POWER™ for battery graphy

Battery Parameterization System

CHUL OH YOON

KUMHO CHEMICAL LABORATORIES
KOREA KUMHO PETROCHEM. CO. LTD.

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OUTLINE

- **INTRODUCTION**
  POWERGRAPHY™: New Concept of Battery Evaluation
- **MODEL**
  Electrochemical Processes in Battery & Equivalent Circuit
- **MEASUREMENT**
  Real-Time Impedance Measurement
- **PARAMETERIZATION**
  Generating Numerical Image of Battery
- **PREDICTION**
  Performance Simulation at Arbitrary Load
- **CHARACTERIZATION**
  Parametric Analysis of Batteries and Materials
- **APPLICATION:**
  Quality Control & EV Battery Management

POWER™ graphy

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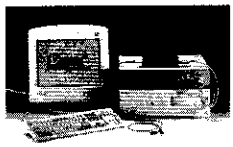
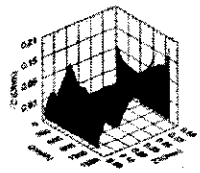
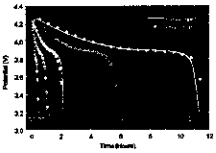
INTRODUCTION

POWERGRAPHY™:
New Concept of Battery Evaluation

Measurement (Hardware) *Parameterization (Software)* *Prediction (Simulation)*

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Battery Parameterization System

Measurement

- *DC electrical measurement*
  - *charge/discharge*
- *AC electrical measurement*
  - *AC impedance*
- *Temperature measurement*
- *Cycling*

- *Battery equivalent circuit*
- *Automatic parameterization*

Numerical Image

- *Thermodynamic properties*
- *Kinetic properties*

Performance Simulation

- *Arbitrary load*
- *DC/AC/transient*
- *Power/energy*

Parametric Analysis

- *Capacity/Power*
- *Materials/Process*
- *Life*

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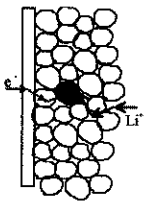
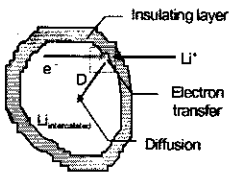
MODEL

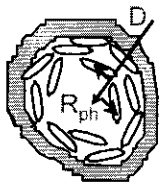
Electrochemical Processes in Battery & Equivalent Circuit



Composite electrode as a transmission line



Single particle processes



Phase kinetics

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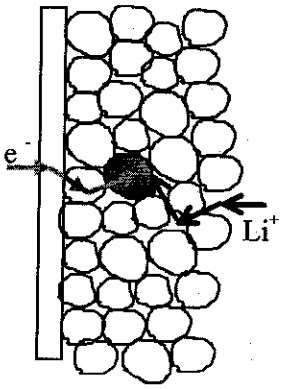
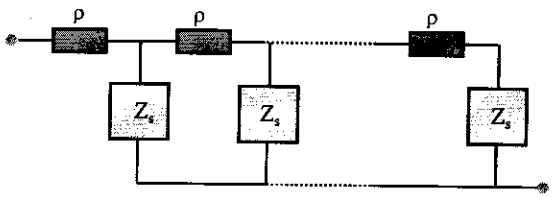
Frequency-domain model of kinetic processes

I. Composite Electrode as Transmission Line





Equivalent circuit of the macroscopic layer of porous material

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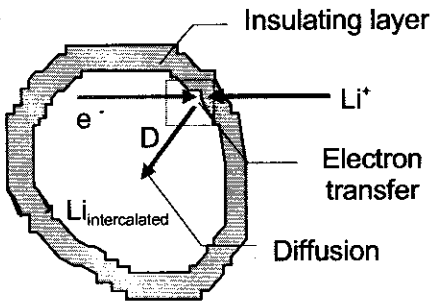
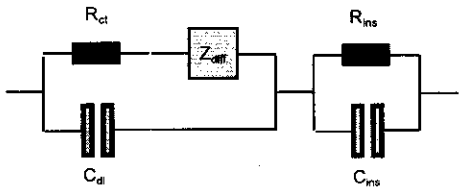
Frequency-domain model of kinetic processes

II. Single Particle Processes

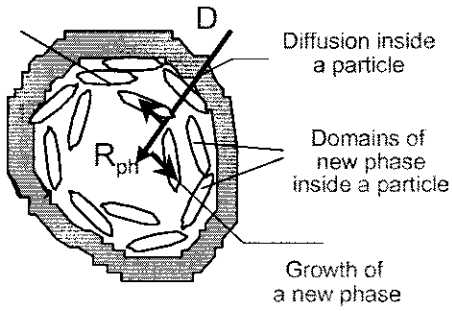


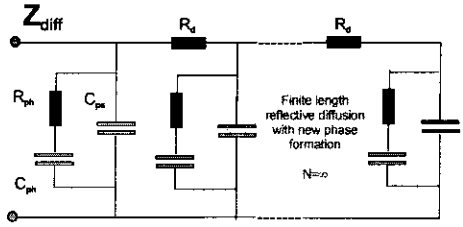


Equivalent circuit of a single particle

Frequency-domain model of kinetic processes

III. Phase Kinetics





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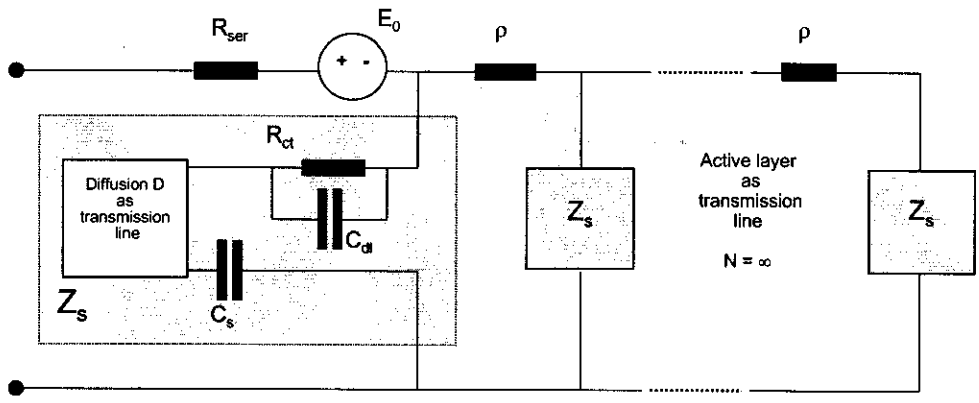
Generalized Battery Equivalent Circuit



