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RESERVE STATE OF HEALTH (RSOH) IMPLICATIONS OF LEAD ACID BATTERY OVER-DISCHARGE

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ABSTRACT

When Combat Vehicle Operators operate C4ISR equipment in a "Silent Watch" mission scenario batteries are charged prior to, and during emplacement. Batteries are then discharged powering the C4ISR system (Radios and BFT) while on watch. Without battery monitoring soldiers often discharge batteries till equipment shuts down (i.e. the radio shuts off). This over-discharges the batteries resulting in reduced life. This paper shows the effect on Reserve State Of Health (Capacity) compared with batteries only discharged to 10% State of Charge (SOC).

INTRODUCTION

Combat vehicle operators may cycle the vehicles engines during 'Silent Watch' conditions to minimize fuel usage. Batteries are charged during emplacement and then discharged powering the C4ISR system (Radios and Blue Force Tracking) while on watch. Without Battery Monitoring Systems (BMS) the operator has either coarse voltmeters or the load simply shutting down (.i.e. the radio shuts off). The vehicle is run, and without a BMS the operator can only run for a predetermined time assuming the batteries have been recharged. This leads to over-discharge of the batteries.

This paper compares the Capacity, which is a measure of Reserve State of Health (RSOH), of batteries operated in these conditions versus ones operated from 100% State Of Charge (SOC) down to 10% SOC. It also shows a similar test run on deep discharge batteries for comparison. The SOC was determined by the Ultra EMS Vehicle Power System Controller, a Military-Off-The-Shelf (MOTS) Battery Management System (BMS). Optima Size 34 Batteries were chosen since they are currently fielded on various military Mine Resistant Ambush Protected (MRAP) vehicles.

COMBAT VEHICLE VOLTAGE MEASUREMENT

Typical combat vehicle battery voltage measurement is done via a dashboard mounted gage similar to that in Figure 1. This gauge has 4 regions: Red, from 18-22V, Yellow from 22-26V, Green 26-30V and Red 30-34V. Furthermore there is a white slash corresponding to 28V which is the nominal alternator voltage when the engine is running.[1] This is all the information the operator has of battery condition to detect when battery voltage, and hence SOC, is running low. 0% SOC corresponds to 21V (a little bit in the red region) – there isn't even a clear demarcation at this critical voltage.

Table 1 shows the published input voltage range of some common Radio Vehicle Adapters. The lower range of input voltages for the VAs is approximately 18V. With the lack of information from the gauges the operator often uses the clear-cut criteria of radios off=start engine. Necessity breeds innovation, and the voltmeter just doesn't provide the required information.

Charging has a similar issue – high power alternators can always drive the battery voltage to 28V placing the needle on the white slash. Unless we are monitoring battery current there is no means to detect when the batteries are charged. The results is the soldier using a wristwatch timing the engine on period – run engine for a predetermined time and hope batteries are charged.

BATTERY TERMINAL VOLTAGE

The most common model for lead acid battery performance is the Randles Model shown in Figure 2. This model is a nonlinear dynamic model which takes into account the varying open circuit voltage of the battery and the varying impedances, both dependent on SOC. The open circuit voltage of the battery is a function of the SOC according to the Nernst Equation. R_{pol} stands for electrolyte, connection resistances and charge transfer resistance. The Warburg impedance $Z_{Warburg}$ is the chemical resistance of the diffusion phenomenon.[2] R_{pol} and $Z_{Warburg}$ combined form the kinetic chemical resistance of the battery.

The discharge-recharge curve for a pair of brand new ARMASAFE™ Plus 6TAGM batteries is shown in Figure 3.This plot has the terminal voltage, both loaded and unloaded, plotted as the ordinate against the ampere hours discharged and re-charged. The unloaded terminal voltage is plotted in purple and cyan, while the loaded voltage is plotted in light and dark brown. The abscissa is the ampere hours discharged from a fully charged battery – 0 AH corresponds to a fully charged battery while -110 AH correspond to complete discharge. Note in Figure 3 the loaded voltage discharge curve for the upper battery crosses 10.5V after discharging 102 AH while the lower battery crosses 10.5V after discharging 106 AH. This represents a marginal difference in capacity typical of 5 cycles.

