Power Quality Issues and Optimization of Energy and Power Sources of Mobile Systems

S. Ioannou, C. Keleshis, A. Teller and M.A. Lange

Energy, Environment and Water Research Center
The Cyprus Institute, Nicosia, Cyprus

March 28th, 2011

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Overview

- Motivation and Objectives
- Lithium Battery Technology
- Comparison of State of the Art Lithium Batteries
- Optimization Algorithm
- Battery Runtime and Remaining Energy Estimation
- New Proposed Model for Battery Runtime and Remaining Energy Estimation
- Discussion

MOTIVATION

- Unmanned Systems (midsize to small) have limited payload and volume availability and as a result reduced endurance and range.

OBJECTIVE

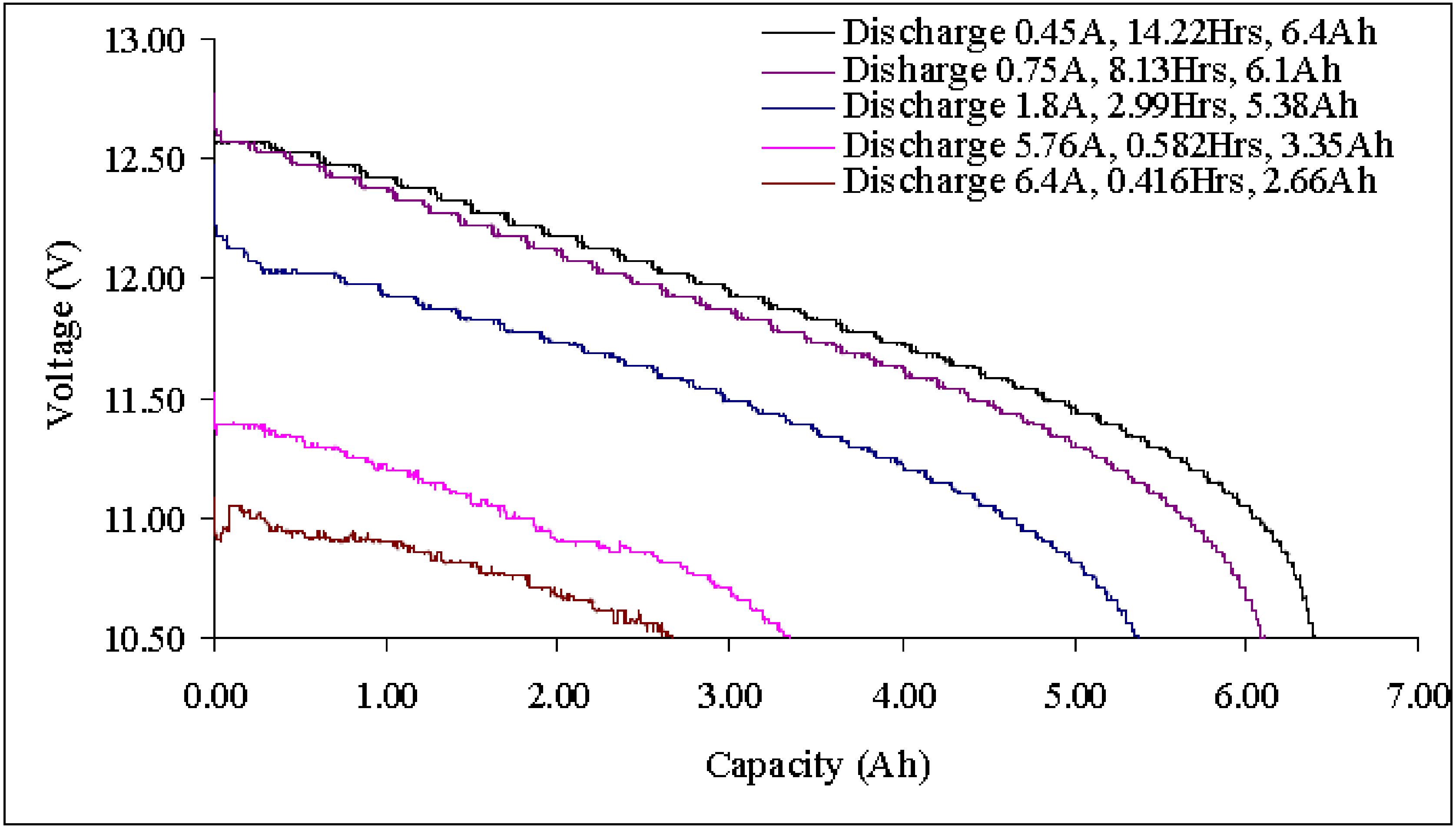
- Improve endurance and operation range of both Unmanned Ground and Aerial Vehicles (UGVs and UAVs).

Lithium Battery Technology

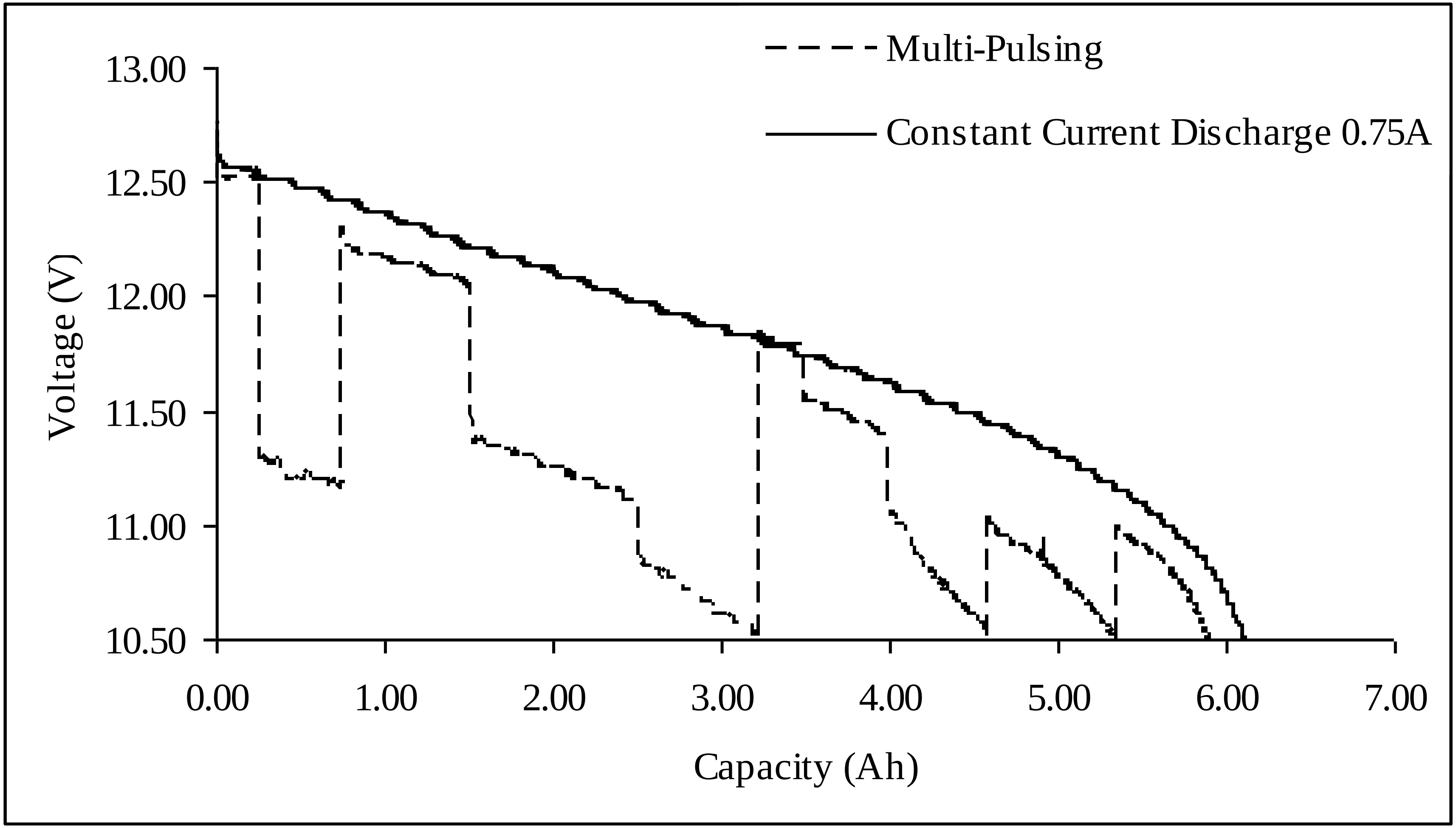
- **Performance Metrics**
  - Battery capacity in Ah
  - Gravimetric Energy Density in Wh/kg
  - Volumetric Energy Density in Wh/L

- **All measures depend on discharge current, thus making comparisons under different discharge rates difficult.**

Battery Characterization (Constant Load Currents)



Battery Characterization (Pulsed Load Currents)



Conservations of Energy

- Power Supplied = Power Absorbed

$$\frac{v_{in}}{v_{out}} = \frac{i_{out}}{i_{in}}$$

- Potential Problems
  - Computer Reset
  - Battery Catastrophic Failure

Analysis for a 480Wh Mission of Lithium Batteries with the Highest Energy Density

Brand	Model	W/Kg	W/L	Wh/Kg	Wh/L	Number of Cells	Kg	Liters
Saft	Lithopack C	5	6	572	628	24.69	0.84	0.76
Saft	Lithopack	28	30	519	570	27.21	0.93	0.84
Saft	PS 52 A	58	76	400	529	5.33	1.20	0.91
Saft	LSC 9V	5	2	372	175	44.44	1.29	2.74
Saft	PS 53 B	53	70	365	485	1.83	1.32	0.99
Saft	LS 9V	12	6	341	161	48.48	1.41	2.99

- Yellow - Less that 20W/Kg.
- Deep Green - with 3Kg offers 1557Wh (3 day mission with 22W loads or 31 hour mission with 50W load).
- Green - Can meet a 3 day mission for less than 4 Kg.

Identified Problems

- For example the PS52A and PS53B (similar power and energy densities).
- But PS52A and PS53B has 7.2V and 21V voltages respectively.
- Both have maximum discharge current of 1.8A.

