



**AN EXPERIMENTAL INVESTIGATION TO IMPROVE
LEAD ACID BATTERY RECHARGING ALGORITHMS
FOR ENVIRONMENTAL PERFORMANCE**

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14. ABSTRACT Perform functional testing of lead acid batteries to demonstrate potential improvements to battery charging algorithms Rationale -Improving charging algorithms can improve battery lifetime -Current charging algorithms are constant voltage and may only provide for temperature compensation (if at all) -Variable voltage algorithms that also incorporating state-of-charge compensation can improve battery charge operations -Improving battery state of knowledge (charge status) can extend battery usage beyond SLI (starting, lights, ignition) operations to enable silent watch operations Approach -Characterize lead acid battery performance as a function of temperature -Three test phases identified and are being executed -Characterize battery environmental performance (OCV, resistance and capacity tests according to MIL-PRF-32143A) -Controlled alternator charging performance -Vehicle simulation tests					
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Program Overview

Goals

- Perform functional testing of lead acid batteries to demonstrate potential improvements to battery charging algorithms

Rationale

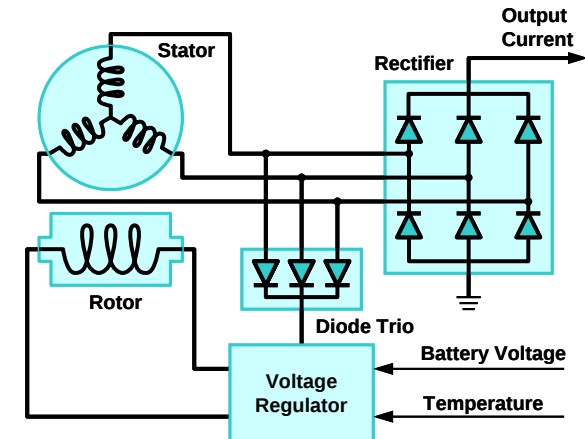
- Improving charging algorithms can improve battery lifetime
 - Current charging algorithms are constant voltage and may only provide for temperature compensation (if at all)
 - Variable voltage algorithms that also incorporating state-of-charge compensation can improve battery charge operations
- Improving battery state of knowledge (charge status) can extend battery usage beyond SLI (starting, lights, ignition) operations to enable silent watch operations

Approach

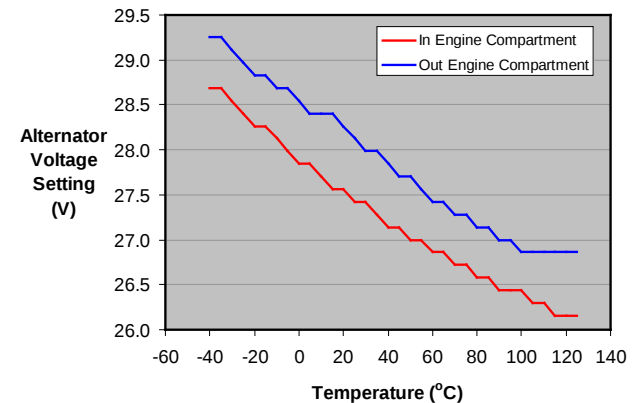
- Characterize lead acid battery performance as a function of temperature
- Three test phases identified and are being executed
 - Characterize battery environmental performance (OCV, resistance and capacity tests according to MIL-PRF-32143A)
 - Controlled alternator charging performance
 - Vehicle simulation tests

Alternator Operations

- Alternators provide current to provide battery charging and vehicle current demands
- Voltage regulator accepts voltage feedback from battery circuit
- Typical alternator circuits employ an adjustable rotor field current to provide desired output voltage (current)
- Alternator *may* employ temperature feedback from battery
 - Different algorithms are employed if batteries are co-located with the alternator (i.e. in engine compartment)
 - Vehicle packaging may dictate other locations
- In general, battery resistance decreases at higher temperatures
 - Reducing alternator output voltage at higher temperature reduces current output for battery recharging
- The greater depth of discharge exercised for silent watch (engine off) operations increases the need for state-of-charge and temperature compensation.



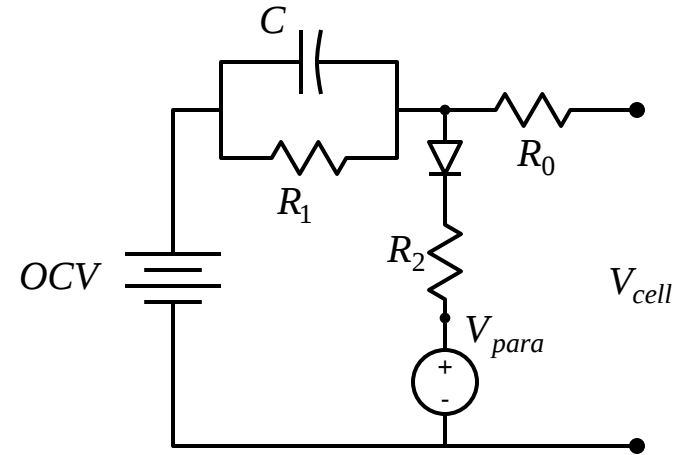
Typical Alternator Layout



Temperature Compensation Exemplar

Battery Equivalent Circuit

- Although many forms of equivalent circuit models exist, the most common form is the Thevinin equivalent circuit
- Battery is characterized by an open circuit voltage (OCV) source in series with an R-C pair and a line resistance, R_0
- A parallel charging resistance leg accounts for parasitic losses during charging operations
- Under steady-state operations (constant current), the battery direct current resistance (DCR) is characterized by the sum of resistances R_1 and R_0
- OCV is a function of battery state-of-charge (SOC)
- Resistance values are a function of battery SOC, temperature and current direction (charging vs discharging)
- Cell voltage (V_{cell}) and hence feedback voltage to the voltage regulator is a function of battery OCV, battery DCR and current demand



