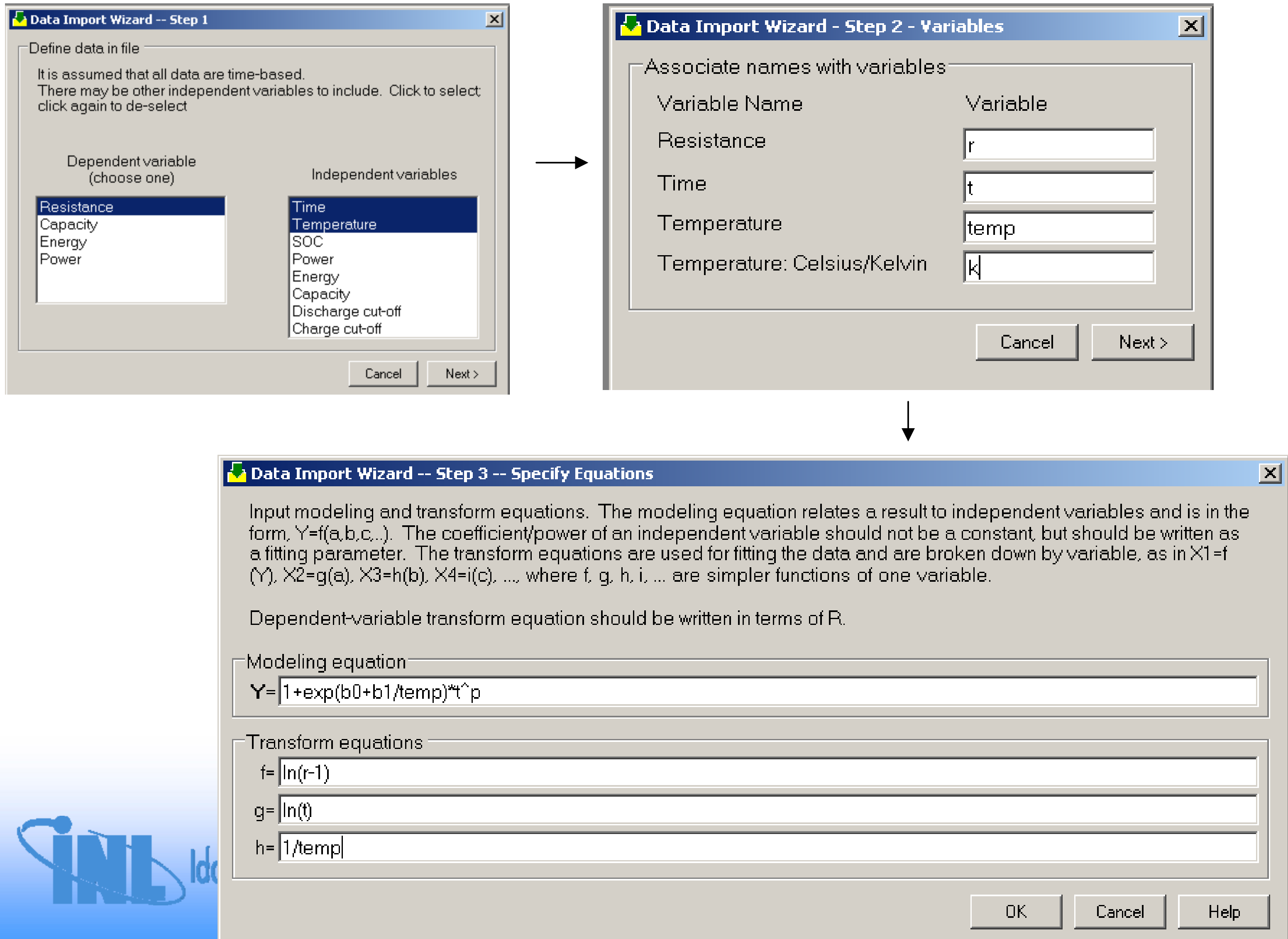
TLVT Accomplishments (cont.)

TLVT Software Development

- **The statistics and mathematics developed for TLVT (e.g., Monte Carlo Simulations, lack-of-fit, etc.) were reduced to software.**
- **User-friendly tool for the analysis and simulation of battery life data.**
- **No battery life model was assumed. The assumptions in the software are:**
  - All data are time-dependent and time is a variable in the model equation
  - The model equation can be linearized

TLVT Accomplishments (cont.)