The measurement was obtained by discharging battery for fixed period in time, measuring terminal voltages, allowing battery to stabilize to open circuit voltage and repeating till battery terminal voltage is at 10.5V. This was repeated charging battery for fixed period in time, measuring terminal voltages, allowing battery to stabilize to open circuit voltage and repeating till battery terminal current is under .5A.

The open circuit voltage is nearly a linear function of the SOC while the loaded terminal voltage describes a hysteresis loop. The width of the hysteresis loop is due to the kinetic chemical resistance of the battery and broadens as the conductivity of the electrolyte is approaching zero as the H_2SO_4 (sulfuric acid) and Pb (lead) is converted to $PbSO_4$ (lead sulfate) and H_2O (water).

Compare this with the discharge curve of well used ARMASAFE™ Plus 6TAGM batteries shown in Figure 4. The loaded voltage discharge curve for the upper battery crosses 10.5V after discharging 62AH while the lower battery is above 10.5V after 97 AH is discharged. Developing this imbalance is typical in a battery string. Note that the initial discharge voltage curves up to 60AH are identical between lightly used and heavily used batteries – it is the voltage at the tail end of a discharge which collapses at the end of capacity. The discharge plots in Figure 4 are typical of a used pair of lead acid batteries. Note that combat vehicles have 24V electrical systems comprised of two batteries in series and that these batteries do not age uniformly.

Figure 1: MS24532-2 Combat Vehicle Voltmeter

Vehicle Adapter	Input Voltage
RF-7800M-V150	18-34 VDC[3]
RF-7800UL-V150	23-32 VDC[4]
RF-300M-V150	18-34 VDC[5]
RF-5800H-V006	22 to 33 VDC[6]
RF-5800V-PA	20-32 VDC[7]
Thales Vehicle Adapter	12-32 VDC[8]

Table 1: Vehicle Adapter Input Voltage Ranges

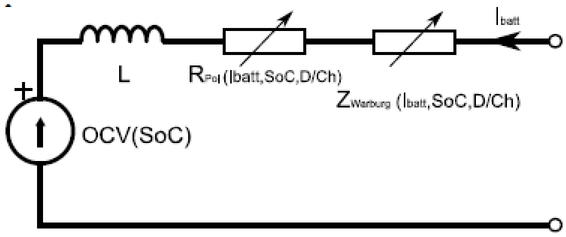

Figure 2: Randles Model Battery

Voltmeters such as those shown in Figure 1 only show the summed voltage – one battery voltage can collapse as shown in Figure 4 while the second battery can support the string voltage, albeit at a lower potential. One battery can be at 11V while the second is at 7V resulting in a string voltage of

18V – one severely below 0% SOC while the second still has capacity left.

100 and 0% State Of Charge

Much is made of the 'State of Charge' being a percentage value. Examining Figure 3 it is easy to determine a 100% point – it is when the battery cannot accept any more potential energy. The 0% SOC point is more elusive. Re-plotting Figure 3 about the -90 to -120 AH region in Figure 5 shows the battery voltage rapidly decreasing from 11V at 99AH discharged down to 9.5V at 108AH of discharge.

Obviously there is still energy left in the battery at this point – there needs to be a arbitrary point defined of what is 0% SOC. Ultra EMS has elected to use the End of Discharge Criteria of the SAE 537J P3.6 Reserve Capacity Test as the 0% SOC point. This test specifies discharging the battery at 25A till the terminal voltage is 10.5V in a loaded condition.[9] Referencing Figure 3 the upper battery in the string reaches 10.5V at -102 AH discharged. It reaches 9.5V at -108 AH and would reach 9V at approximately -110AH. The definition of 0% SOC is a somewhat arbitrary one and depending on the endpoint chosen (10.5V at 25A or 0V at 0A) battery capacity is a varying number with differences of about 10%.