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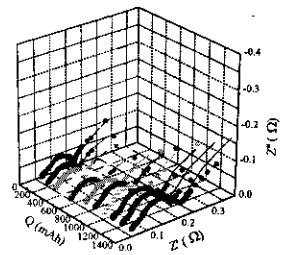
MEASUREMENT

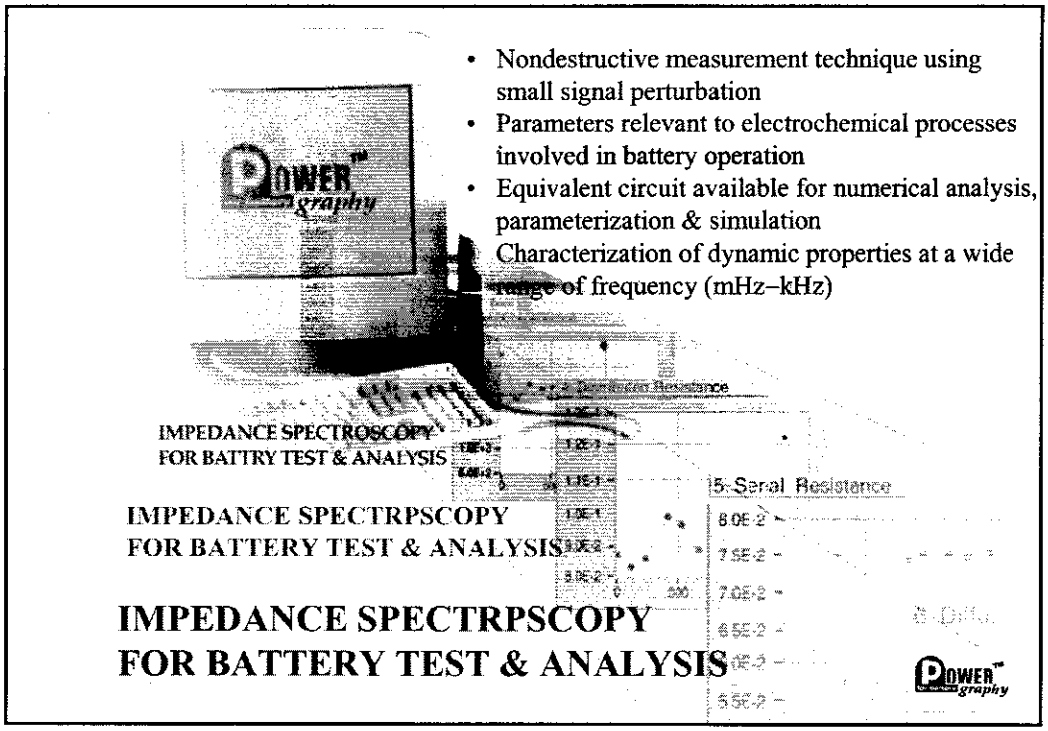
Real-Time Impedance Spectroscopy

Multi-wave FFT Impedance Measurement

Carrier Function Laplace Transform Impedance Measurement



POWER™ for battery graphy



- Nondestructive measurement technique using small signal perturbation
- Parameters relevant to electrochemical processes involved in battery operation
- Equivalent circuit available for numerical analysis, parameterization & simulation
- Characterization of dynamic properties at a wide range of frequency (mHz–kHz)

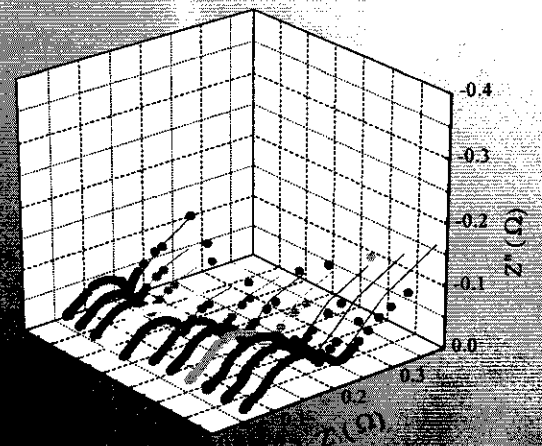
Real-Time Impedance Measurement

System	Excitation	Response	Impedance	Measurement time*
	$I(t)$	$V(t)$	$-Z''$ vs Z'	1 h 40 min
	$I(t)$	$V(t)$	FT → $-Z''$ vs Z'	33 min
Carrier Fourier Laplace transform (CF-LT)	$I(t)$	$V(t)$	LT → $-Z''$ vs Z'	17 min