Thevinin Battery Equivalent Circuit

Open Circuit Voltage

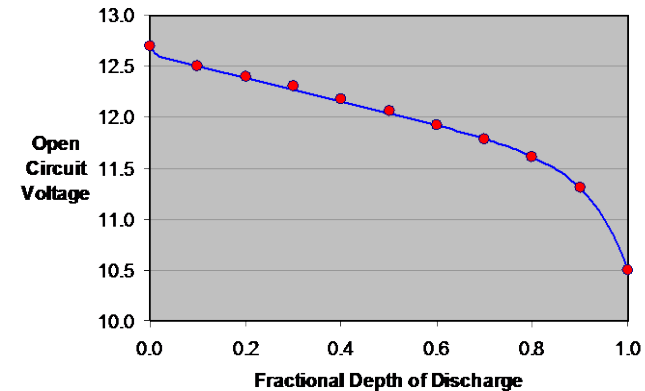
- Open circuit voltage (OCV) is a function of battery state-of-charge (SOC) $OCV = f(SOC)$
- Our suggested OCV correlation form superposes two exponential functions and a linear function

$$OCV = Ae^{-\alpha x} + B[1 - e^{-\beta(1-x)}] + Cx + D$$

x = fractional Depth of Discharge (DOD)

State of Charge, $SOC = 1 - x$

- This functional form captures near-full and near-empty nonlinearity, provides great flexibility and avoids inflection points associated with polynomial forms
- Two coefficients are found through boundary conditions (full & empty OCV) and negative slope imposes limits on a third
- Correlations exhibit very satisfactory agreement with manufacturer data



Typical OCV as a function of Depth of Discharge for a VRLA AGM Battery

Coefficient	Value
A	0.086
B	0.969
α	115.664
β	12.203
C	-1.145
D	11.645

OCV Coefficients for VRLA AGM Battery Manufacturer Data

SOC & Battery Capacity (Current Compensation)

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- SOC can be determined through Coulomb counting:

$$SOC = SOC_{t=0} - \frac{1}{C} \int_0^t I(\tau) d\tau$$

where C is battery capacity
and I is battery current

- However, battery capacity is a function of effective current rate and cell temperature

$$SOC = SOC_{t=0} - \frac{1}{C(\bar{I}, \theta)} \int_0^t I(\tau) d\tau$$

- Historically, cell capacity current compensation can be estimated with Peukert's Law

$$C(I) = (I_0/I)^{k-1} C_0$$

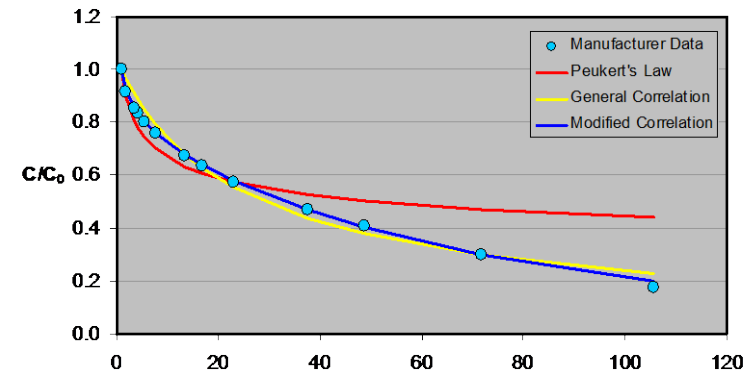
- However, Peukert's Law does not account for temperature effects AND can significantly overestimate capacity at high currents

- A literature survey showed the following general correlation can better estimate performance:

$$C(I) = \frac{\alpha}{1 + (\alpha - 1)(I/I_0)^\beta} C_0$$

- However, a modified correlation shows better agreement with manufacturer data

$$C(I) = \frac{\alpha(I/I_0)^\gamma}{1 + (\alpha - 1)(I/I_0)^\beta} C_0$$



**Battery Current
Compensation Correlations**

	General Correlation	Modified Correlation
α	1.073	1.001
β	0.808	1.532
γ	N/A	-0.122

**Current Compensation
Correlation Coefficients**

Battery Capacity (Temperature Compensation)

**POWER AND
MOBILITY**

- Temperature compensation looks to correct battery capacity
- A simple product solution is desired to couple the current and temperature compensation into a single form

$$C(I, \theta) = f_I(I) f_\theta(\theta) C_0$$

- For temperature compensation, we propose a power law of the form:

$$C(\theta) = C_0 \theta^\delta$$

where θ represents the dimensionless battery temperature

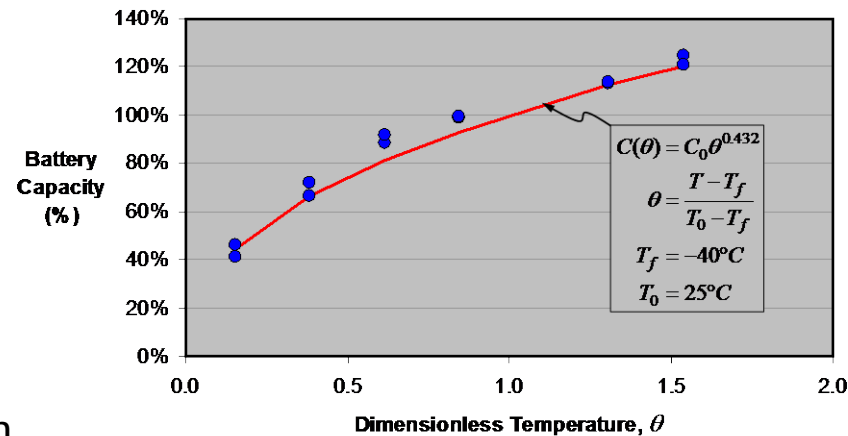
$$\theta = \frac{T - T_f}{T_0 - T_f}$$

- Limits in the dimensionless temperature have been chosen around the rated (nameplate) temperature, T_0 , and the approximate electrolyte freezing temperature, T_f

$$T_0 = 25^\circ\text{C} \quad \text{and} \quad T_f = -40^\circ\text{C}$$

- General form of the battery capacity compensation correlation:

$$C(I, \theta) = \frac{\alpha(I/I_0)^\gamma \theta^\delta}{1 + (\alpha - 1)(I/I_0)^\beta} C_0$$

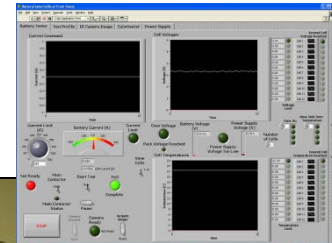


**Measured VRLA AGM Battery
Capacity Compensation
and
Temperature Correlation**

Environmental Testing (Key Apparatus)

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- Primary environmental testing utilizes the SAIC-developed Advanced Battery Tester coupled to an environmental chamber
- Environmental chamber allows for controlled ambient conditions / battery tempering
- Battery tester allows for programmable time-variant test load profiles under a variety of conditions
- Custom software allows for real-time data display, processing and storage
- Instrumentation includes current, voltage and temperatures



**Battery
Tester
Software**

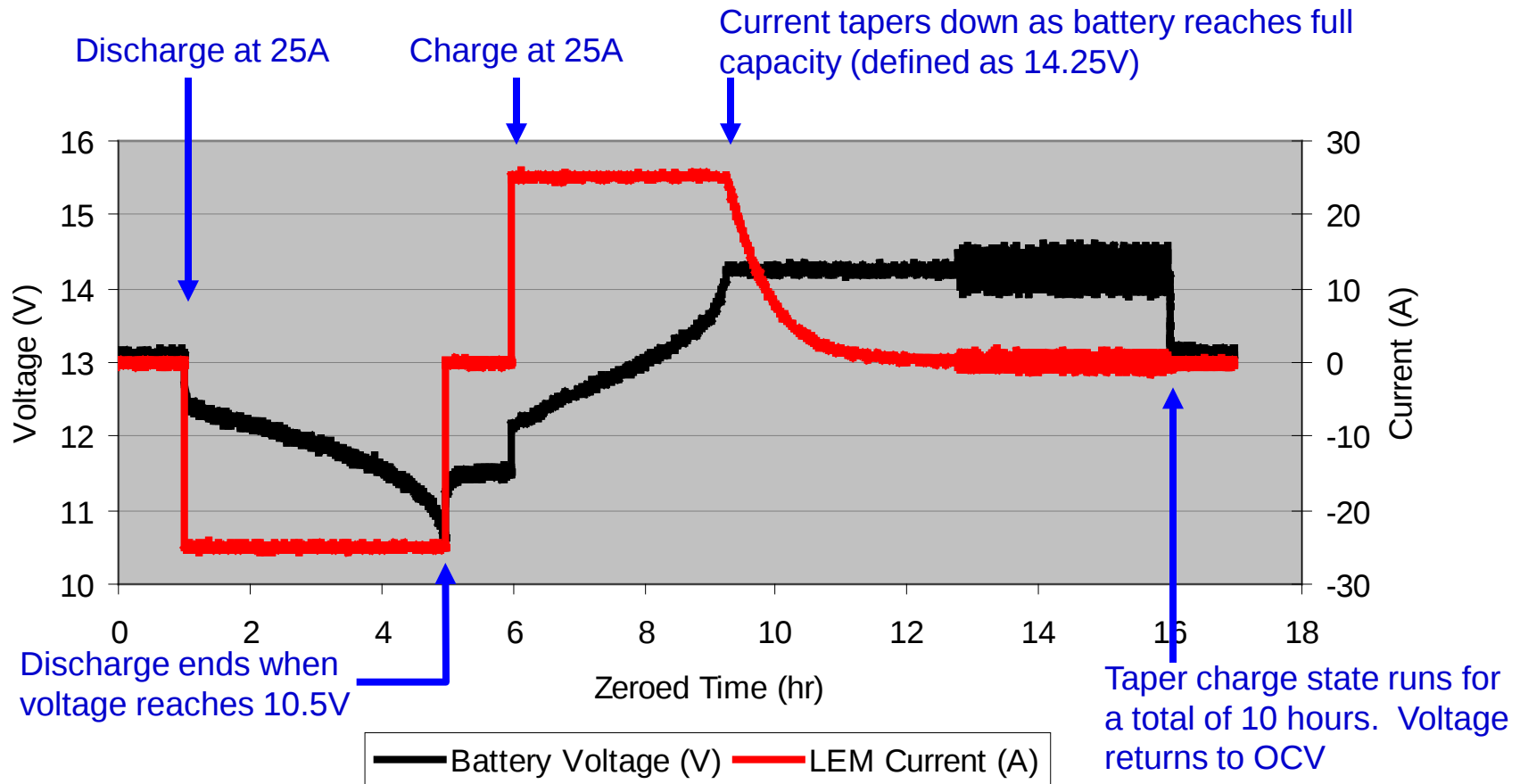
**Environmental
Test Chamber**

**Advanced
Battery
Tester Unit**

Environmental Testing (Reserve Capacity Test)