- Therefore, if operating voltage is 21 then the PS53B will still require 1.32Kg whereas the PS52A will require 3x1.2=3.6Kg

Identified Problems (Cont'd)

- **Energy (Wh)=(Volts)(Amperes)(Hours)**
- **Hence Energy of 480Wh could mean:**
  - 21V, 0.95A and 24 hours
    - PS53B requires a total weight of 1.32Kg
    - PS52A requires a total weight of 3.6Kg
  - 5V, 9.6A and 10 hours
    - Step-Down DC-DC Conversion Required
      - PS53B requires a total weight of 2x1.32Kg
        - (5V/21V=2.3A/9.6A) hence 2 parallel modules
      - PS52A requires a total weight of 4x1.2Kg
        - (5V/7.2V=6.7A/9.6V) hence 4 parallel modules

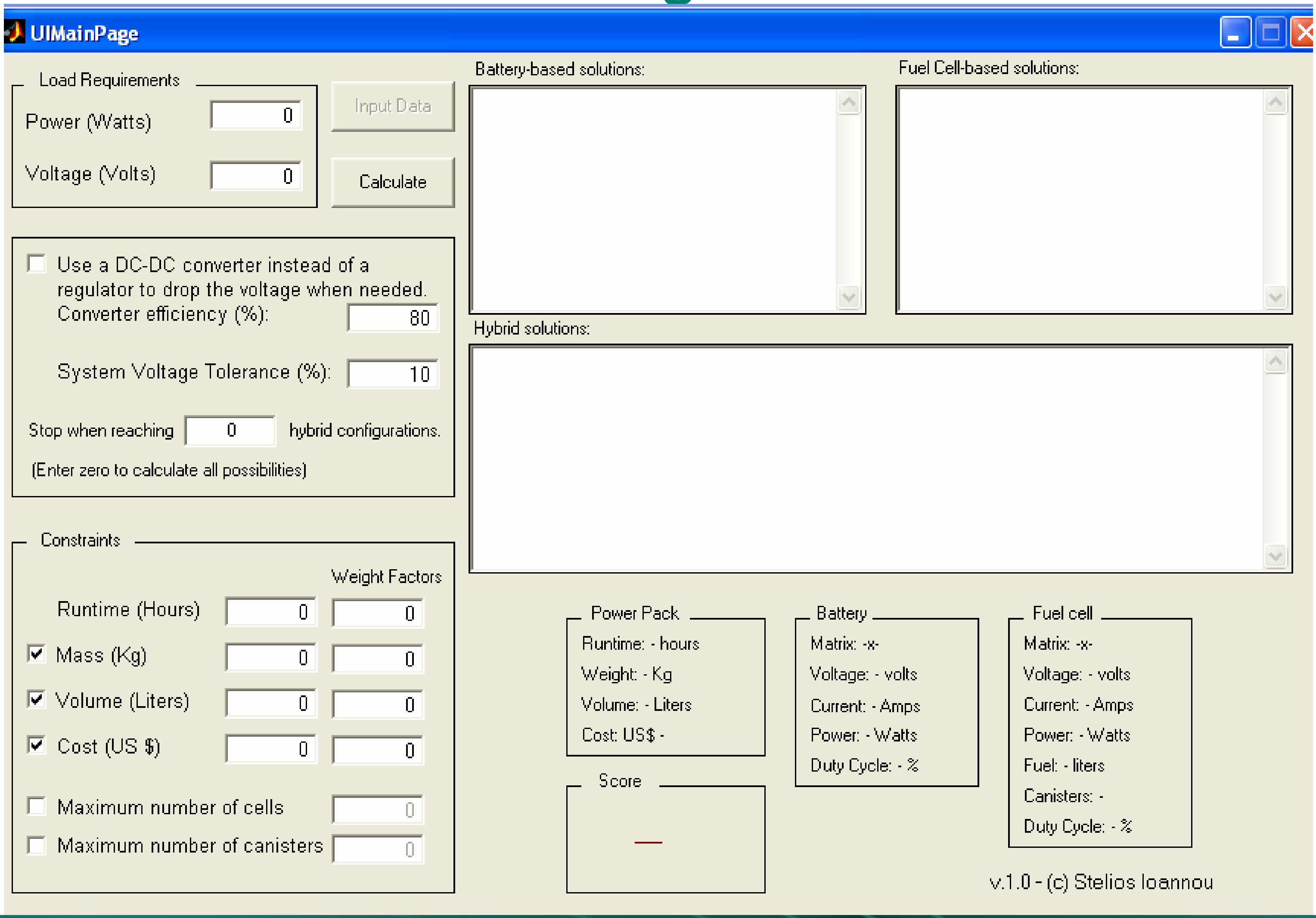
Identified Problems (Cont'd)

- Highest Power and Energy Densities does not guaranty least weight; Load voltage and current should be considered.
- Loss of capacity at higher discharge currents is neglected hence linear runtime is not accurate.
- Linear Runtime (Hrs) = Energy (Wh) / Power (W)

Preliminary Conclusions

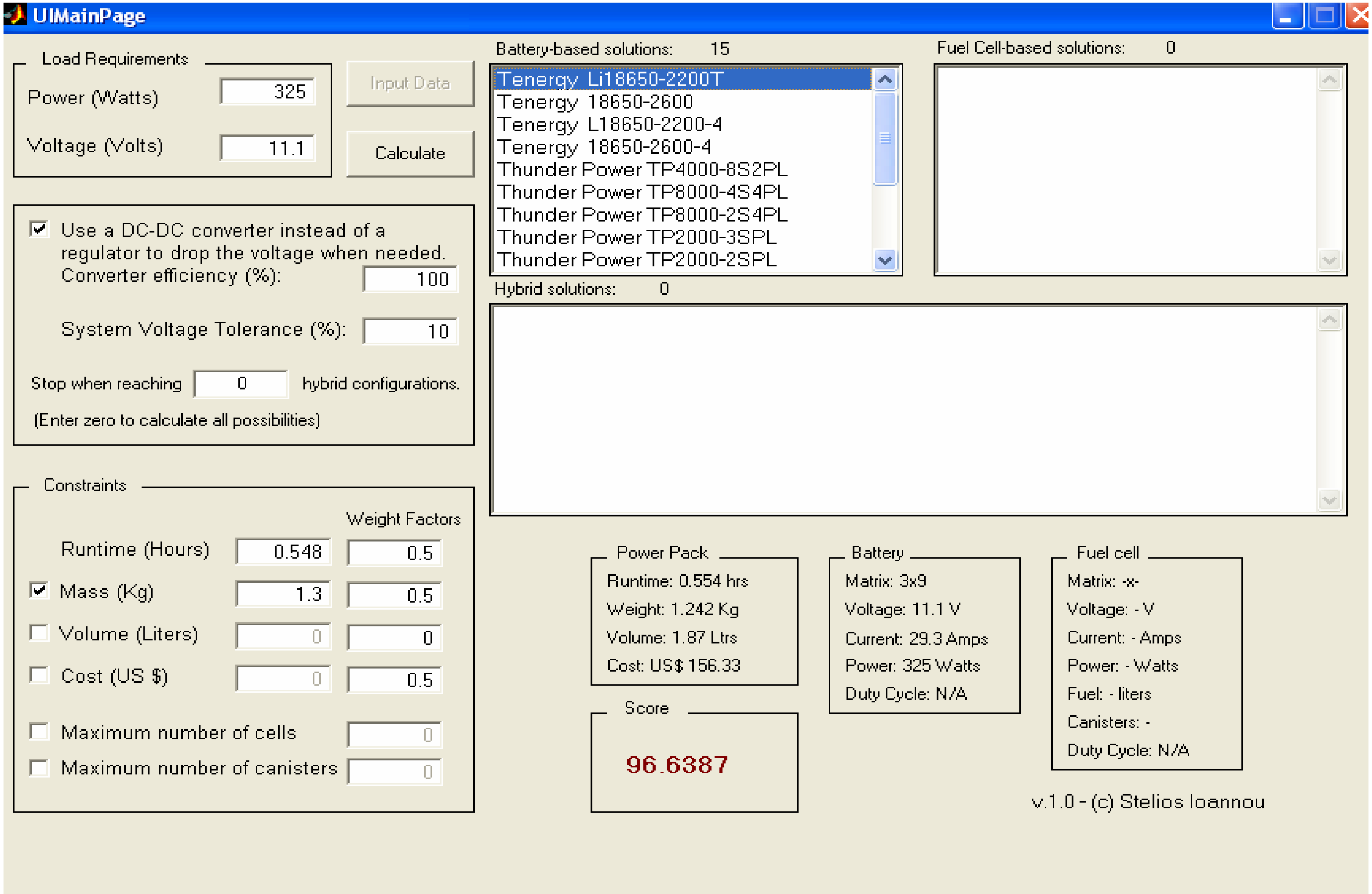
- **Need for the accurate prediction of battery runtime.**
- **Need for the accurate prediction of battery remaining energy.**
- **Need for a tool that can properly size energy and power systems.**
  - Include Hybrid Systems.
  - Excel is too complicated for such task.

Optimization Algorithm for Power and Energy System Configuration



Optimized Energy and Power Solutions

Aero-modeling Application 325W, 11.1V, 1.3Kg and 0.548 Hours

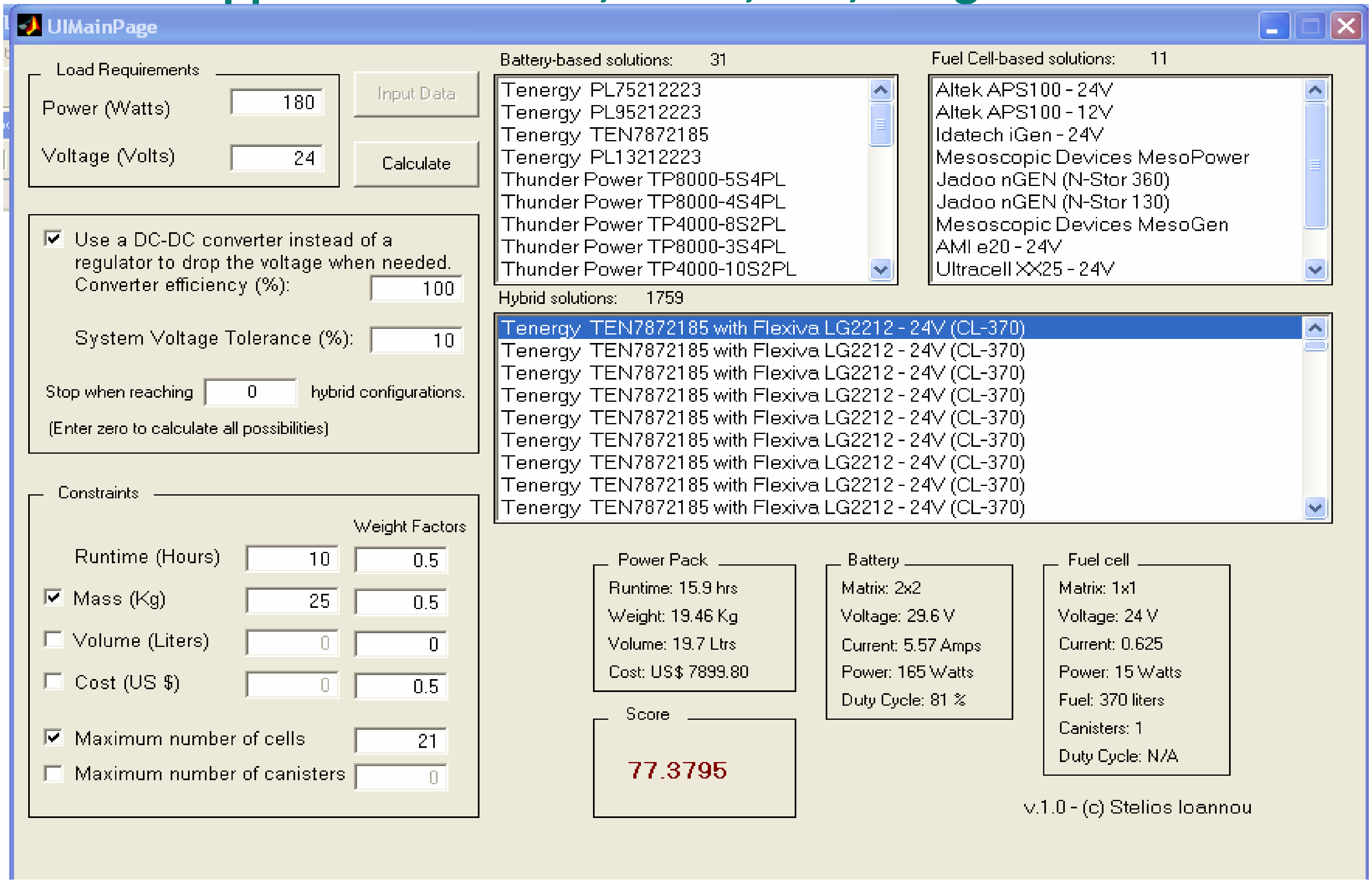


Optimized Energy and Power Solutions (Cont'd)