*Measurement at 1 mHz ~ 1 kHz, 50 frequencies. log spaced, 2 period integration

Impedance spectra of a Li-ion battery

Nyquist plot vs. level of discharge



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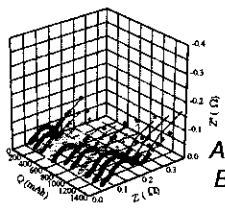
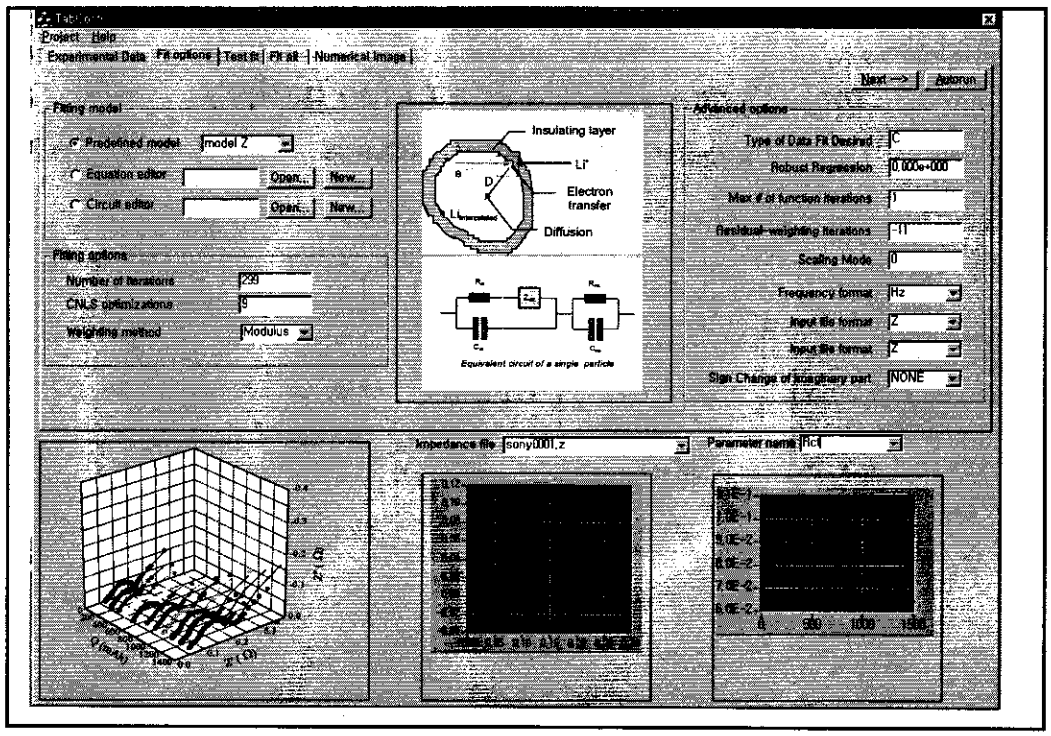
PARAMETERIZATION

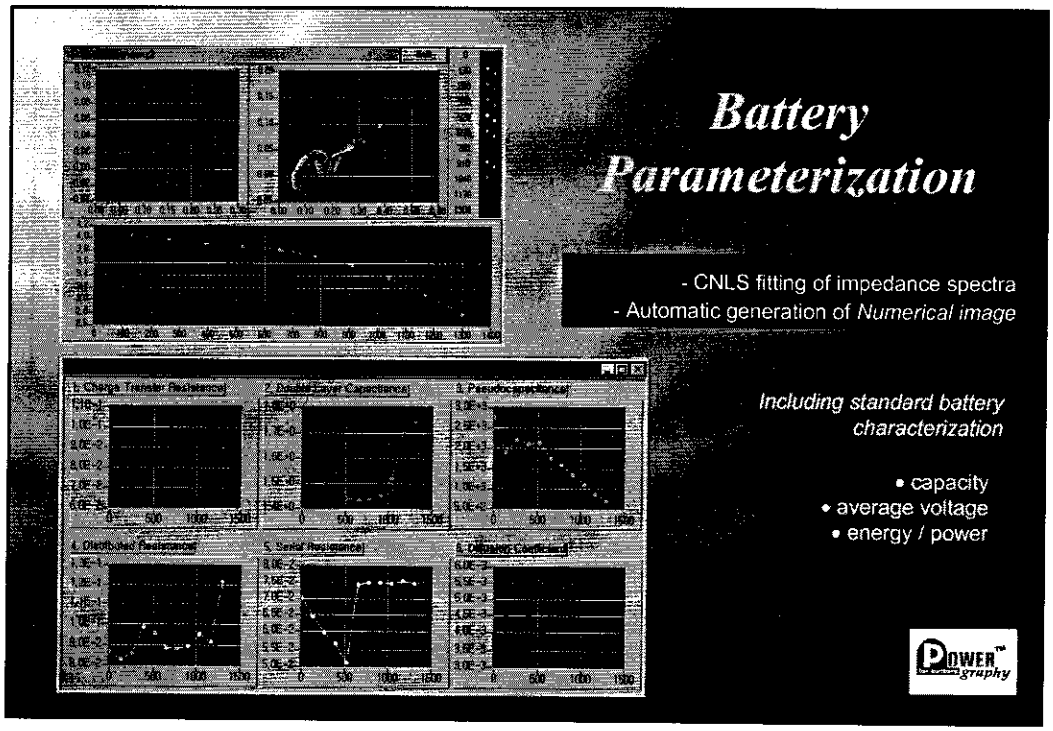
Generating Numerical Image of Battery



Automatic initial guessing
Battery equivalent circuit
CNLS fitting

Numerical Image


Project Help
Experimental Data
Fit options
Test fit
Fit all
Numerical Image
Next -->
Autorun
Fitting model
Predefined model
model 2
Equation editor
Open...
New...
Circuit editor
Open...
New...
Fitting options
Number of iterations
299
CNLS optimizations
9
Weighting method
Modulus
Insulating layer
Li+
Electron transfer
Diffusion
Equivalent circuit of a single particle
Advanced options
Type of Data Fit Desired
C
Robust Regression
0.000e+000
Max # of function iterations
0
Residual-weighting iterations
-11
Scaling Mode
0
Frequency format
Hz
Input file format
Z
Input file format
Z
Sign Change of Imaginary part
NONE
Impedance file
sony0001.z
Parameter name
Rct


Battery Parameterization
- CNLS fitting of impedance spectra
- Automatic generation of Numerical image
Including standard battery characterization
• capacity
• average voltage
• energy / power
POWER graphy

Numerical Image of Li-ion Battery

Q (mAh)	R_{ct} (Ω)	C_{dl} (F)	C_{ps} (F)	ρ (Ω)	R_{ser} (Ω)	D (sec^{-1})	E (V)	C_s (F)
0	0.06870	1.361	4142.4	0.08335	0.07012	0.000951	4.1061	4645.9
130	0.06099	1.458	1939.8	0.07980	0.06436	0.003206	4.0142	5318.0
260	0.06129	1.463	2273.0	0.08385	0.05977	0.003186	3.9447	7736.1
390	0.07014	1.504	2132.8	0.09549	0.05667	0.003420	3.8859	8660.8
520	0.06508	1.415	2151.1	0.09269	0.05095	0.003599	3.8372	9675.2
650	0.07299	1.417	1752.4	0.08679	0.07430	0.003466	3.7767	7039.0
780	0.07892	1.408	1610.8	0.08476	0.07473	0.003159	3.6769	3631.1
910	0.08639	1.422	1333.0	0.08491	0.07471	0.003259	3.5226	2674.5
1040	0.09876	1.485	1101.4	0.08939	0.07462	0.003313	3.3132	1977.4
1170	0.10006	1.649	847.1	0.08340	0.07548	0.003738	3.0419	1604.4