**POWER AND
MOBILITY**

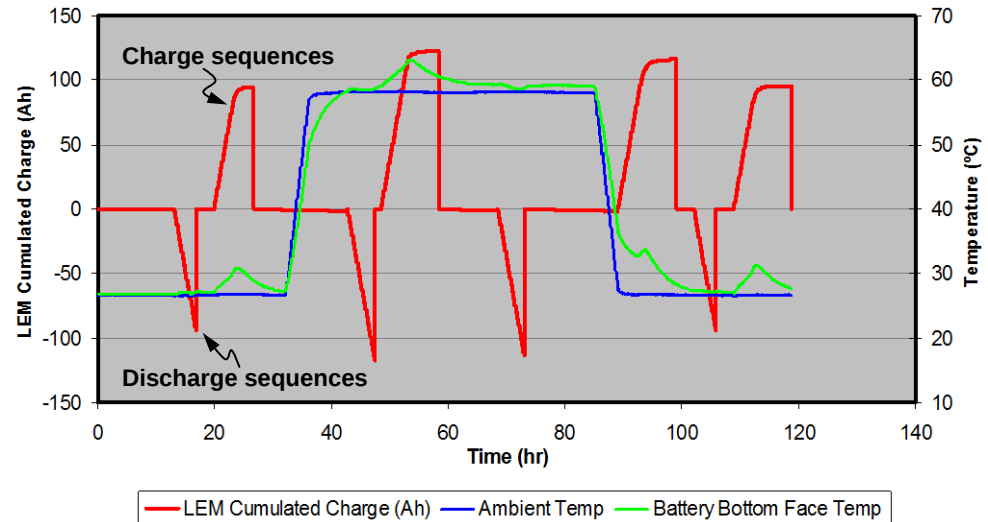
- Environmental testing has used the standard reserve capacity test (MIL-PRF-32143A)



Environmental Testing (General Procedure)

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- Batteries are initially tempered to median ambient temperature (27°)
 - Reserve capacity and recharge according to MIL-PRF-32143A
- Battery test article is tempered to target temperature
 - Reserve capacity test at temperature
 - Recharge at temperature
 - 2nd reserve capacity test at temperature
- Return to median temperature (27°C)
 - Recharge at median temperature
 - Post-temperature reserve capacity test
 - Recharge



**Environmental Test Data Exemplar
(60°C Test Sequence)**

Direct Current Resistance (Charging)

- Battery DCR can be calculated from knowledge of the instantaneous OCV through:

$$DCR = \left| \frac{\text{Cell Voltage} - \text{OCV}}{\text{Cell Current}} \right|$$

- OCV is determined through SOC knowledge
- A correlation mapping DCR as a function of SOC and temperature was sought of the form:

$$DCR = Ae^{-\alpha SOC} + Be^{-\beta(1-SOC)} + CSOC + D$$

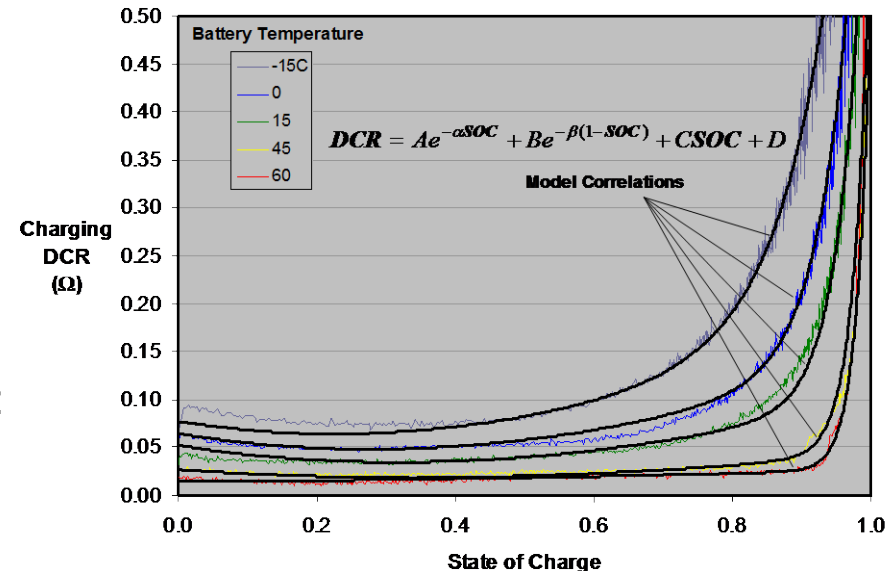
- Each of the coefficients are assumed linear functions of dimensionless temperature

$$\text{Coefficients} : (A, B, \alpha, \beta, C, D) = m\theta + b$$

where

$$\theta = \frac{T - T_f}{T_0 - T_f} \quad \begin{matrix} T_f = -40^\circ\text{C} \\ T_0 = 25^\circ\text{C} \end{matrix}$$

- Good correlation to data implies linear temperature variation may be adequate assumption