Score	Brand / Model	Voltage (Volts)	Matrix s x p	Total Weight (Kg)	Runtime (Hrs)	Total Price US$	Volume (Ltrs)	Duty Cycle %
96.64	T/Li18650-2200T	11.1	3 x 9	1.242	0.554	156.33	1.87	Na
90.62	T/18650-2600	11.1	3x8	1.104	0.584	239.76	1.61	Na
90.10	T/Li186502200-4	14.8	1x7	1.187	0.576	216.65	0.652	75
75.68	T/18650-2600-4	11.1	3x8	1.104	0.584	767.04	1.61	Na
73.58	TP4000-8S2PL	29.6	1x2	1.244	0.601	699.90	0.735	38
73.52	TP8000-4S4PL	14.8	1x2	1.266	0.601	659.90	0.74	75
72.75	TP8000-2S4PL	14.8	2x2	1.28	0.601	699.90	0.742	75
71.86	TP2000-3SPL	11.1	1x10	1.2	0.56	729.50	0.65	Na
71.83	TP2000-2SPL	14.8	2x8	1.28	0.601	799.20	0.676	75
71.82	TP2000-4SPL	14.8	1x8	1.28	0.601	799.60	0.65	75
71.82	TP4000-2S2PL	14.8	2x4	1.28	0.601	799.60	0.87	75
71.29	TP6000-5S3PL	18.5	1x2	1.254	0.56	659.90	0.748	60
71.09	TP4000-5S2PL	18.5	1x3	1.248	0.56	689.85	0.778	60
69.96	T/Li186502200-4	11.1	3x9	1.242	0.554	782.73	1.81	Na
69.86	TP4000-3S2PL	11.1	1x5	1.275	0.56	749.75	0.786	Na

Optimized Energy and Power Solutions

ATRV-Jr Application 10Hour, 180W, 24V, 25Kg and max. 21 cells



Mathematical Modeling

- **Mathematical modeling of power systems is not a new field, especially for batteries.**
  - Physical – Detailed description of physical processes.
  - Empirical – Equations with empirically fitted parameters.
  - Abstract – Batteries represented as electrical circuits.
  - Mixed models – Combination of the above.

- **Mathematical models are evaluated based on accuracy, computational complexity, configuration and analytical insight.**

- ***Based on the application, design engineers have used these models for optimal power management algorithms as well as customizing power sources under volume and weight constraints***

Most Commonly Used Empirical Model

- **Peukert's Law or Peukert’s Equation**
  - Peukert was the first to establish a mathematical relationship between battery capacity and discharge current in 1897.

$$C_p = I^p t$$

where C_p is Peukert Capacity, I is discharge current, t is runtime and p is Peukert exponent.

Most Common Model (Cont'd)

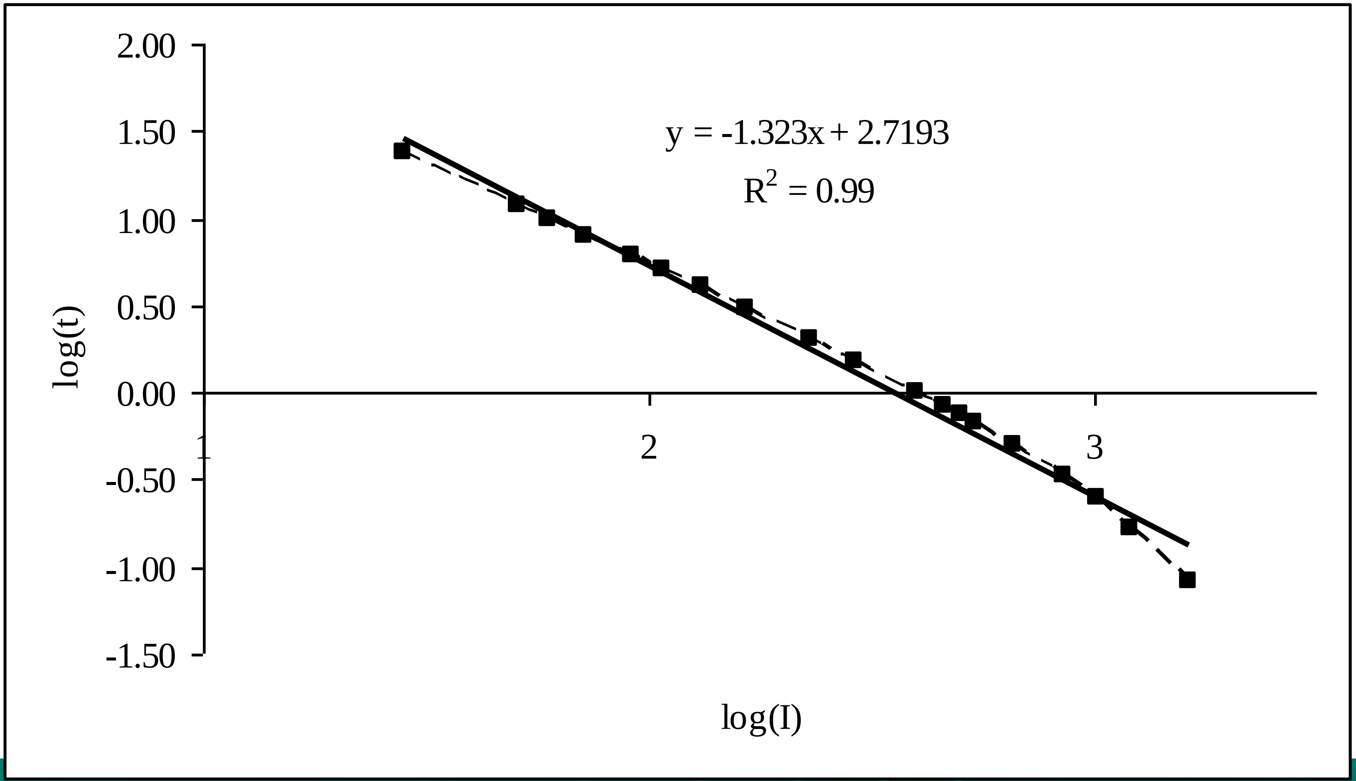
- **Because manufacturers record battery capacities at different discharge currents and times then Peukert's equation can be re-written as:**

$$t_2 = \frac{\left(\frac{C_1}{t_1}\right)^p t_1}{I_2{}^p}$$

where subscript *1* is for reference or advertised values and subscript *2* is for new discharge values.

Peukert's Exponent

- Peukert's Exponent is a constant value that depends on the battery.
- It can be graphically found

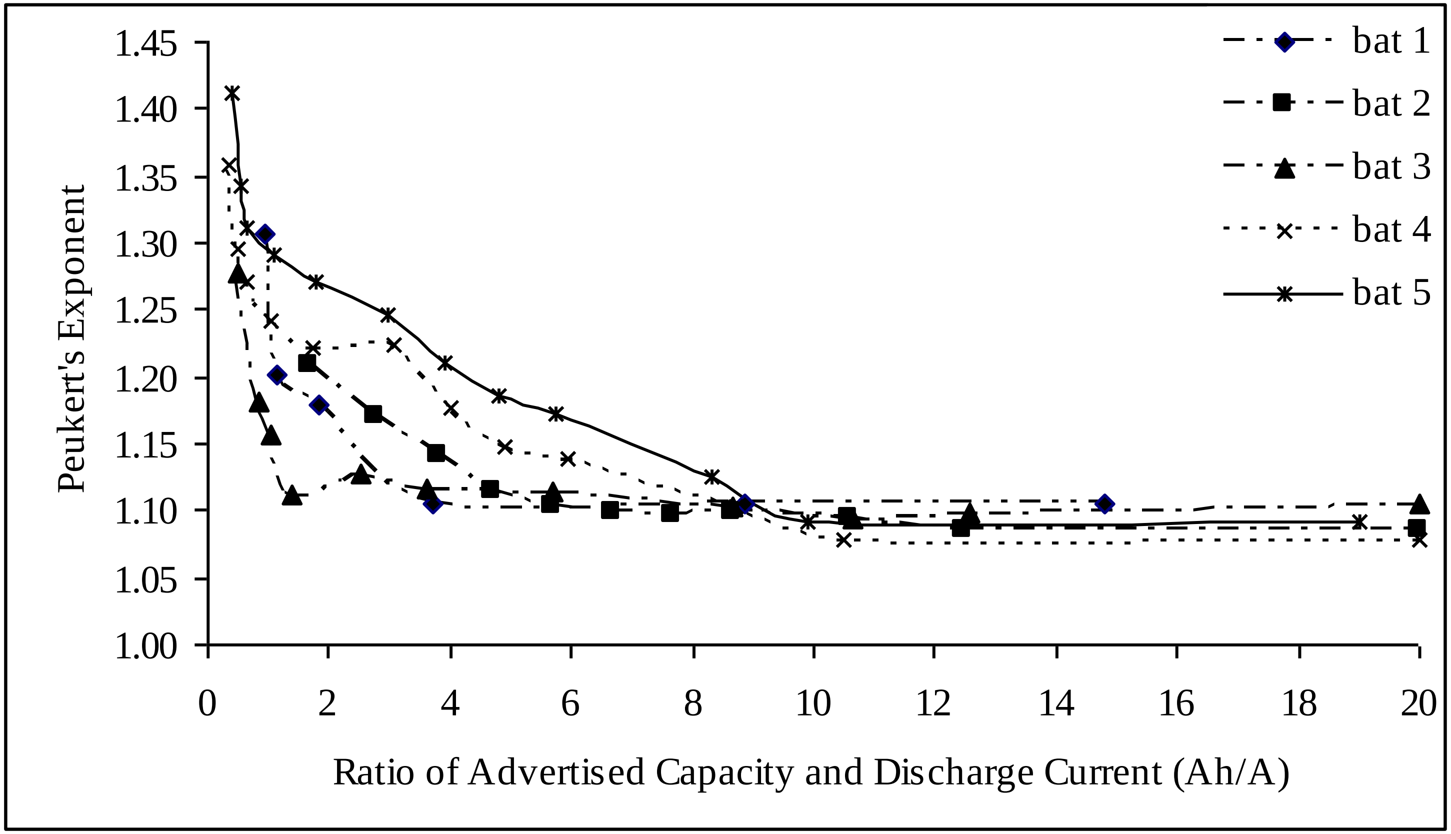


Peukert's Exponent (Cont'd)

- Calculated by the two data point method.

$$p = \frac{\log(t_2) - \log(t_1)}{\log\left(C_1 / t_1\right) - \log\left(C_2 / t_2\right)} = \frac{\log(t_2) - \log(t_1)}{\log(I_1) - \log(I_2)}$$

Peukert's Exponent (Cont'd)