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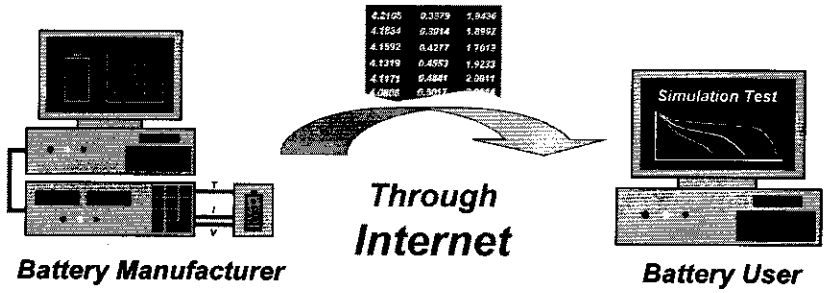
POWERGRAPHY™ represents a method to generate a *Numerical image*, which is an equivalent numerical representation of battery for parametric analysis and numerical simulation under arbitrary load conditions.



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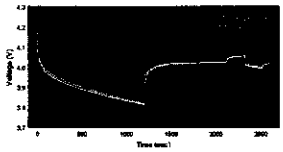
PREDICTION

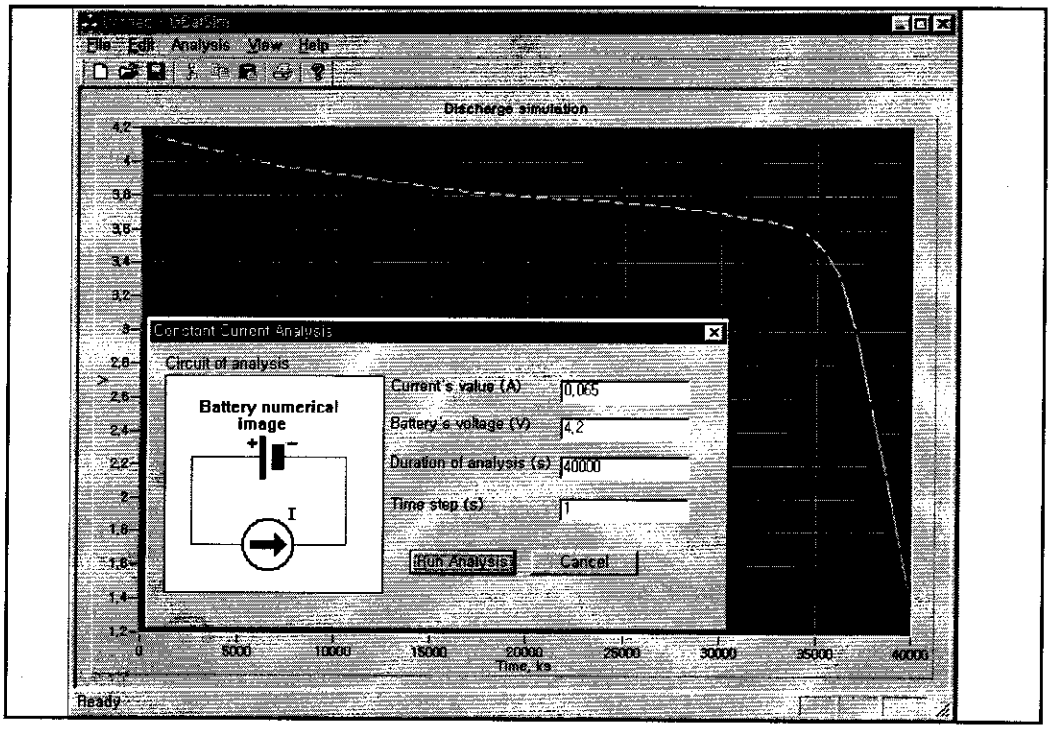
Performance Simulation at Arbitrary Load