TEST SETUP

Three strings of batteries were cycled in the Ultra EMS Vehicle Power Systems Integration Lab. The batteries were installed in an environmental chamber shown in Figure 6 and the chamber temperature fixed at 20 C. The batteries were then cycled from 100% SOC to 0% SOC via the Ultra EMS Vehicle Power Systems Test Stand shown in Figure 7. The Vehicle Power Systems Test Stand is a three channel system, computer controlled, capable of running 0-3000A Discharges on Bank 1 and 0-80A Discharges on Banks 2 and 3 for Arbitrary waveforms. Power Supply and Programmable Loads are controlled off an IEEE-488 Bus and every measured parameter, (voltage, current, temperature) has independently verified measured parameters through a data acquisition system. Data is logged every 15S to a CSV file.

String 1 was comprised of two Optima 8014-045-FFP Yellow Top Group 34/78 Batteries. Strings 2 and 3 were each comprised of two Optima 8004-003-FFP Red Top Group 34/78 Batteries. Brand new crated batteries were provided by Optima.

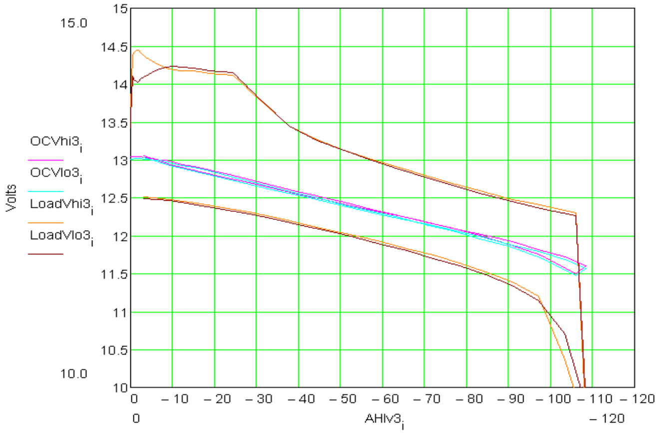

Figure 3: Discharge/Recharge Curve for New Hawker Armasafe Batteries

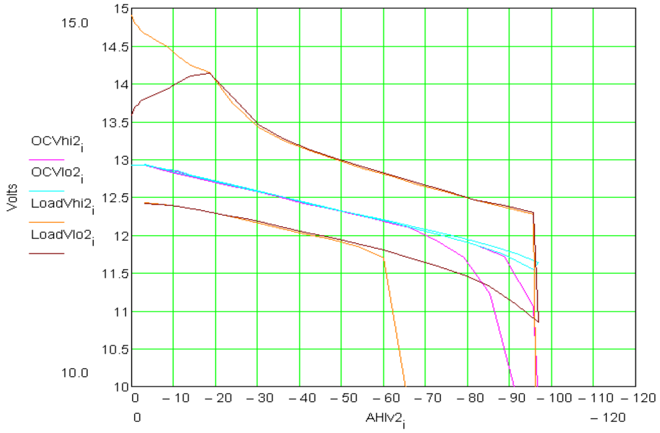

Figure 4: Discharge/Recharge Curve for Used Hawker Armasafe Batteries

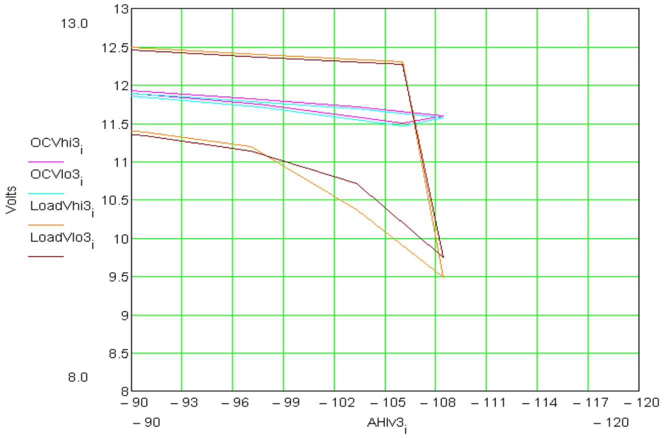

Figure 5: Discharge/Recharge Curve for New Hawker Armasafe Batteries, Near 10.5V

Batteries were cycled through the profile shown in Figure 8. The batteries were connected to a current limited power supply, set at 28.5V and 120A total for charging through the test stand under software control. The charge current was split between the three strings resulting in a typical current of 40A/string. The string were run in charge mode for 3:45, a typical bulk charge at the current limit of 40A for 1 hour. At this point the system transitions into absorption charge for 2:45 and the charge is completed. At the end of the charge cycle typical battery current was .3A with 28.5V split across two batteries for an hour indicating the string was fully charged. At this point the batteries were put in discharge, each current regulated at 25A. The load on String 1 is a 0-3000A load which has a +/-2A accuracy at the 25A set-point while Strings 2 and 3 were each run off identical 0-80A loads.