Charging DCR as a function of SOC and Temperature

Coefficient	m	B
A	-1.113	1.753
B	-0.308	0.980
α	0.129	0.602
β	33.369	0.797
C	-0.616	0.982
D	1.059	-1.655

Correlation Coefficients

Direct Current Resistance (Discharging)

- Battery DCR can be calculated from knowledge of the instantaneous OCV through:

$$DCR = \left| \frac{\text{Cell Voltage} - \text{OCV}}{\text{Cell Current}} \right|$$

- OCV is determined through SOC knowledge
- A correlation mapping DCR as a function of SOC and temperature was sought of the form:

$$DCR = Ae^{-\alpha SOC} + Be^{-\beta(1-SOC)} + CSOC + D$$

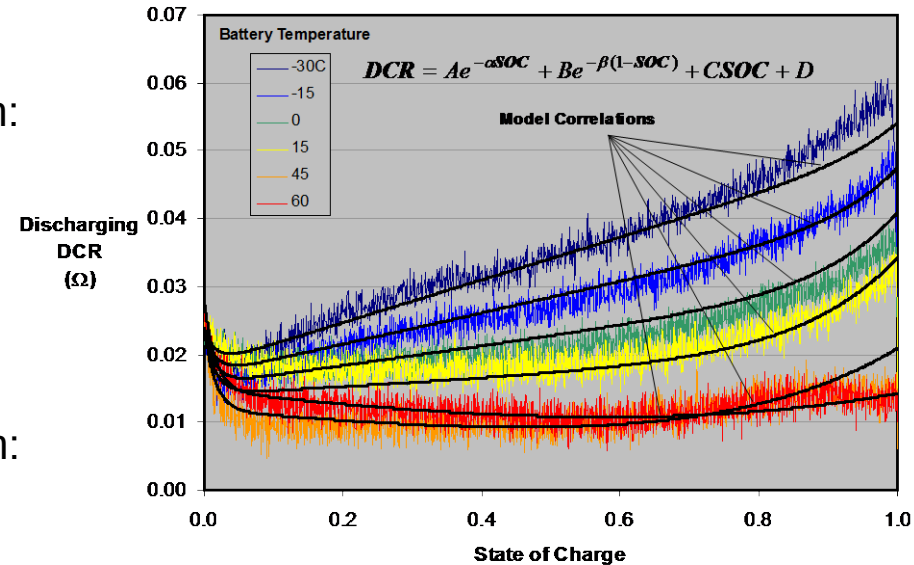
- Each of the coefficients are assumed linear functions of dimensionless temperature

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where

$$\theta = \frac{T - T_f}{T_0 - T_f} \quad \begin{matrix} T_f = -40^\circ\text{C} \\ T_0 = 25^\circ\text{C} \end{matrix}$$

- Poorer correlation to data than charging illustrates non-linear temperature behavior



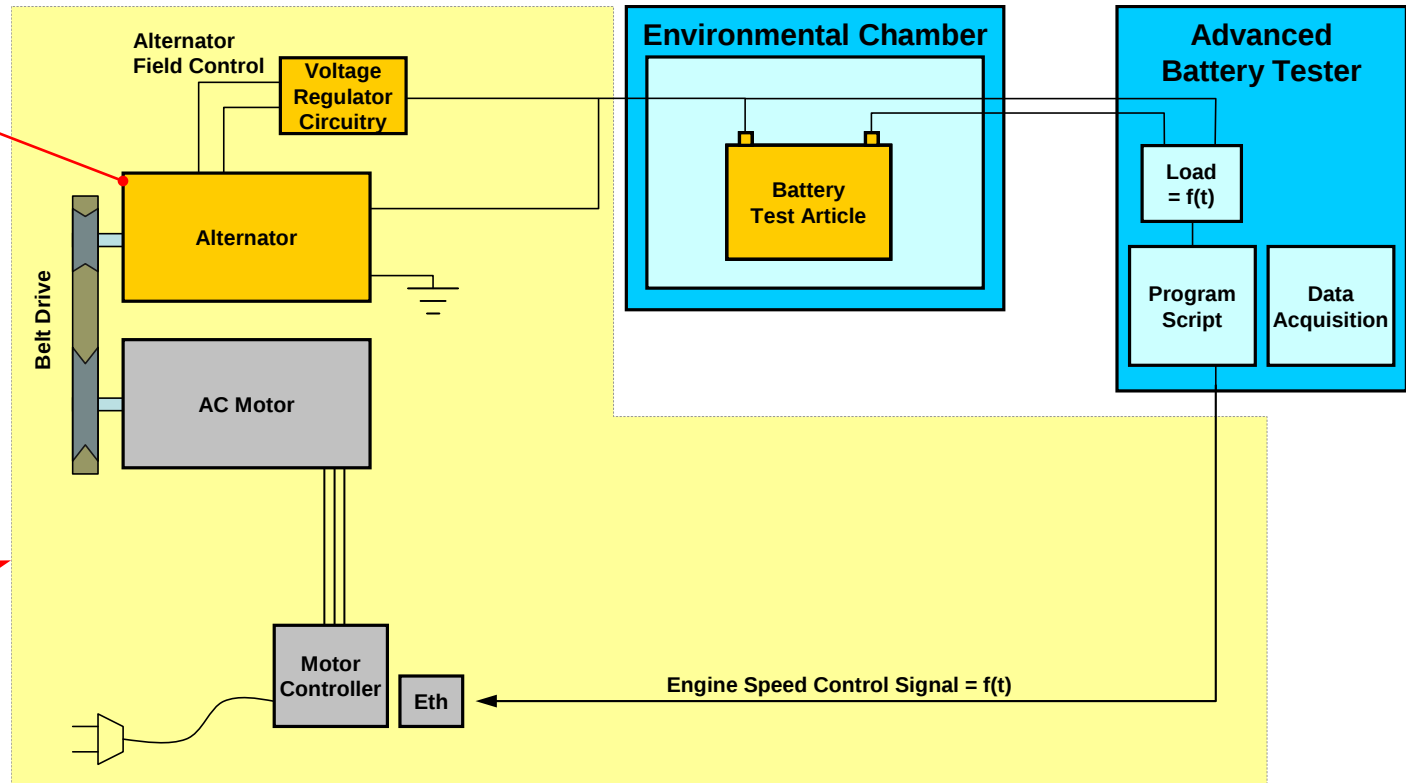
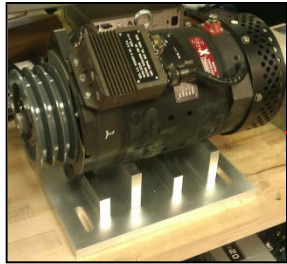
Discharging DCR as a function of SOC and Temperature