Numerical Image

System of Nonlinear ODE SPICE

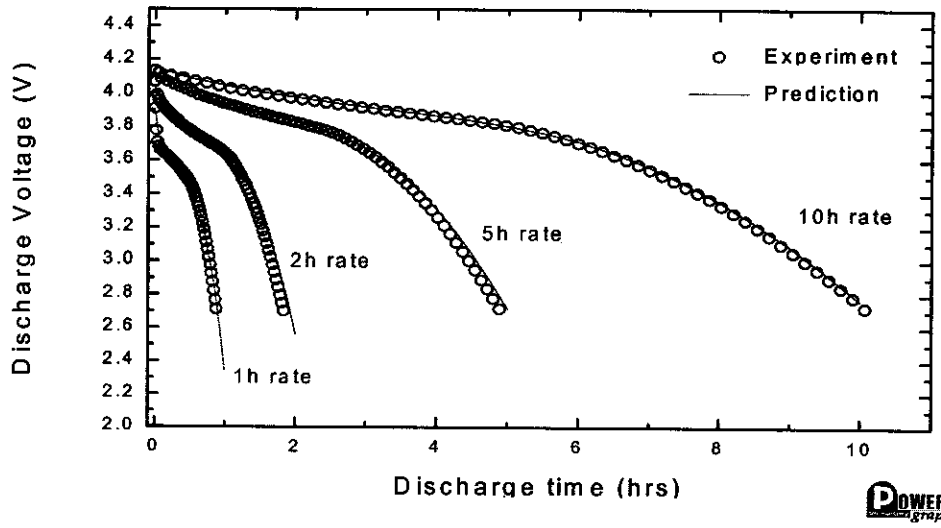


POWER graphy



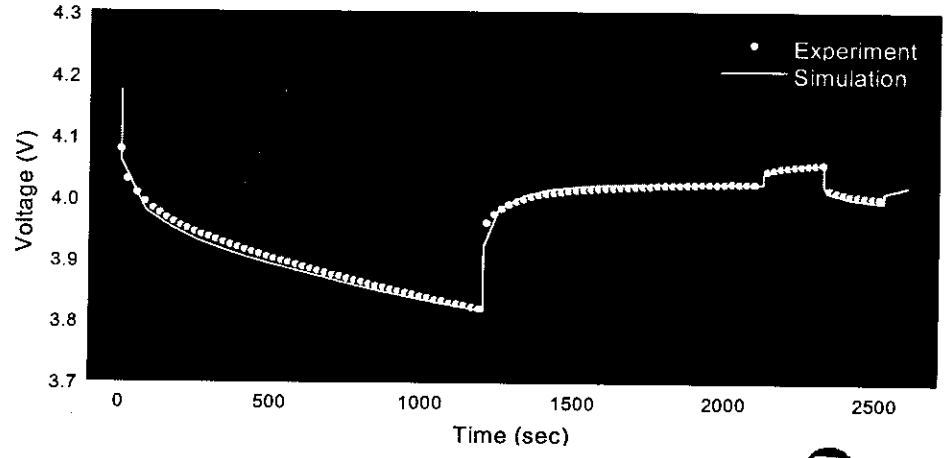
Numerical Simulation of Battery Discharge Curves

(Li-ion 18650)

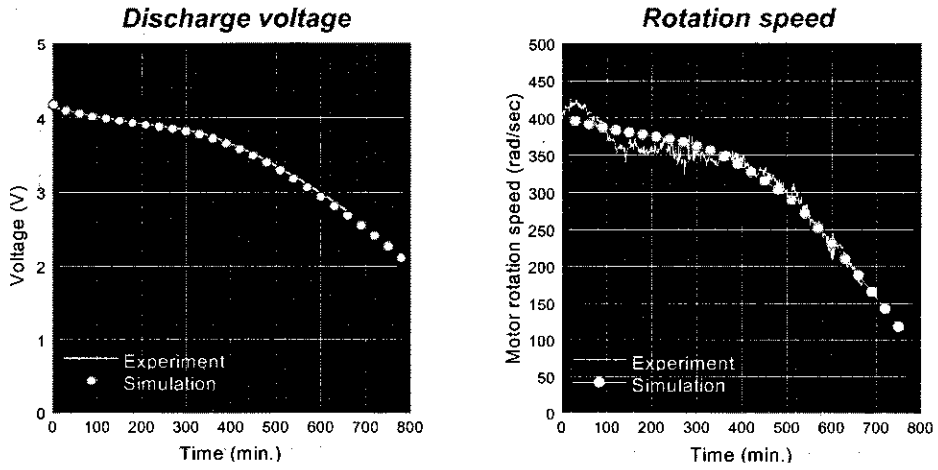


Numerical Simulation of Patterned Discharge

(Li-ion 18650)



Digital simulation of DC Motor Operation



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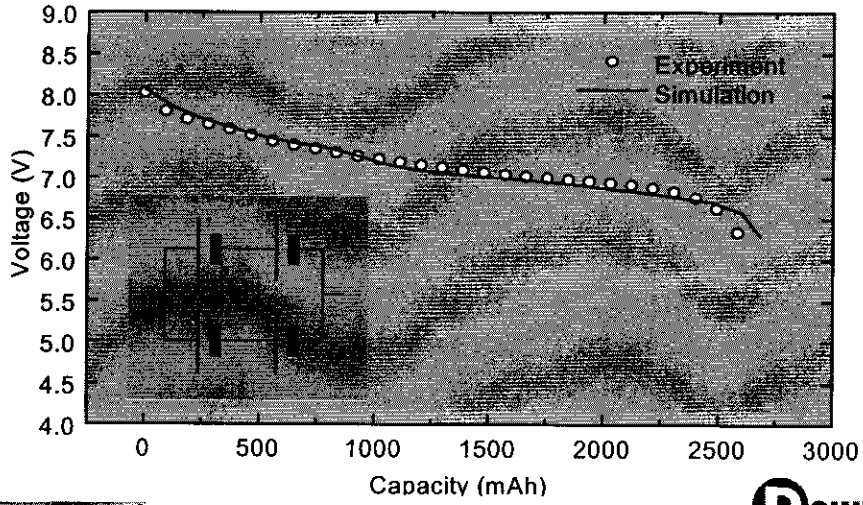
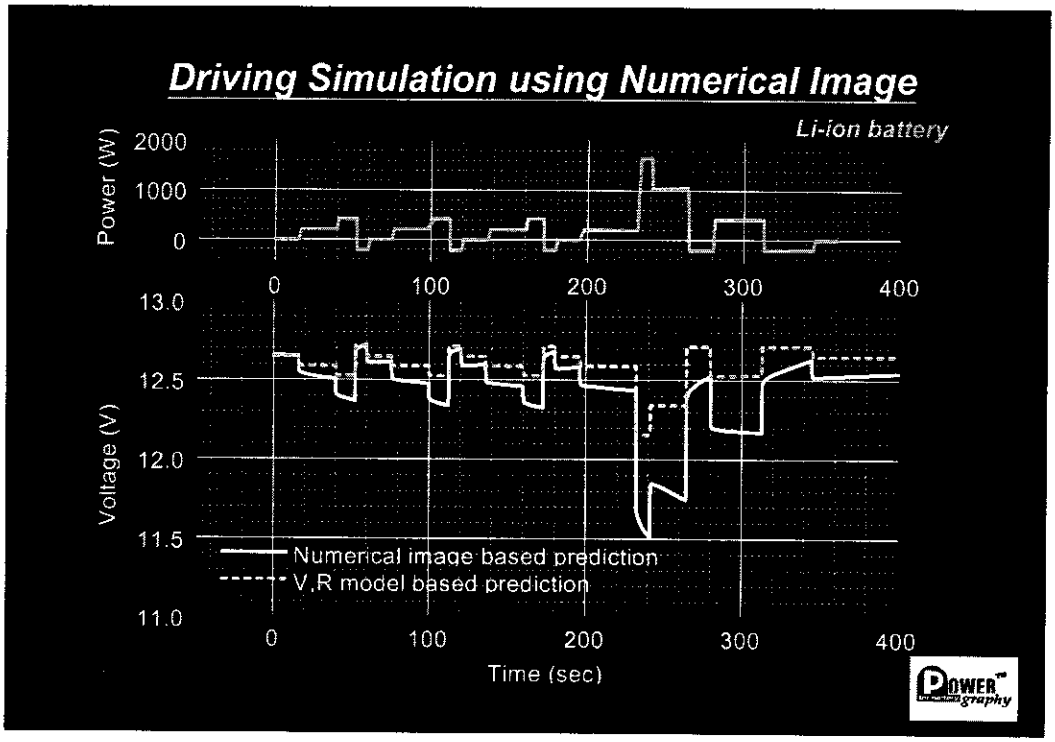
Digital Simulation of a Battery Pack