The discharge on Strings 1 and 3 were aborted when the lowest SOC on the lowest battery was 10%. The discharge on Strings 2 was aborted when the combined voltage of the batteries was 18V, approximately when the radios would shut down. Terminating discharge based on SOC for Strings 1 and 3 represent use of a BMS while the termination criteria of 18V for the pair represent what is commonly done in the field with the crude readings provided by voltmeters shown in Figure 1.

Discharges were run in groups of 8 (2days) for a total of 60 discharges. Data was logged every 15S and comprised of Voltage, Current, Temperature, Conductance, State of Charge and Time-to-Flat.

Primary criteria presented here is the ampere-hours provided during the discharge from each string and the termination voltage. It was felt that this provides an unambiguous measure of capacity since each battery was run at the same current.

State of Charge Measurement

The discharge on Strings 1 and 3 were aborted when the lowest SOC on the lowest battery was 10%. This SOC was measured with the Ultra EMS Vehicle Power System Controller (VPSC). The VPSC is a Military-Off-The-Shelf (MOTS) combat vehicle front power system controller developed by Ultra EMS at our own expense. The VPSC incorporates a real-time complex algorithm with voltage, current, temperature, conductance, and time measurements to provide highly reliable and accurate monitoring of the State of Charge (SOC) of a vehicle's batteries. This SOC is then used to infer State of Life (SOL) and Time to Flat (TTF) to provide the vehicle crew with accurate real-time battery data. The VPSC also incorporates hardware and algorithms to Manage Battery Balancing, Bank Disconnect and Smart Charging. Page 1 of the VPSC datasheet is shown in Figure 9.