Coefficient	m	b
A	5.698E-03	4.647E-03
B	1.455E-02	2.159E-03
α	3.133E-01	6.282E+01
β	-7.978E+00	1.385E+01
C	-3.714E-02	3.712E-02
D	-6.255E-03	1.935E-02

Correlation Coefficients

Evolution of the Test Apparatus

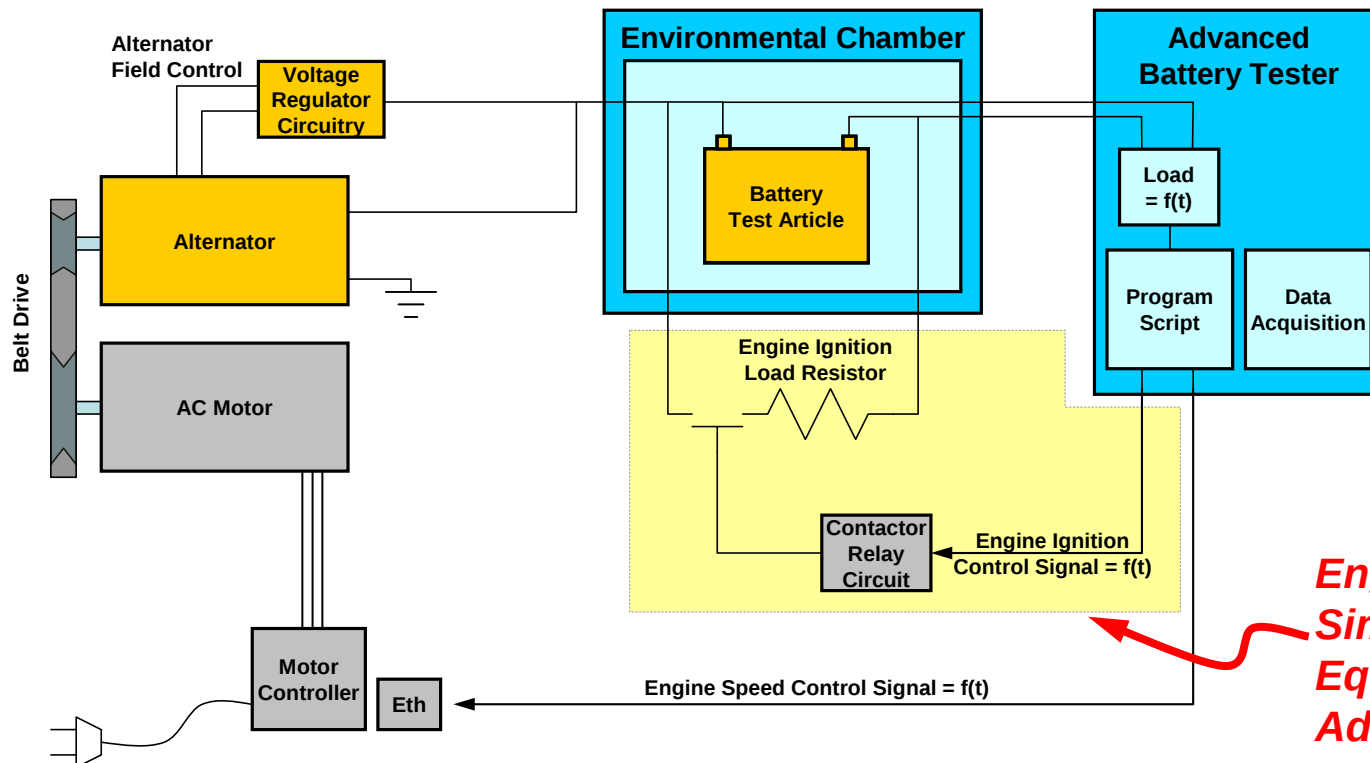
- Addition of alternator to test apparatus permits “vehicle simulation”
- AC motor, with speed control, simulates engine crank shaft
- Battery tester acts as programmable load to simulate vehicle power draw
- C.E. Niehoff & Co. alternator model N1609-1