POWER™ for battery graphy



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CHARACTERIZATION

Parametric Analysis of Batteries & Materials

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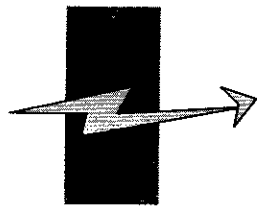
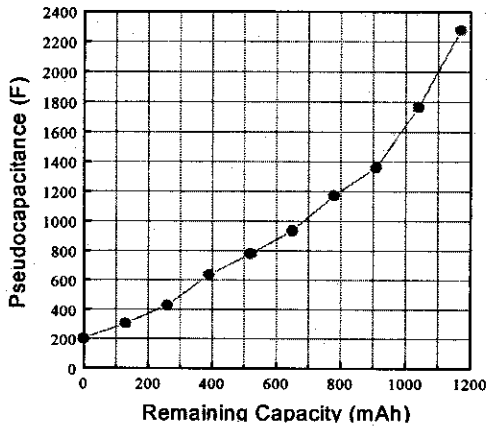
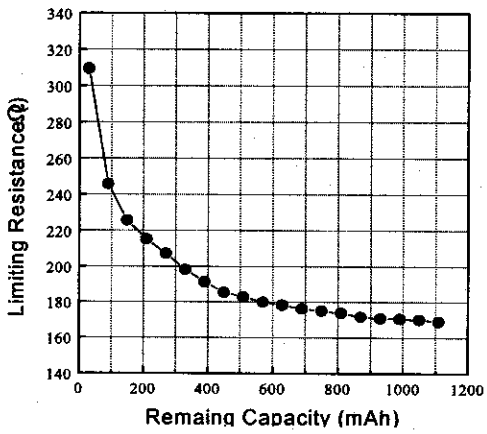


- ✓Charge / Discharge
- ✓Energy / Power
- ✓Internal resistance
- ✓Capacitance
- ✓Cycling
- ✓Temperature
- ✓Material parameters
- ✓Control parameters