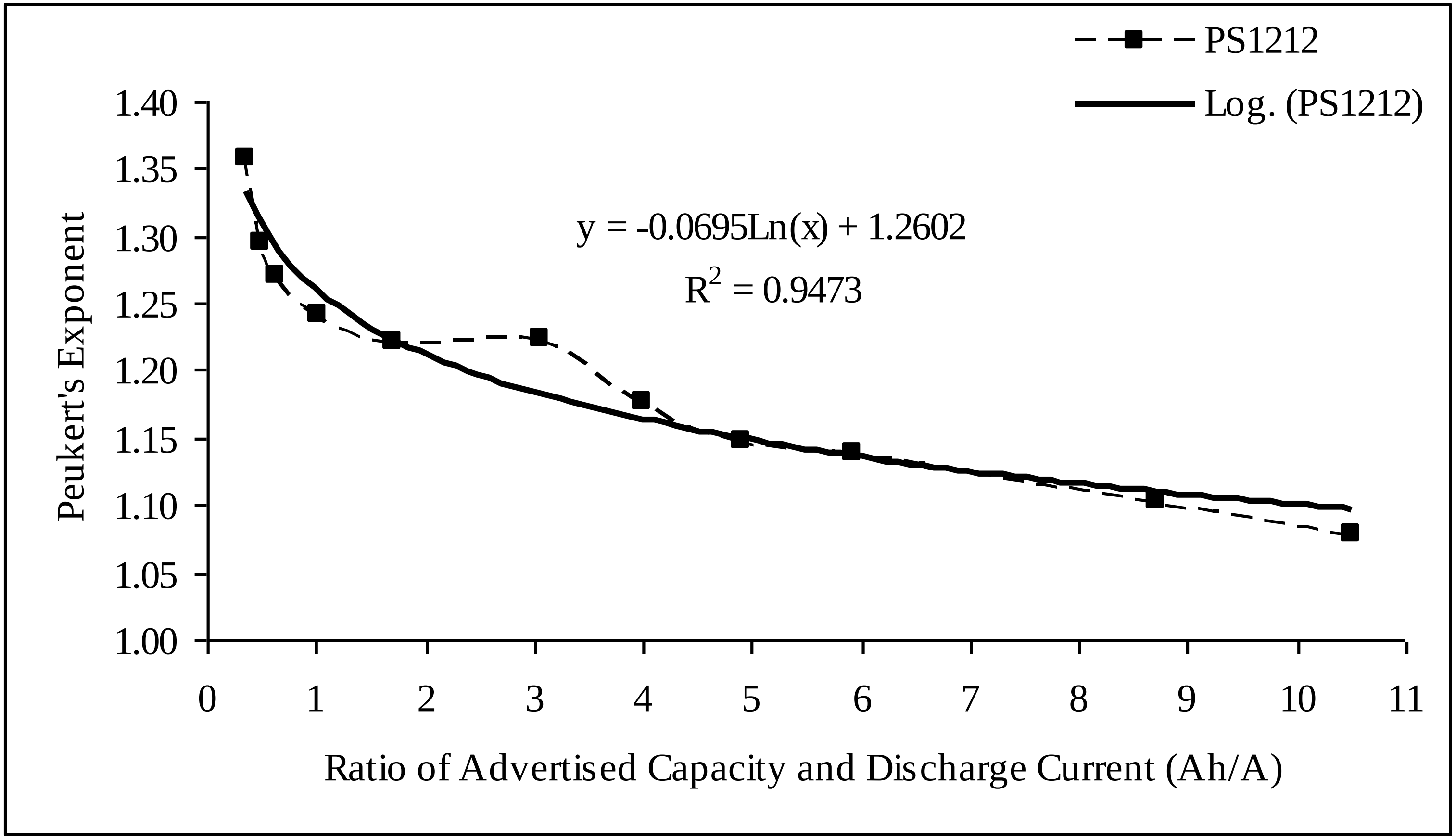
- It can be seen that Peukert's Exponent is not constant and significantly increases at discharge times less than 4 hours.

Proposed Variable Exponent Model

$$t = \frac{t_{ref}\left(C/t_{ref}\right)^{a-b\ln\left(\frac{C}{I}\right)}}{I^{a-b\ln\left(\frac{C}{I}\right)}} = t_{ref}\left(\frac{C/t_{ref}}{I}\right)^{a-b\ln\left(\frac{C}{I}\right)}$$

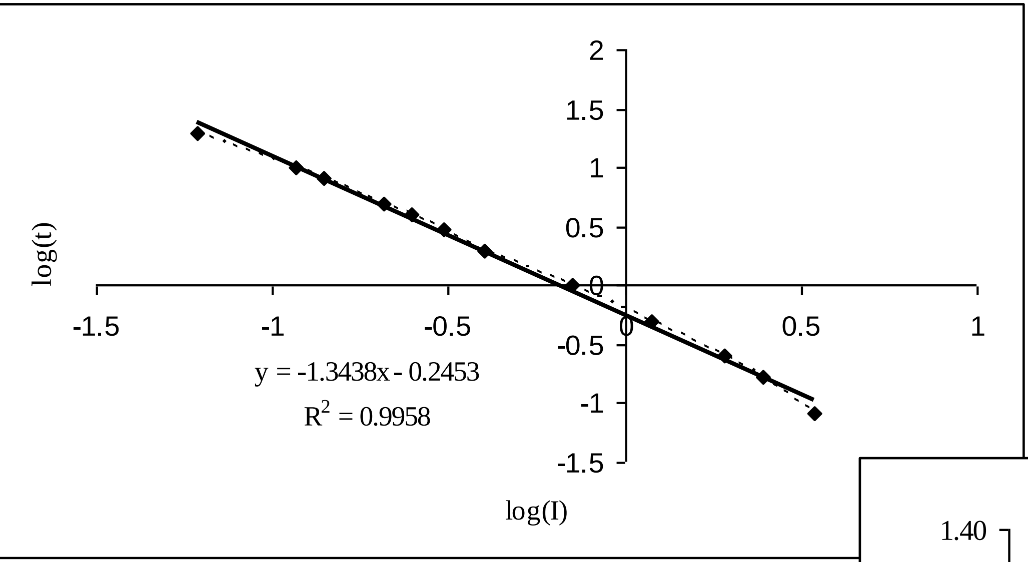
- **Where *a* and *b* depend on the specific battery and as before t_{ref} and *C* are the nameplate values for the discharge time and capacity, respectively.**

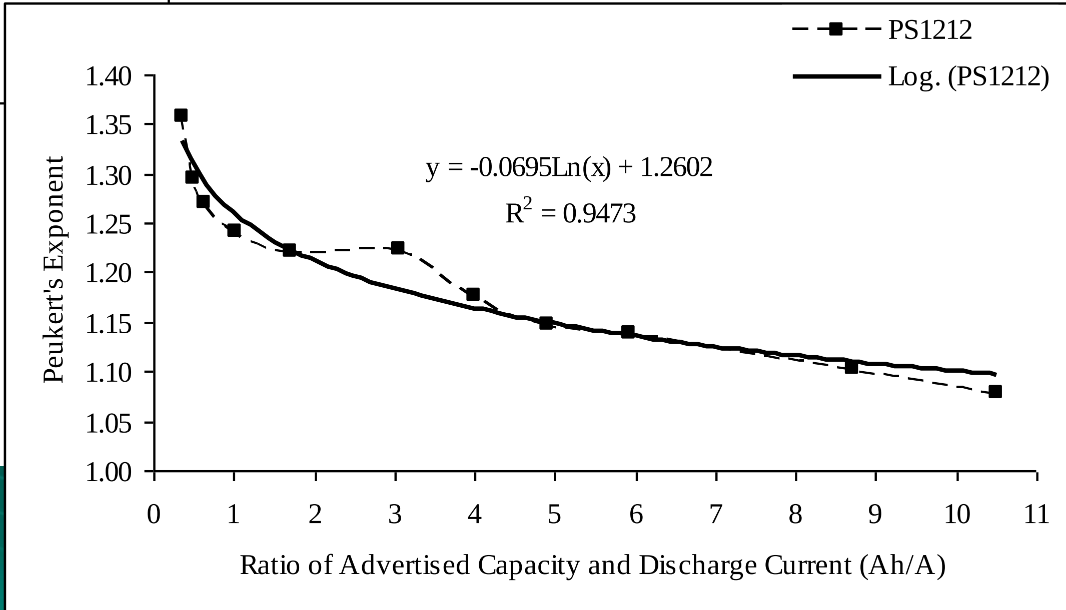
Graphical Estimation of *a* and *b*



Comparison of Results

Comparison of Results for PS1212 Lead Acid Battery

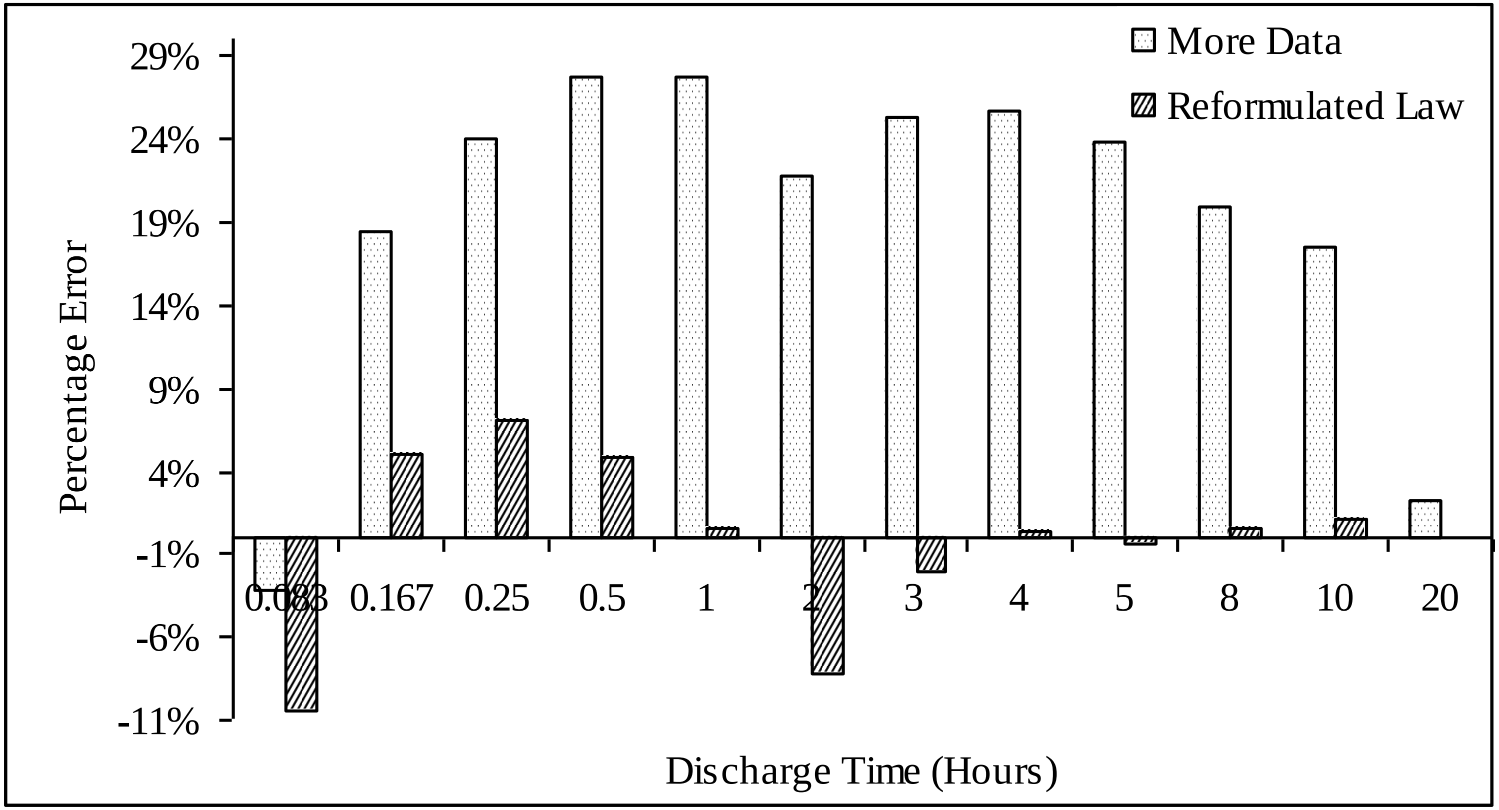




Comparison of Results
(PS1212 Lead Acid Battery)