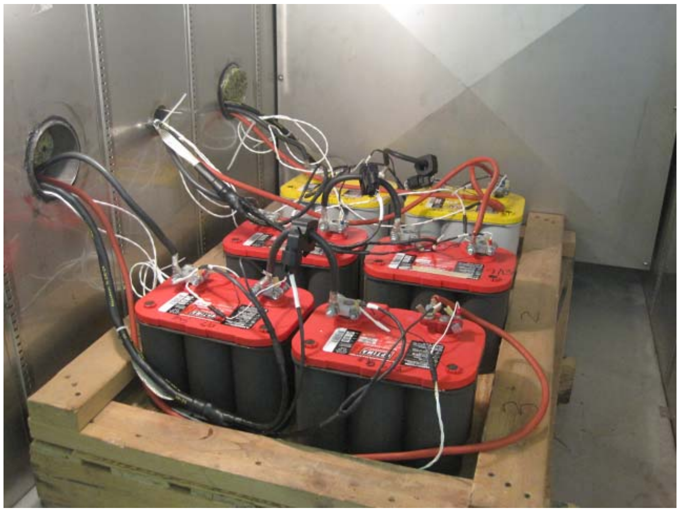

Figure 6: Batteries Installed In Chamber

Figure 7: Ultra EMS Vehicle Power Systems Test Stand

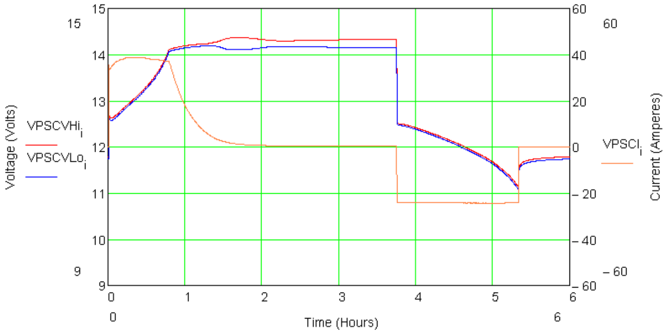

Figure 8: Sample Profile

EMS

Vehicle Power System Controller

Features

- One controller and four current sensors for 4 pairs of12V batteries.
- Measures voltage, current, temperature and conductance of each battery.
- Calculates and reports :
  - State Of Charge (SOC)
  - State Of Life (SOL)
  - Time To Flat (TTF)
- Controls:
  - Battery Balancing
  - Bank Interconnect.
  - Smart Charging.
- J1939 CAN interface Compatible
- Qualification tested to US Military Specifications
- Rugged design in metal

The Ultra Electronics Vehicle Power System Controller (VPSC) provides the military vehicle integrator with a compact means of *Monitoring* and *Managing* the vehicle batteries.

The VPSC incorporates a real-time complex algorithm with voltage, current, temperature, conductance, and time measurements to provide highly reliable and accurate *Monitoring* of the State of Charge (SOC) of a vehicle's batteries. This SOC is then used to infer State of Life (SOL) and Time to Flat (TTF) to provide the vehicle crew with accurate real-time battery data.

The VPSC also incorporates hardware and algorithms to *Manage* Battery Balancing, Bank Disconnect and Smart Charging.

Military vehicle systems operate on 24Volts delivered via two 12 Volts batteries in series. Series batteries do not share voltage or remain balanced during operation. One battery will develop lower capacity over time. This capacity difference may be as much as 20% for two identical batteries from the same lot installed in the same battery box. The VPSC contains a +/- 5A bidirectional power converter equalizing the pair, drawing power from the large capacity battery to supplement the smaller capacity battery giving an effective increase of 10% for the bank.

Regulated Voltage Control (RVC) has shown promise increasing fuel economy in today's commercial vehicles. The VPSC implements RVC through the J1939 Bus setting the vehicle alternator voltage to the optimum value for the battery SOC, engine temperature and throttle position at each point in time. For example when the throttle is depressed over 80% maximum power is needed at the drive wheels – the VPSC rolls back charging current to allow the power to go to the wheels where it is needed.

Ultra ELECTRONICS

Figure 9: Ultra EMS Vehicle Power System Controller

TEST RESULTS

Plots of Voltage and State of Charge versus time are shown in Figure 10 through Figure 18[10][11][12]. Time is shown in seconds in theses plots from the start of the run group; each division is .25H.