POWER™ for battery graphy

Correlation between Battery parameters & Capacity

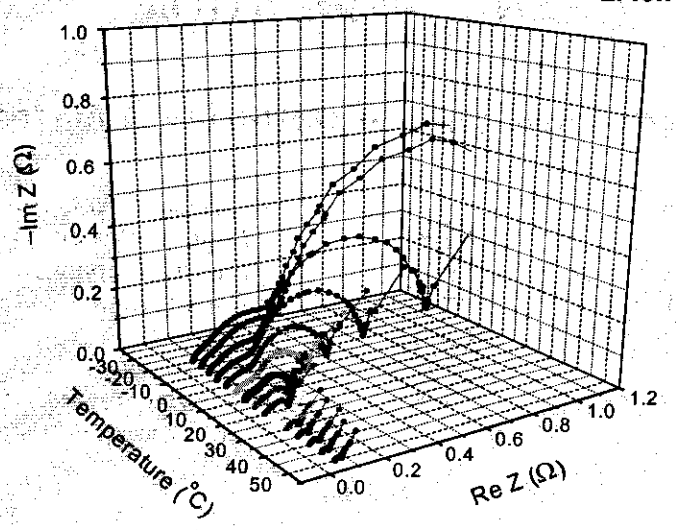




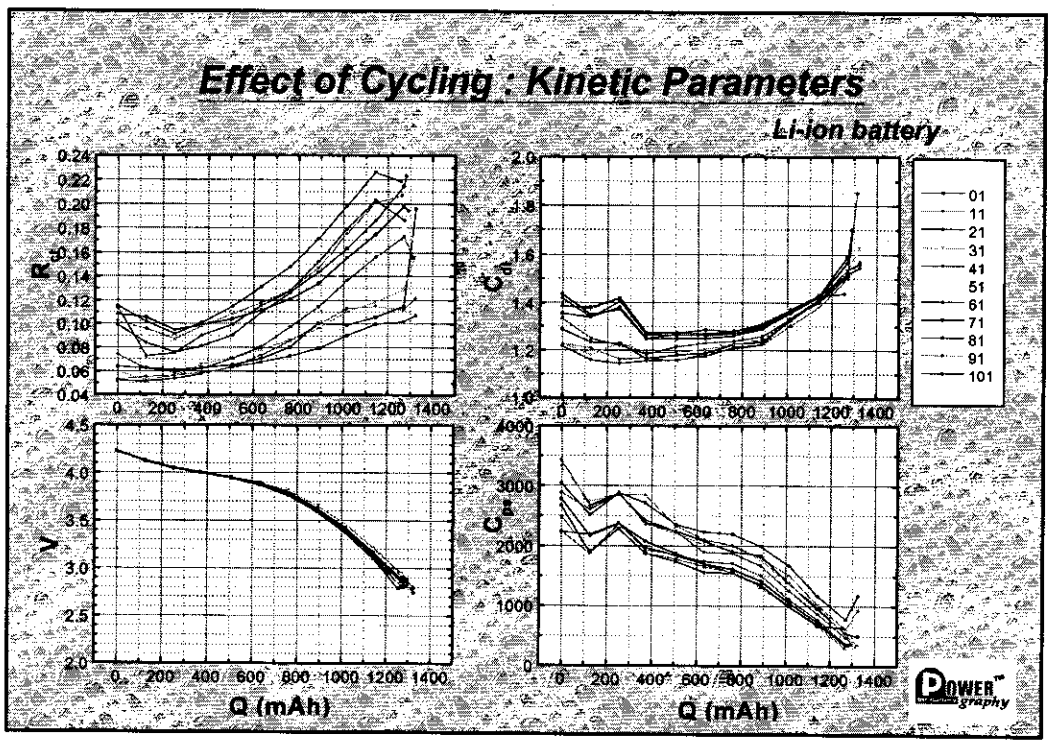
POWER™ for battery graphy

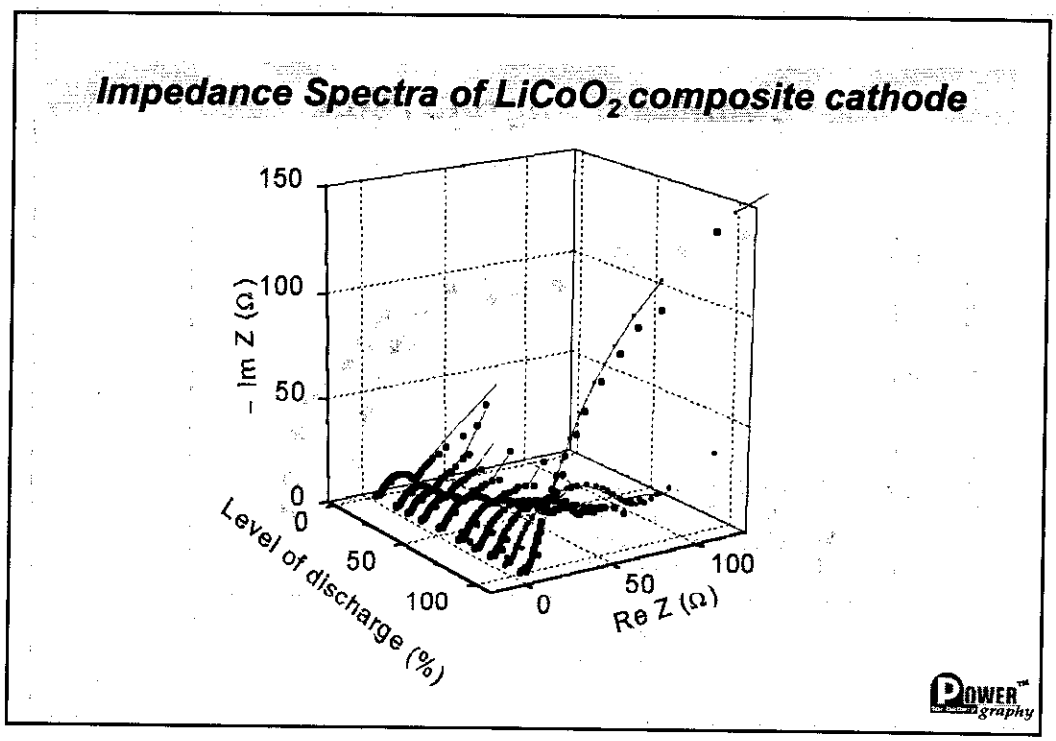
Effect of Temperature : Impedance Spectra

Li-ion battery



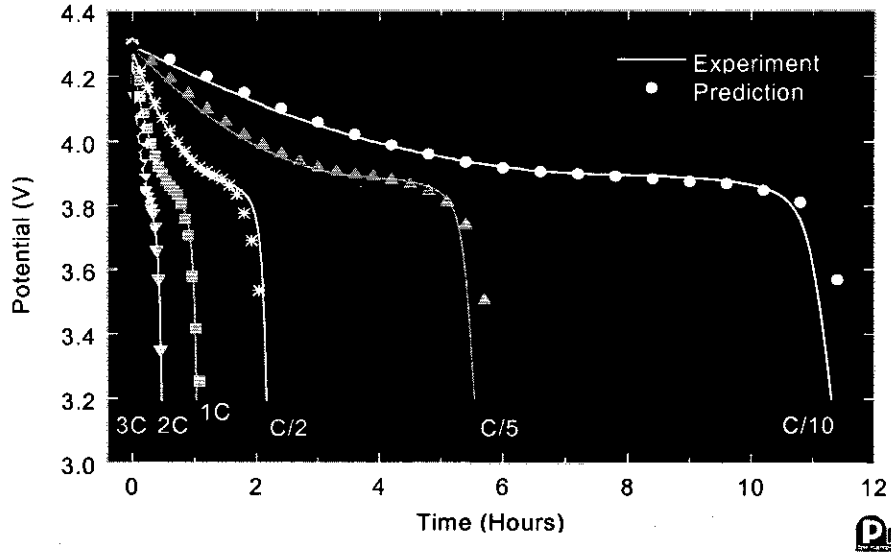
POWER™ graphy


Effect of Cycling : Kinetic Parameters
Li-ion battery
R
C
Y
C
Q (mAh)
Q (mAh)
01
11
21
31
41
51
61
71
81
91
101
POWER graphy

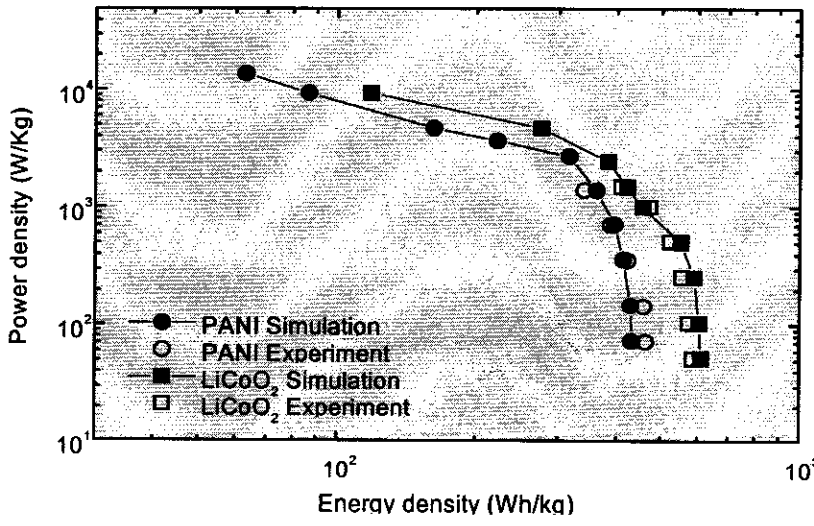

Impedance Spectra of LiCoO2 composite cathode
150
100
50
0
- Im Z (Ω)
Level of discharge (%)
0
50
100
0
50
100
Re Z (Ω)
POWER graphy