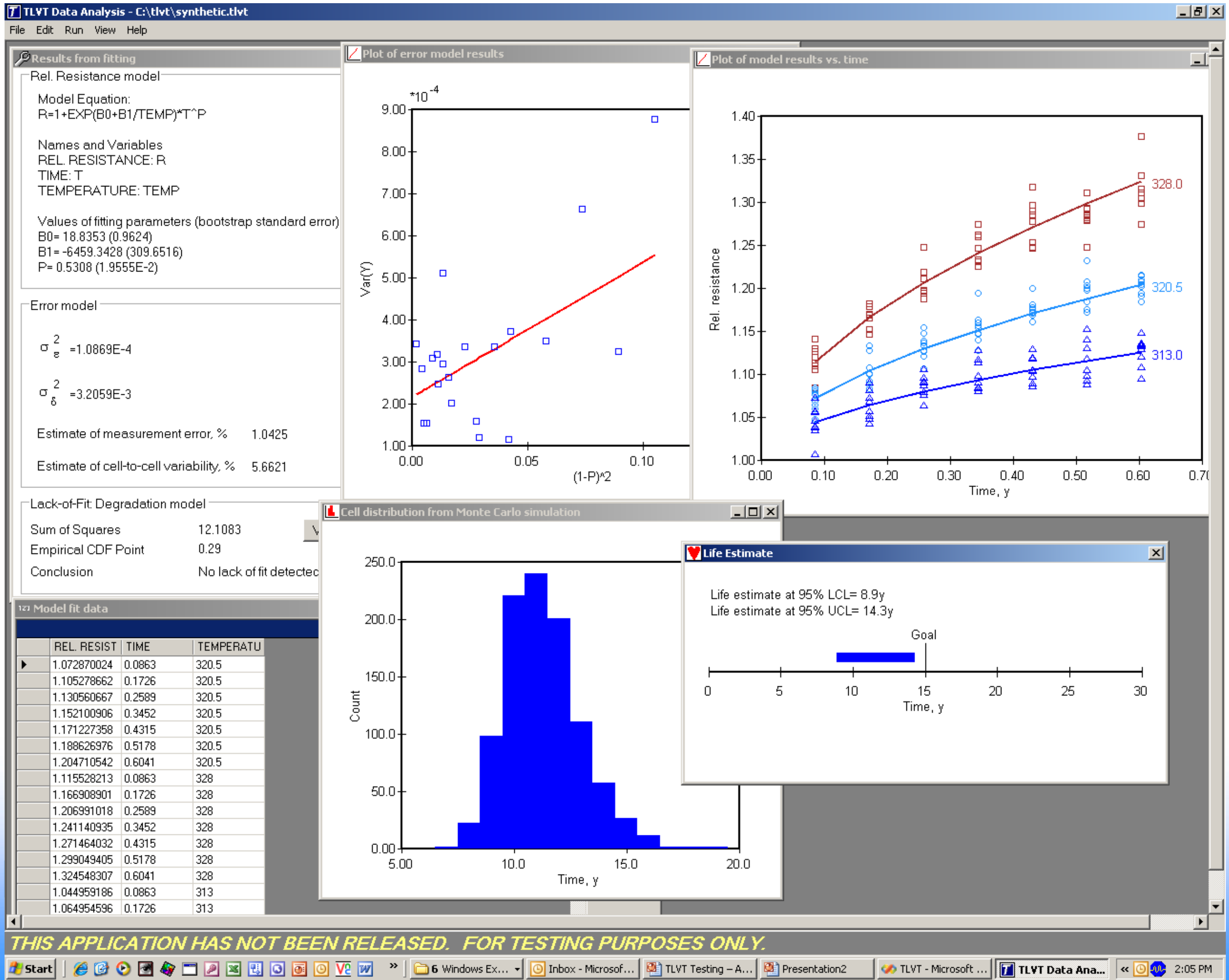
Software Interface (specifying a life model)



TLVT Accomplishments (cont.)