Cycle 1 Results

Cycle 1 plots are shown in Figure 10 through Figure 12. Figure 10 shows the discharge voltage on the Yellow Tops in String 1 gradually decreasing to 11V as the battery is discharged to approximately 10% SOC (note 0% SOC is 10.5V). Both batteries are balanced, and after the discharge the battery recovers some charge are as the chemistry stabilizes. Figure 11 shows the discharge voltage on the Red Tops in String 2 gradually decreasing to 11V as the battery is discharged to approximately 10% SOC; but since this string is discharged to a summed 18V level the discharge continues down to approximately 9V per battery. Past 11V the voltage decreases very rapidly. Both batteries are balanced. Figure 12 shows the discharge voltage on the Red Tops in String 3 gradually decreasing to 11V as the batteries are discharged to approximately 10% SOC (note 0% SOC is 10.5V). Both batteries are balanced, and after the discharge the batteries recovers some charge are as the chemistry stabilizes similar to the Yellow Tops.

Cycle 30 Results

Cycle 30 plots are shown in Figure 13 through Figure 15.

Figure 13 shows the discharge voltage on the Yellow Tops in String 1 gradually decreasing to 11V as the batteries are discharged to approximately 10% SOC. Both batteries remain balanced.

Figure 14 shows the discharge voltage on the Red Tops in String 2 gradually decreasing to 11.5V; however at this point the batteries have developed a marked imbalance. The upper battery in the string discharges to a lower potential than the lower battery and has substantially less capacity than the lower.

Figure 15 shows the discharge voltage on the Red Tops in String 3 gradually decreasing to 11V as the batteries are discharged to approximately 10% SOC. Both batteries remain balanced similar to the Yellow Tops in String 1, the other bank whose discharge is SOC Controlled.

Cycle 60 Results

Cycle 60 plots are shown in Figure 16 through Figure 18. Figure 16 shows the discharge voltage on the Yellow Tops in String 1 and in Figure 18 the Red Tops in String 3 gradually decreasing to 11V as the batteries are discharged to approximately 10% SOC (note 0% SOC is 10.5V). Again, both batteries remain balanced; however String 1 is beginning to diverge.

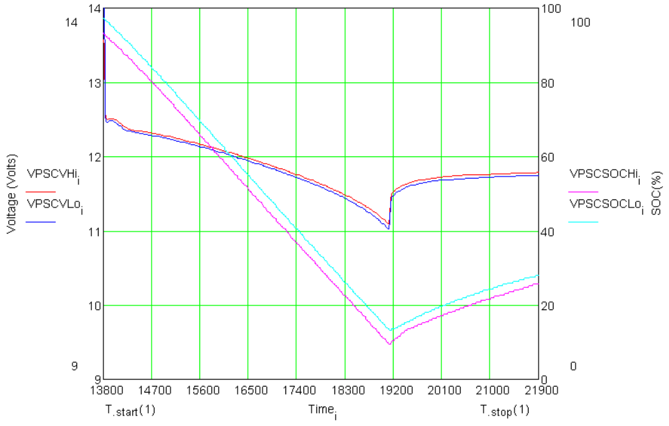

Figure 10: String 1, (Yellow Top, Cycle 1, Discharge SOC Controlled)

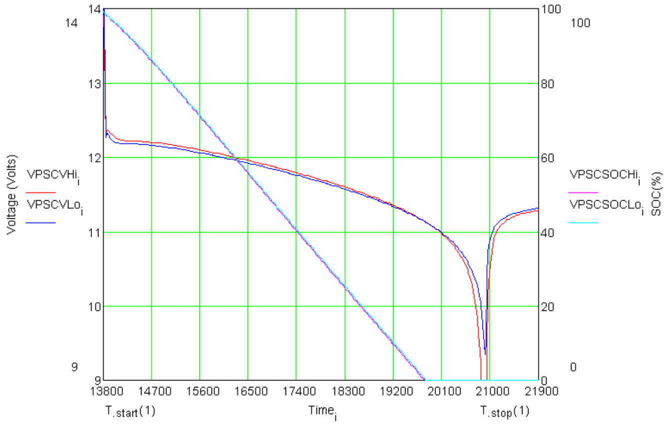

Figure 11: String 2, (Red Top, Cycle 1, Discharge Voltage Controlled)