Digital Simulation of Electrode Materials

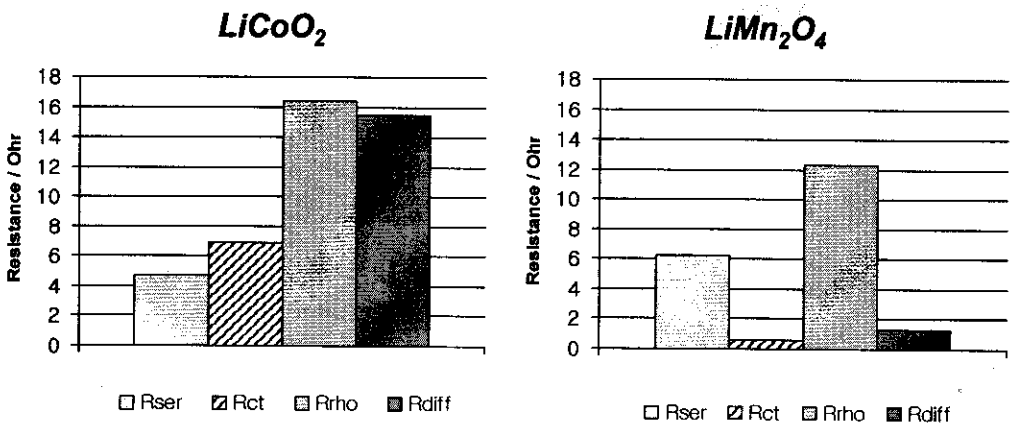
$LiCoO_2$ cathode vs. lithium



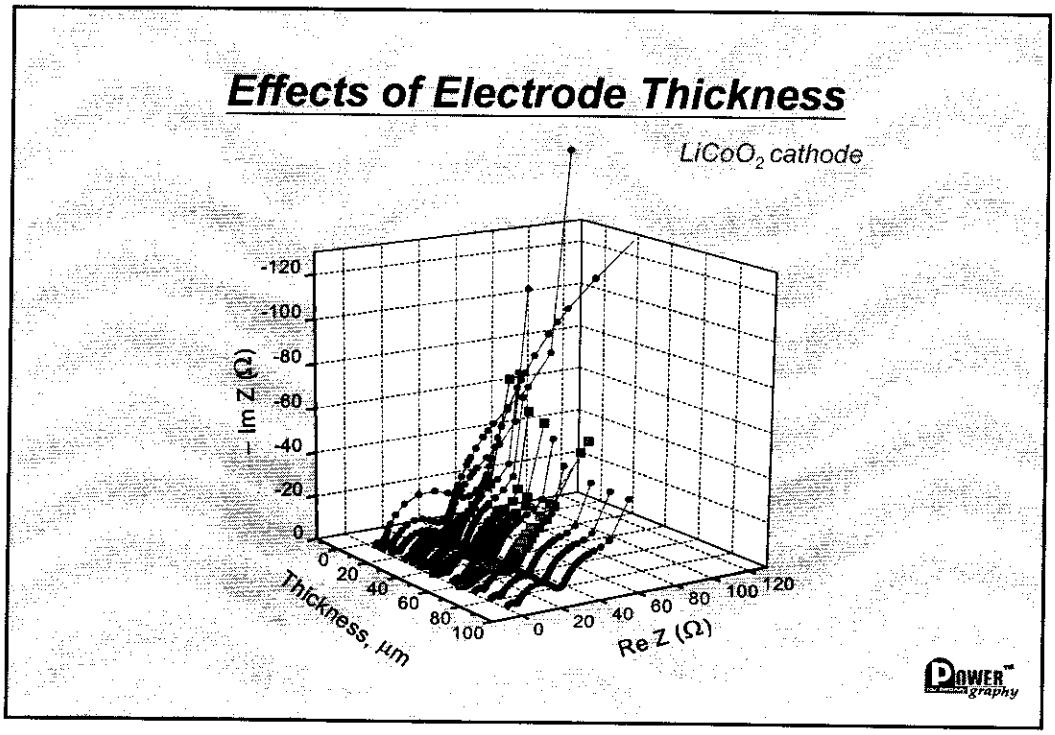
Simulated Ragone Plots



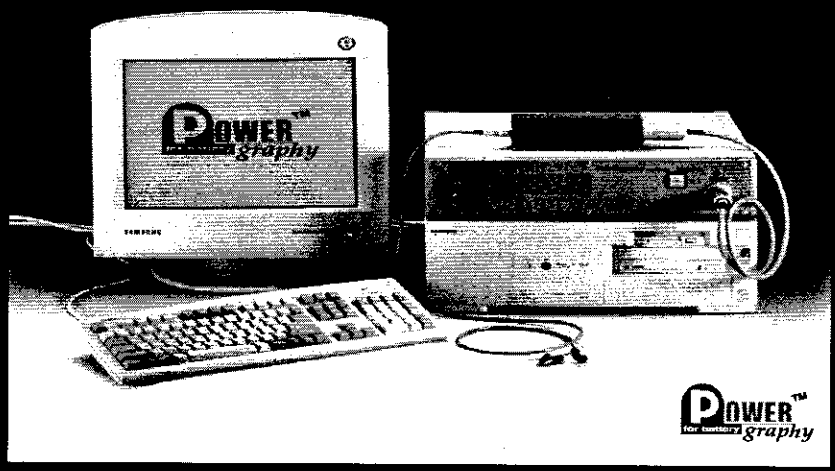
Comparison of kinetic properties of electrodes



Effects of Electrode Thickness



Prototype model BPS 1000 FL



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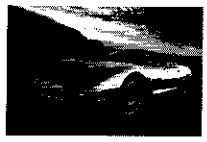
APPLICATION

Battery Test / Quality Control / Battery Management

Battery Test & Design

Battery Quality Control



EV Battery Management

Satellite Battery Remote Control