**Alternator
Equipment
Added**

Evolution of the Test Apparatus

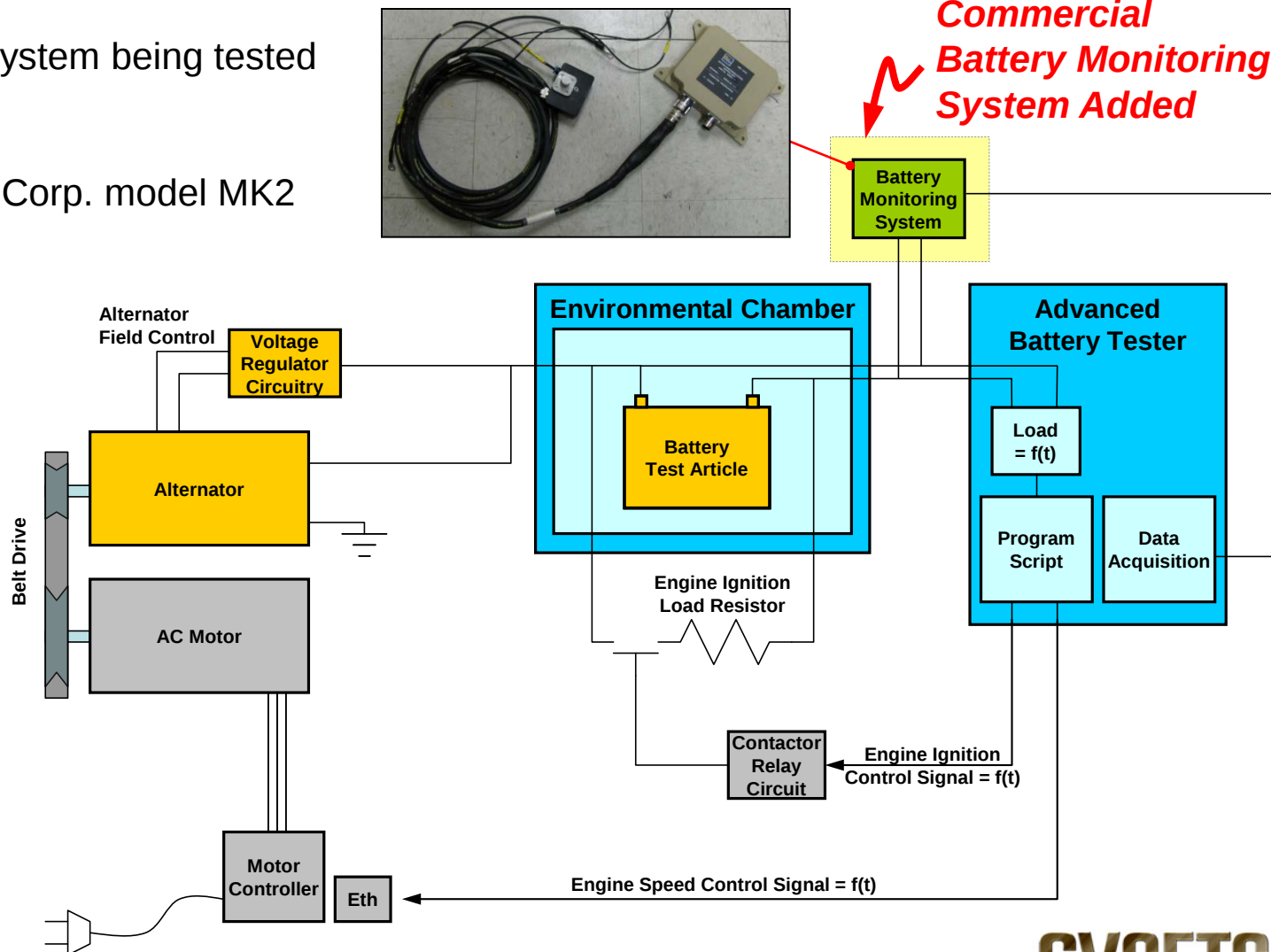
- Addition of engine ignition resistor permits simulation of engine cranking
- Programmable relay control to ignition load resistor
- Battery tester acts as programmable load to “tune” ignition power draw



Evolution of the Test Apparatus (Battery Monitoring System)

POWER AND MOBILITY

- Commercial BMS system being tested for data fidelity
- EMS Development Corp. model MK2 BMS
- Provide feedback for SOC, V, et al
- Compare accuracy to Advanced Battery Tester data