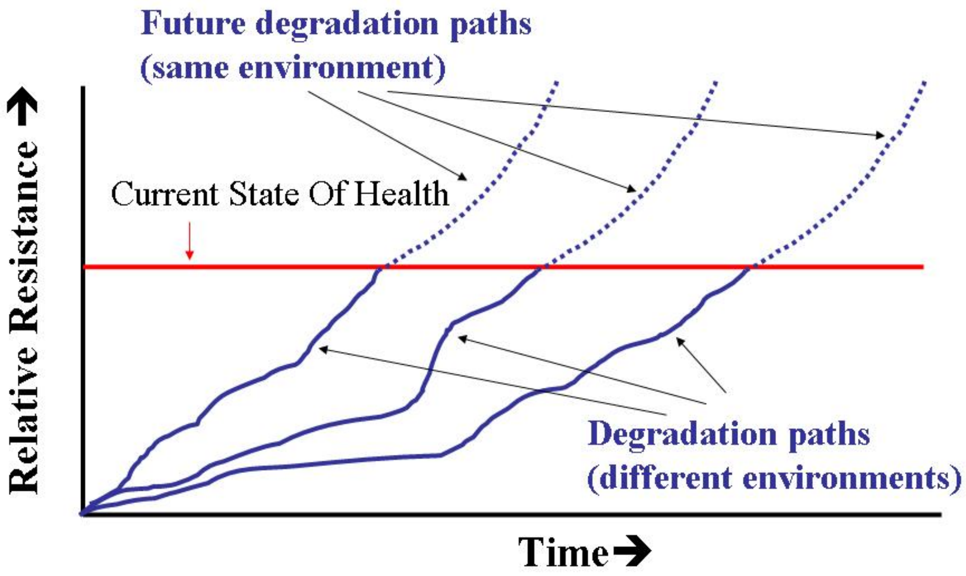
TLVT Software Development

- **All views can be copied and pasted into documents for reports**



TLVT Accomplishments (cont.)

Memory Effects (Path Dependence)



Does the rate of future degradation depend only on the current state of health and the future environment?

The answer is crucial for determining whether models developed with test items at static accelerating conditions can be used to accurately predict life under realistic dynamic conditions.

Technology Transfer

- **We are developing a methodology for predicting calendar life and cycle life with high statistical confidence.**
  - The initial TLVT Manual was published in February 2005.
  - Validation effort has led to improvements in the methodology, and a new manual should be published by August 2008.
- **The new revision to the TLVT Manual will be complementary to the standardized DOE and USABC Manuals (FreedomCAR HEV and PHEV, ultracapacitors, etc.)**
- **DOE and USABC use these standardized manuals to judge the progress of programs with regard to meeting life targets. Success here would hopefully translate to successful introduction to the marketplace.**
- **The TLVT life estimation methodology has been successfully beta tested by some of the FreedomCAR developers.**

Future Activities

- **Continue TLVT Manual validation in FY08:**
  - Anticipate using TLVT methodology with ~100 cylindrical cells with a different chemistry.
  - Test matrix will include calendar- and cycle-life testing with at least 3 temperatures and 2-3 SOCs.
  - Supplemental testing activities:
    - Memory effects (path dependence)
    - Low temperature performance
    - Small study on effect of throughput and power rating
- **Identify key path dependence factors that may impact future testing.**
- **Complete TLVT software tool with user's manual.**
- **Publish Revision 1 of the TLVT Manual by August 2008.**

Future Activities (cont.)

- **Upcoming Milestones and Decision Points:**
  - Testing:
    - Acquire off-the-shelf cells. **March '08** **In progress**
    - Complete Cell Aging:
      - Calendar and Cycle-Life. **February '09** **On schedule**
      - Supplemental Testing. **December '09** **On schedule**
  - Analysis
    - Revision 1 of TLVT Manual. **August '08** **On schedule**
    - Identify key path dependent factors for future testing. **December '09** **On schedule**

Summary

- **Potential for petroleum displacement:**
  - A high confidence in battery life estimation is considered a key performance metric for EV, HEV, and PHEVs.
- **Approach:**
  - TLVT manual validation with test cells and demonstrating statistical methods for predicting life.
- **Accomplishments:**
  - Initial round of validation testing was completed
  - An improved methodology and software package has been developed for assessing battery life.

Summary (cont.)

- **Technology Transfer:**
  - This methodology has been successfully used by some of the FreedomCAR developers in beta tests.
- **Future Plans:**
  - Publish Revision 1 of the TLVT Manual by August 2008
  - Initial second round of validation testing with a different cell chemistry.

Publications

- **J. P. Christophersen, G. L. Hunt, C. D. Ho, and D. Howell, "Pulse resistance effects due to charging or discharging of high-power lithium-ion cells: A path dependence study," *J. Power Sources,* 173, 998-1005 (2007).**

- **J. P. Christophersen, G. L. Hunt, I. Bloom, E. Thomas, and V. Battaglia, "Battery Technology Life Verification Testing and Analysis," Proceedings from the *23rd Electric Vehicle Symposium,* December 2007*.***