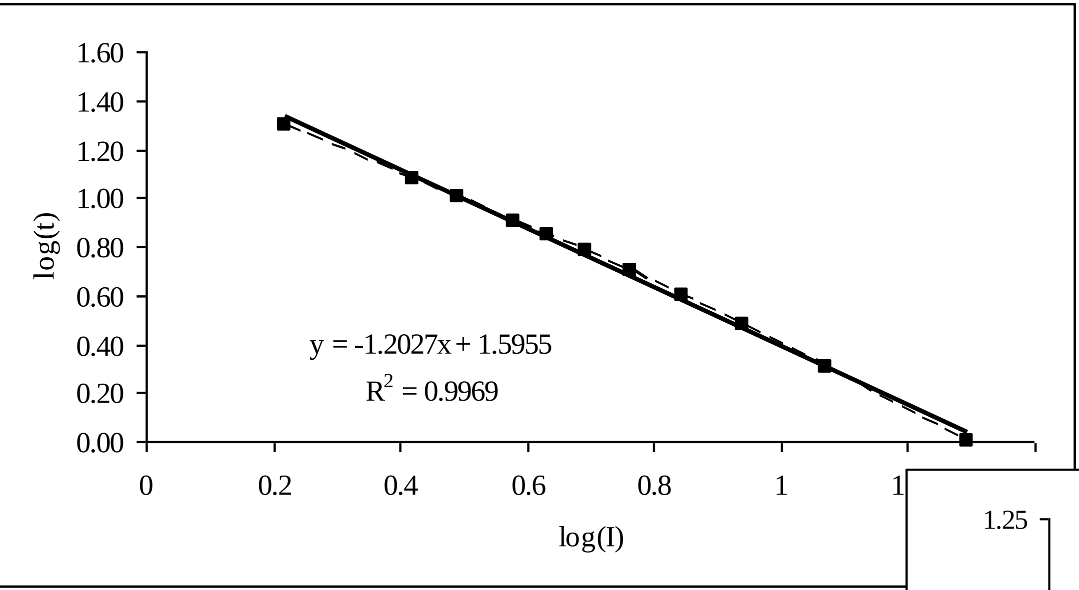
Datasheet Runtime (hr)	Linear t = C/ I % Error	$t=t_{ref}[(C/t_{ref})/I]$^1.3438 % Error	$t=t_{ref}[(C/t_{ref})/I]$^1.078 % Error	Reformulated Law % Error
20.0000	1.64%	2.20%	1.77%	0.00%
10.0000	-3.45%	17.53%	1.77%	1.16%
8.0000	-7.14%	19.93%	-0.25%	0.56%
5.0000	-16.50%	23.76%	-5.75%	-0.31%
4.0000	-20.97%	25.73%	-8.22%	0.28%
3.0000	-30.72%	25.34%	-15.03%	-2.00%
2.0000	-50.00%	21.87%	-29.25%	-8.16%
1.0000	-69.01%	27.72%	-39.21%	0.49%
0.5000	-101.68%	27.79%	-59.52%	4.86%
0.2500	-150.00%	24.06%	-90.45%	7.07%
0.1667	-192.68%	18.36%	-118.67	5.04%
0.0833	-316.18%	-3.25%	-202.73	-10.43%

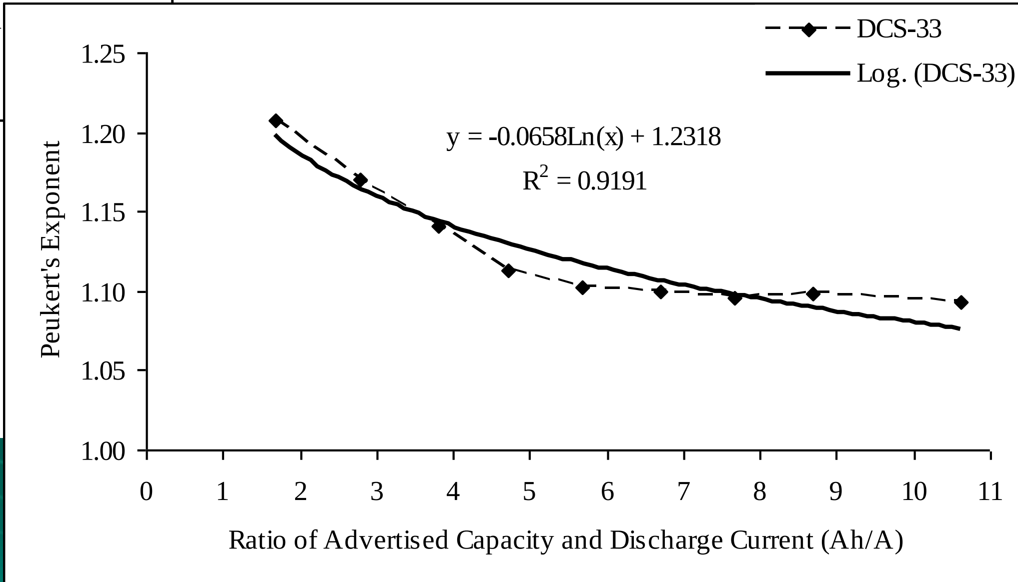
Comparison of Results (Cont'd)



Comparison of Results (Cont'd)

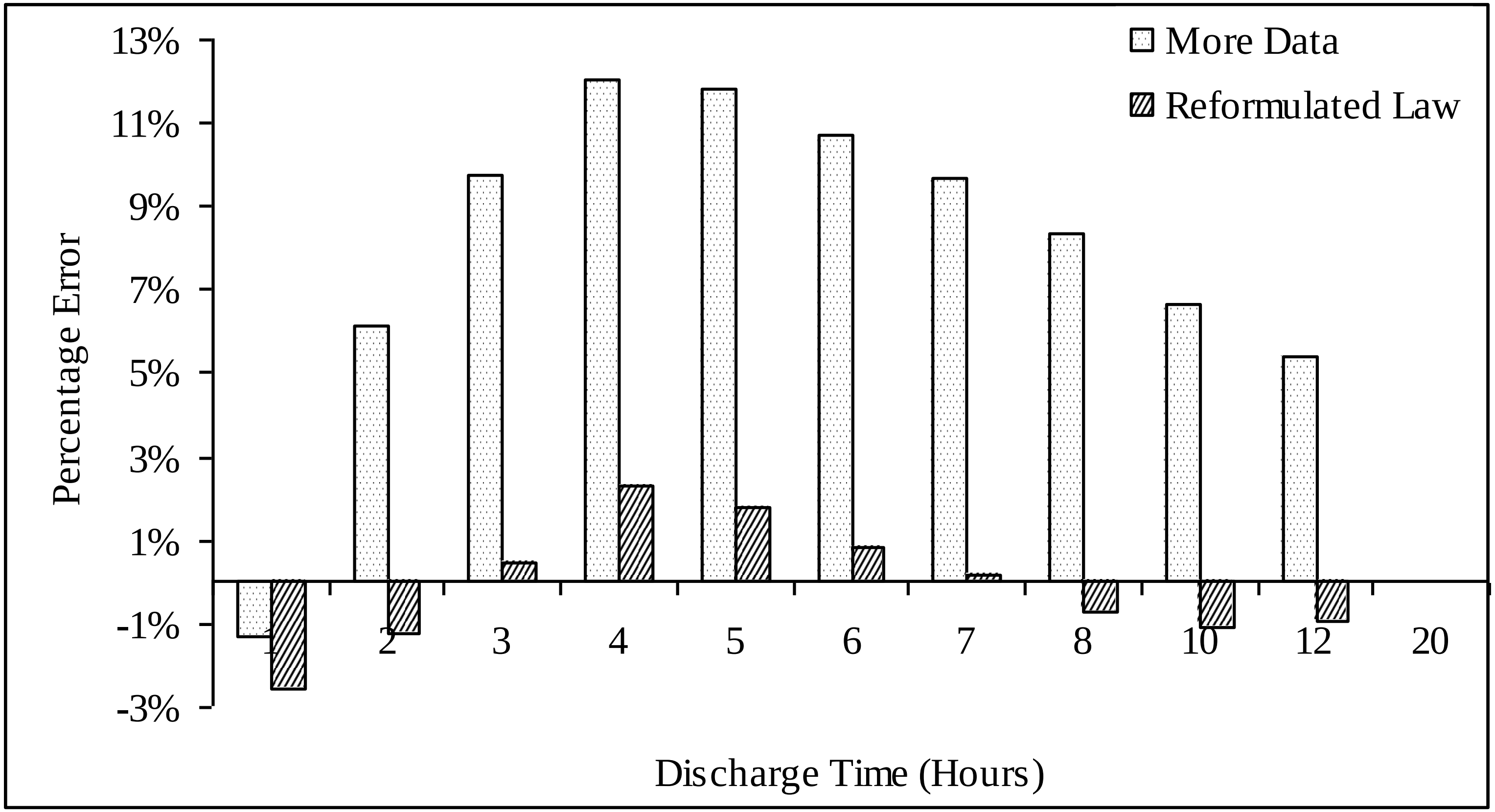
Comparison of Results for DCS-33 Lead Acid Battery