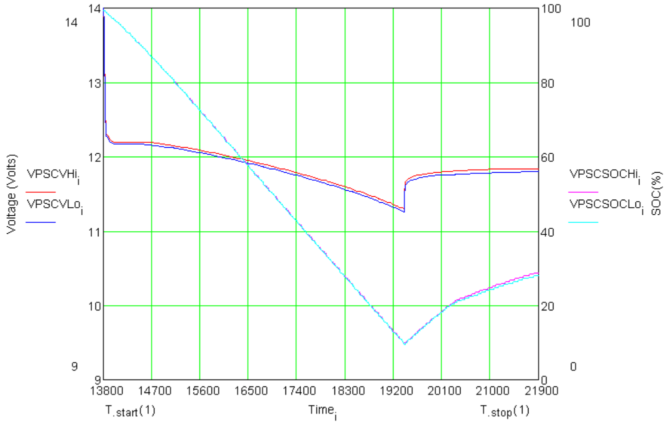

Figure 12: String 3, (Red Top, Cycle 1, Discharge SOC Controlled)

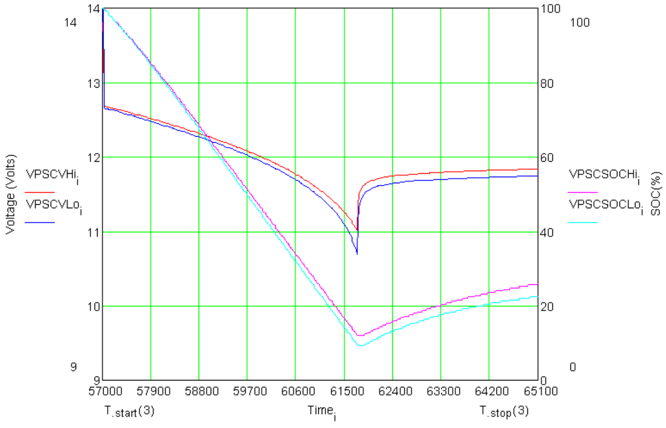

Figure 13: String 1, (Yellow Top, Cycle 30, Discharge SOC Controlled)

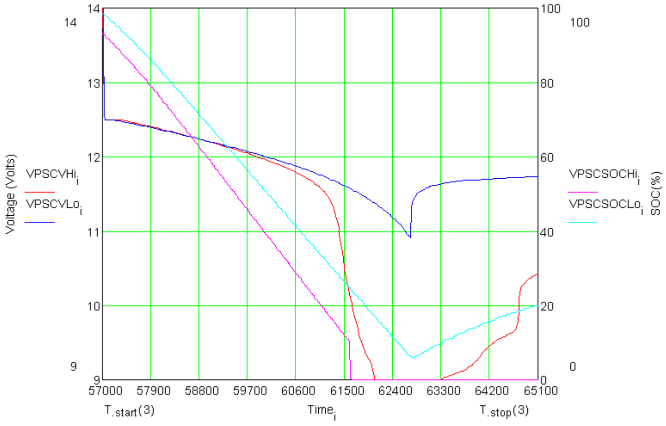

Figure 14: String 2, (Red Top, Cycle 30, Discharge Voltage Controlled)

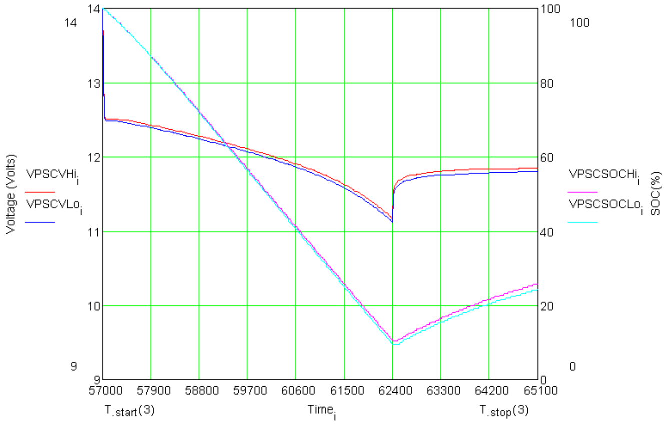

Figure 15: String 3, (Red Top, Cycle 30, Discharge SOC Controlled)