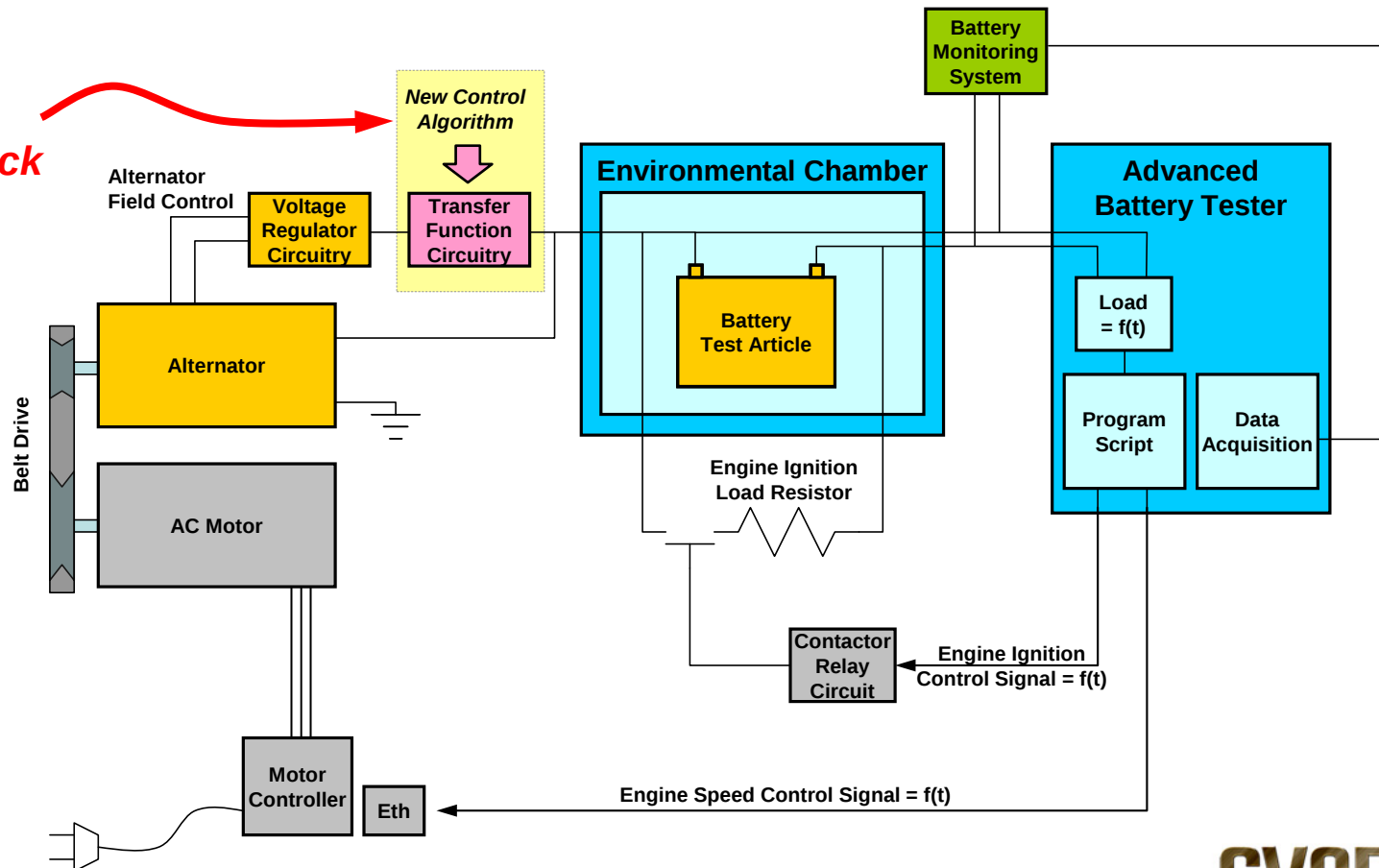
Evolution of the Test Apparatus (Alternator Feedback Control)

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POWER AND
MOBILITY

- Initially provide voltage feedback from Advanced Battery Tester controlled signal to provide programmable alternator voltage as a function of battery voltage, temperature and SOC
- Once optimized, look to develop electronics card for alternator feedback

**New Alternator
Voltage Feedback
Control Added**

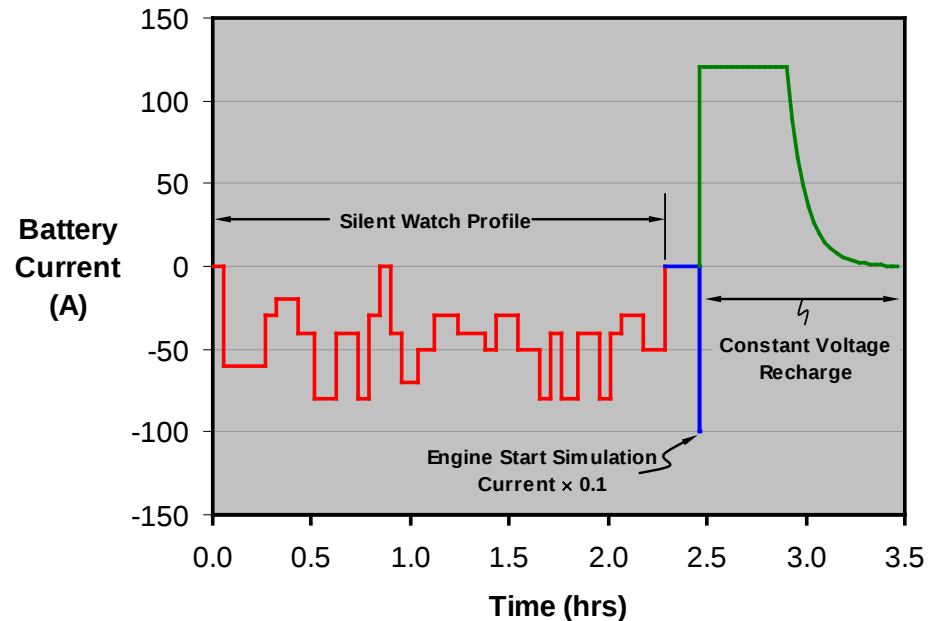


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GVSETS

Scheduled Testing

- Test articles are currently being capacity tested to ensure “matching pairs” are used for 2-series connection
- Phase 2 testing will compare alternator fixed voltage algorithm to TARDEC-developed algorithm
 - Fixed charge-discharge profiles
 - Range of temperatures
- Phase 3 testing will simulate silent watch mode profile comparing algorithms
 - Simulated silent watch load profile
 - 10-minute rest
 - 1000 A engine simulation
 - Recharging algorithms
 - Range of temperatures
- Currently completing integration of the test apparatus
- System will be able test a number of test profiles to include vehicle driving simulation (engine rpm response) and dynamic vehicle electrical loading



Silent Watch Mode Test Profile