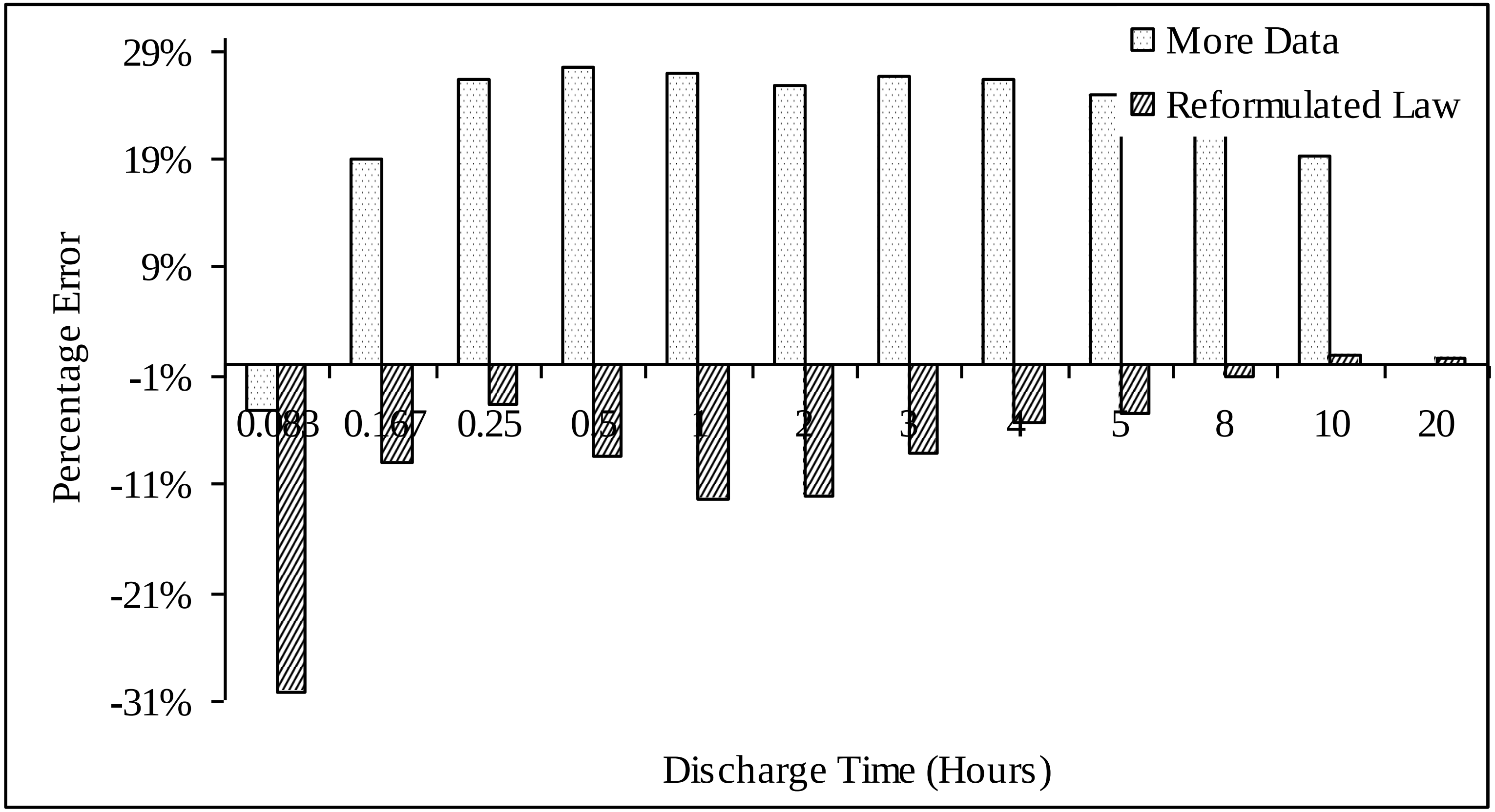
Comparison of Results (Cont'd)

Comparison of Results for DCS-33 Lead Acid Battery



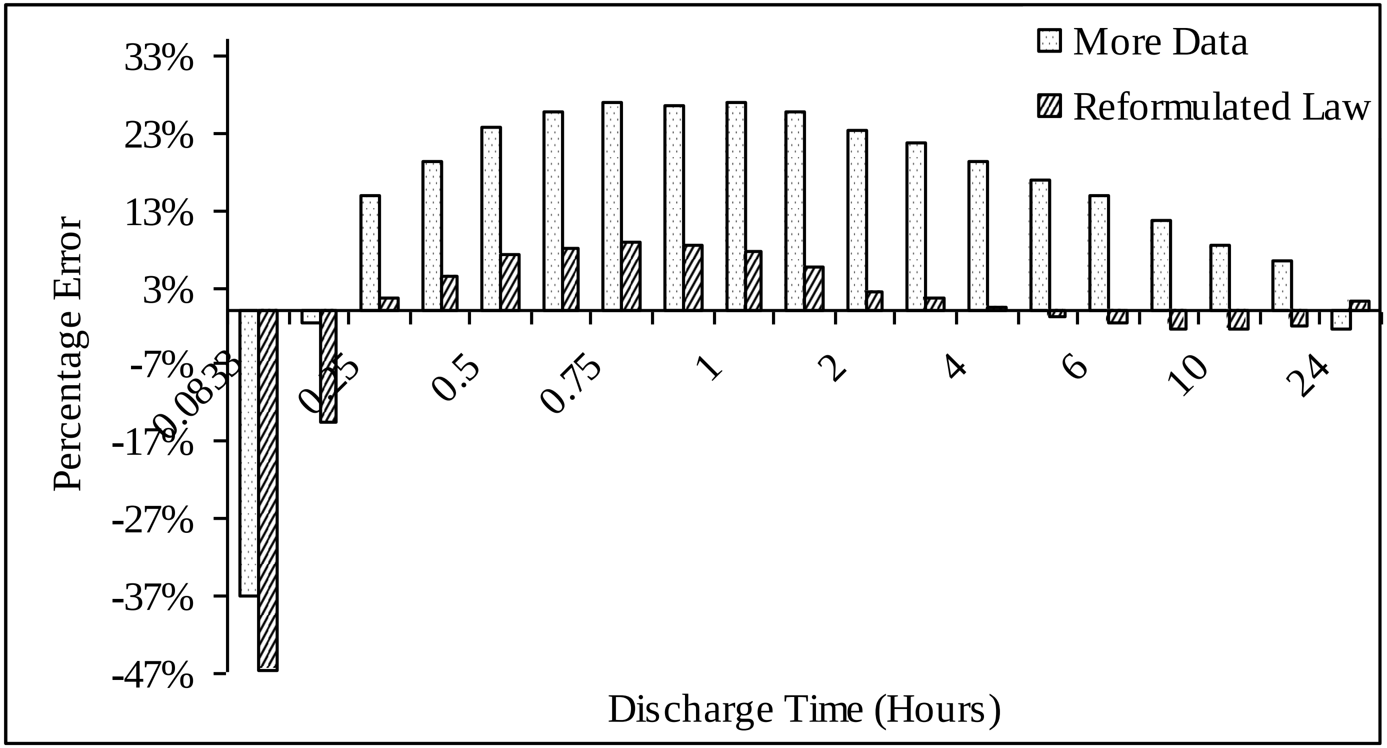
Comparison of Results (Cont'd)

Comparison of Results for PS12380 Lead Acid Battery



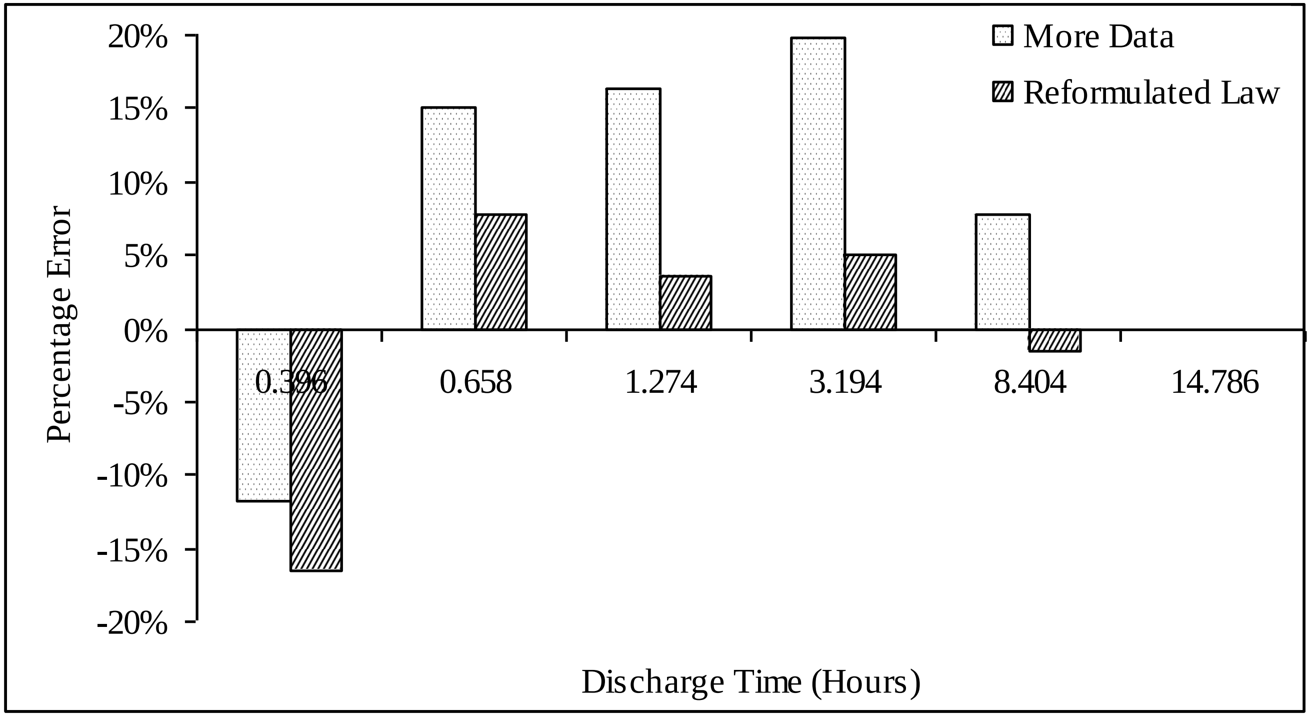
Comparison of Results (Cont'd)

Comparison of Results for PRC-6200S Lead Acid Battery



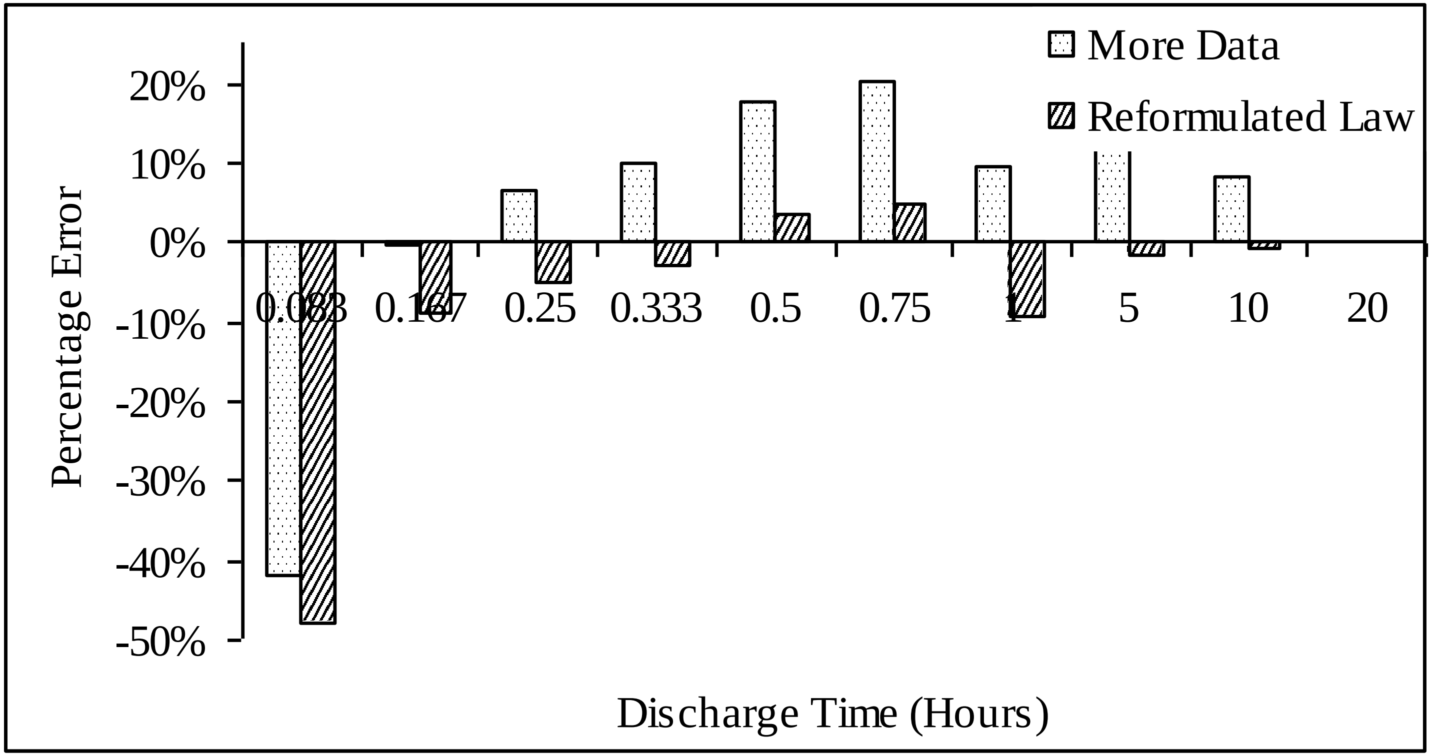
Comparison of Results (Cont'd)

Comparison of Results for 6.654Ah at 14.786 hours



Comparison of Results (Cont'd)

Comparison of Results for PSH-12180FR Lead Acid

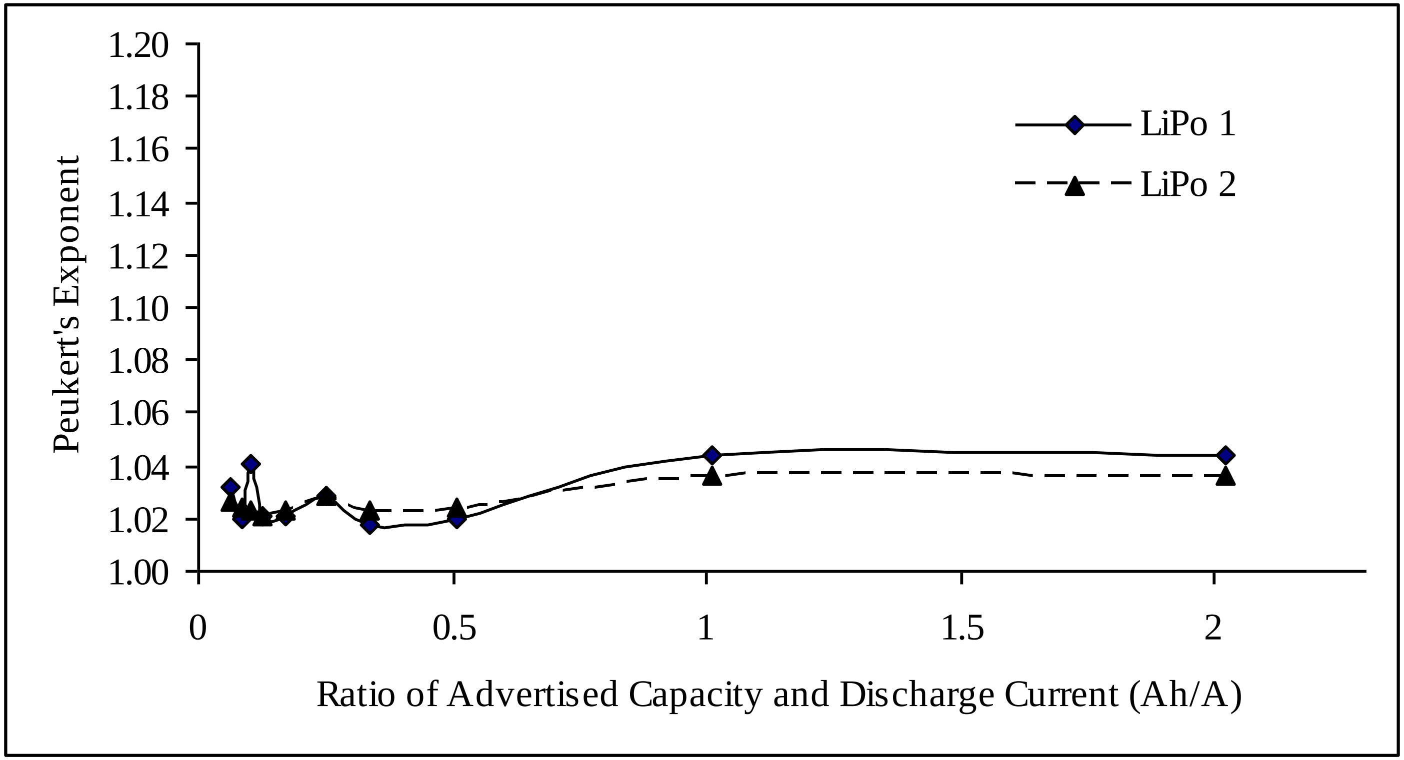


Comparison of Results (Cont'd)

- From Comparison of results it can be seen that accuracy improves with extensive battery characterization.

- But it is very time consuming.

Peukert's Law for Lithium Batteries



- Peukert's Exponent for Lithium Batteries is Constant.

Peukert's Law for Lithium Batteries (Cont'd)

Datasheet	Linear $t = C/I$	$t=t_{ref}[(C/t_{ref})/I]$^1.0233	$t=t_{ref}[(C/t_{ref})/I]$^1.0367
Runtime (hr)	% Error	% Error	% Error
2.027	0.23%	0.00%	0.00%
0.988	-2.33%	-0.93%	0.00%
0.490	-3.17%	-0.13%	1.71%
0.324	-4.06%	-0.04%	2.33%
0.239	-5.81%	-1.05%	1.73%
0.159	-5.69%	0.02%	3.29%
0.119	-5.81%	0.57%	4.20%
0.094	-7.06%	-0.08%	3.86%
0.078	-7.57%	-0.12%	4.05%
0.058	-9.37%	-1.13%	3.46%

- The two data point method, has a maximum error of only 4.2%.
- The extensive characterization method, has a maximum error of only 1.13%
- The linear method has a maximum error of 9.37% which for a 3 minute discharge time the runtime deviation is only 280 milliseconds.

Remaining Battery Energy Estimation

- **1st Model**

$$C_{remain} = C_{total} - \int_0^t i(t)dt$$

- **2nd Model**

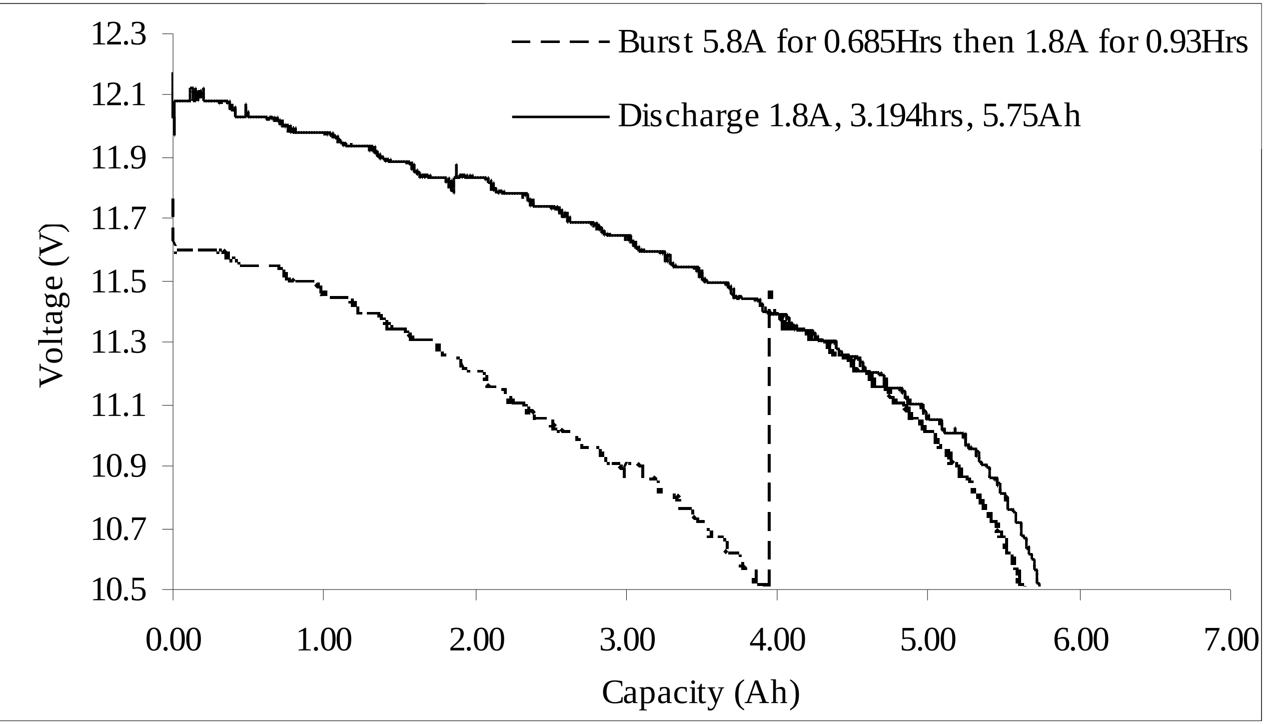
$$C_{remain} = eC_{total} - \int_0^t i(t)dt$$

- **Proposed Model**

$$C_{remain} = ti_{LOAD} - \int_0^t i_{total}(t)dt$$

Where *t* is the runtime and is given by the reformulated equation. This new method can give the real time capacity estimation depending on the present load current and taking advantage of the variable exponent which leads to more accurate runtime calculations.

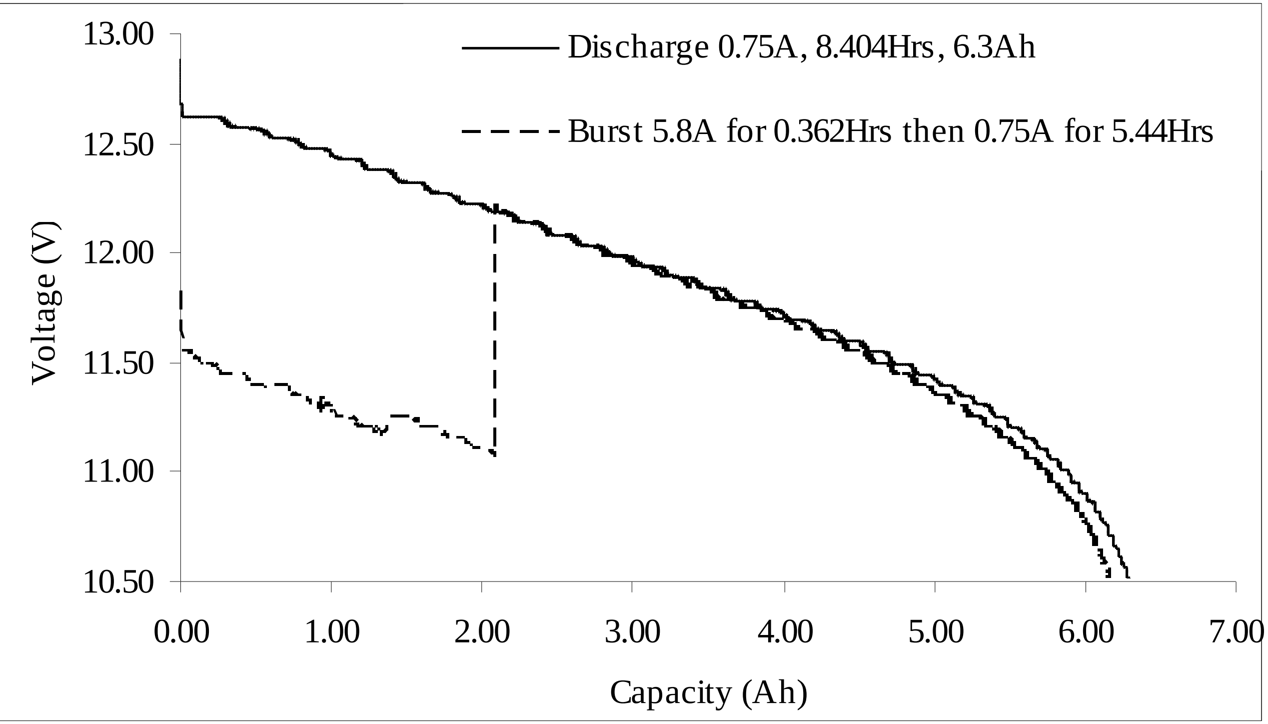
Results for the 6.65Ah at 14.786 hours



- Proposed Model Remaining Energy is 1.49Ah
- From Experimental Results is 1.67Ah
- 12% Difference

$$C_{remain} = (1.8)\left(14.786\left(\frac{6.65/14.786}{1.8}\right)^{1.2441-0.0776\left(\frac{6.65}{1.8}\right)}\right) - \int_{0}^{0.685} 5.8\,dt$$

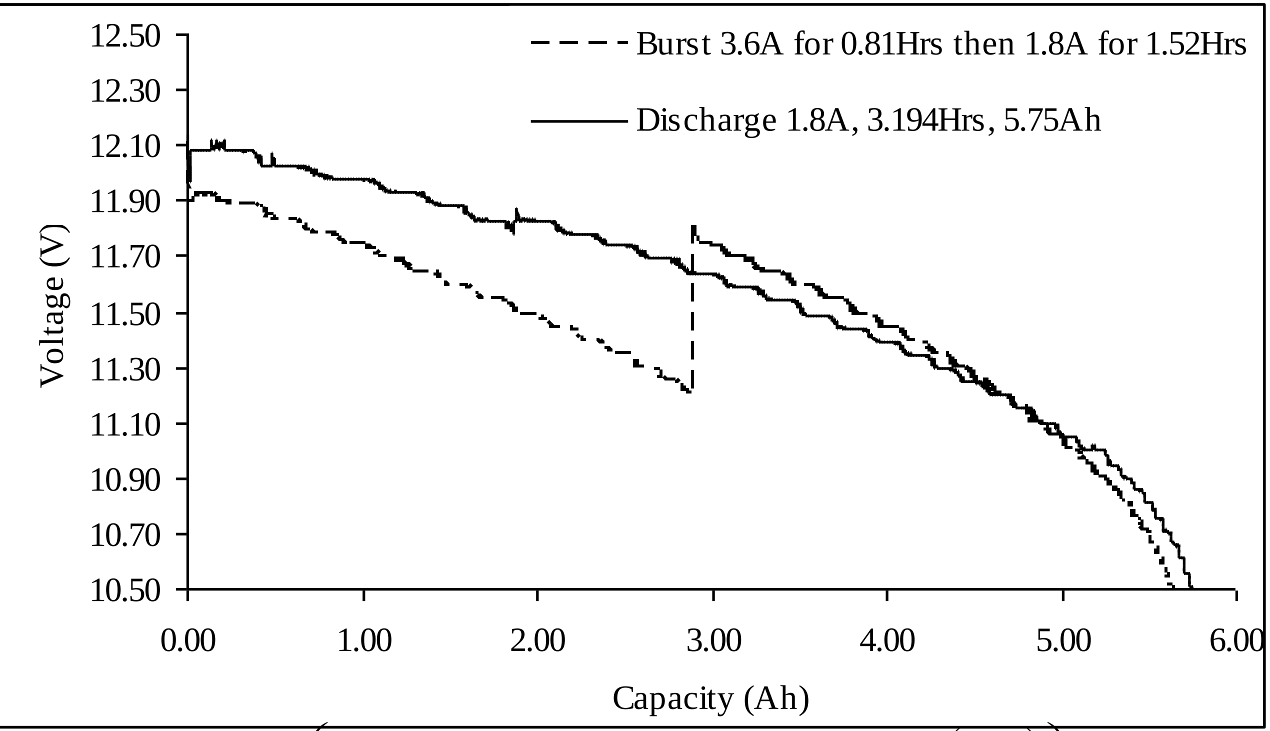
Results for the 6.65Ah at 14.786 hours (Cont'd)



- Proposed Model Remaining Energy is 4.3Ah
- From Experimental Results is 4.08Ah
- 5.4% Difference which translates to a runtime difference of 17.6 minutes in 326.4 minutes (5.44 hrs) operation.

$$C_{remain} = (0.75)\left(14.786\left(\frac{6.65/14.786}{0.75}\right)^{1.2441-0.0776\left(\frac{6.65}{0.75}\right)}\right) - \int_{0}^{0.362} 5.8dt$$

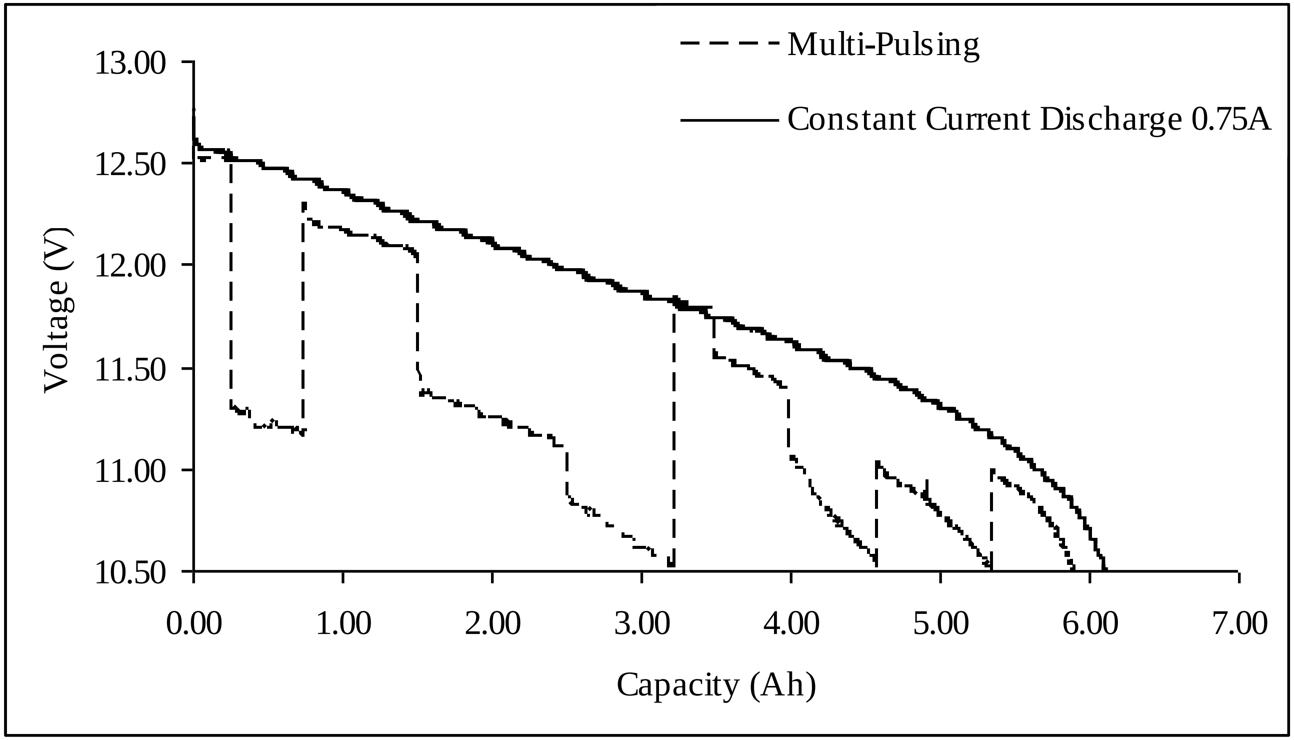
Results for the 6.65Ah at 14.786 hours (Cont'd)



$$C_{remain} = (1.8)\left(14.786\left(\frac{6.65/14.786}{1.8}\right)^{1.2441-0.0776\left(\frac{6.65}{1.8}\right)}\right) - \int_0^{0.81} 3.6\,dt$$

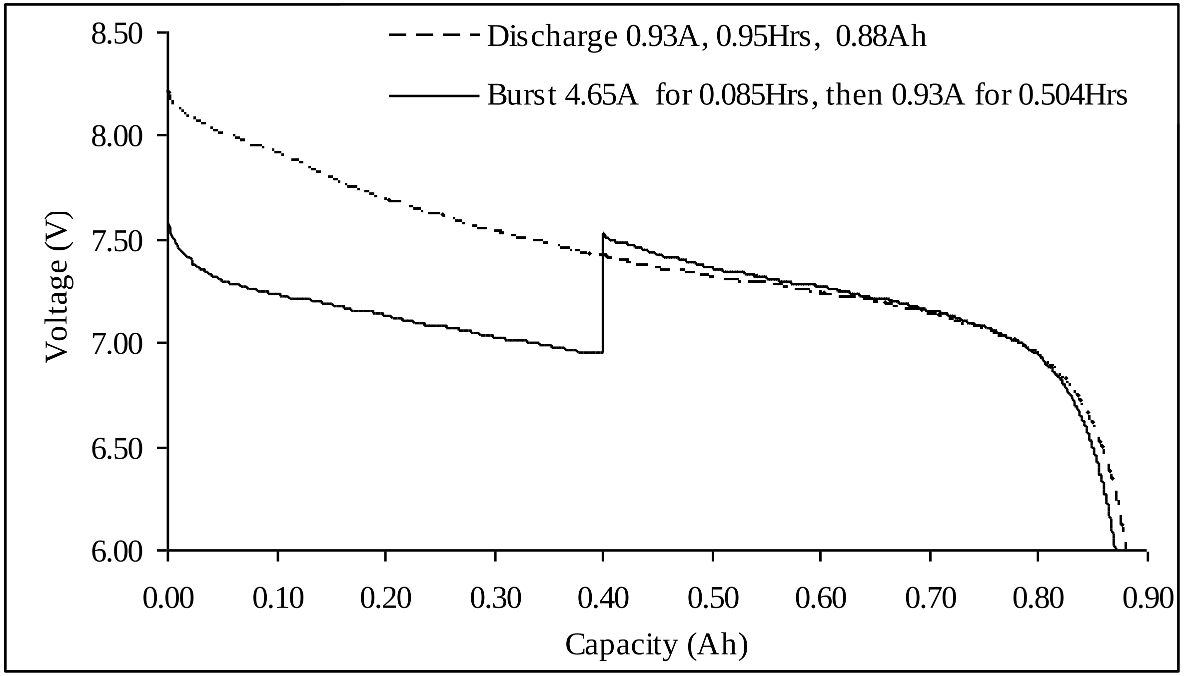
- Proposed Model Remaining Energy is 2.53Ah
- From Experimental Results is 2.74Ah
- The 8.14% difference translates to a runtime difference of 7.44 minutes out of 91.33 minutes (1.52 hours) of operation.

Results for the 6.65Ah at 14.786 hours (Cont'd)



- Proposed Model Remaining Energy is 0.887Ah
- From Experimental Results is 0.9734Ah
- 9.73% Difference

Results for Lithium Batteries



- 7% Difference between experimental and theoretical results from proposed model.

Thank you !

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