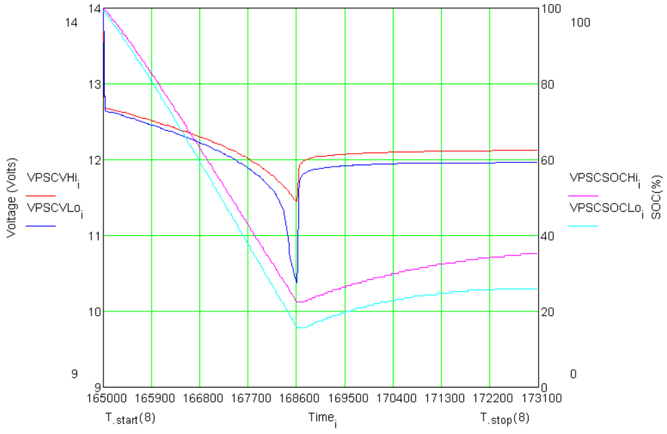

Figure 16: String 1, (Yellow Top, Cycle 60, Discharge SOC Controlled)

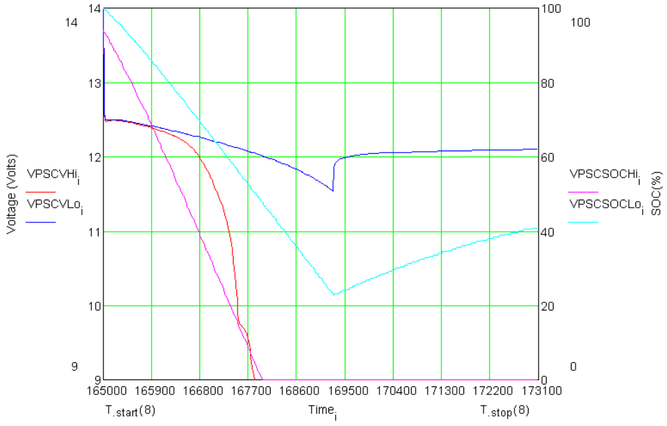

Figure 17: String 2, (Red Top, Cycle 60, Discharge Voltage Controlled)

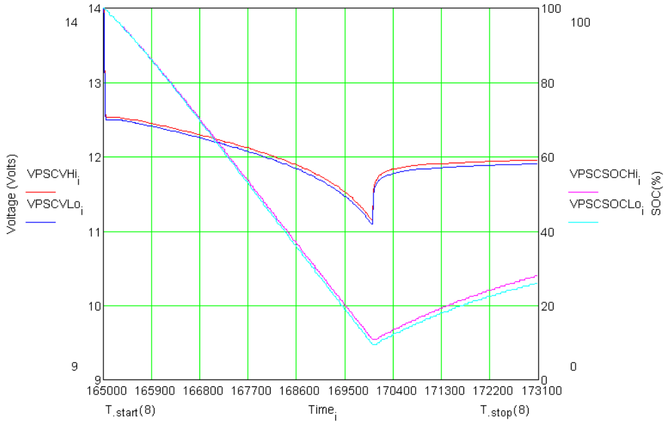

Figure 18: String 3, (Red Top, Cycle 60, Discharge SOC Controlled)

Figure 17 shows the discharge voltage on the Red Tops in String 2 continuing the divergent behavior. The upper battery in the string discharges to a lower potential than the lower battery and has substantially less capacity than the lower.

Summary of Test Results

Strings 1 and 3 had the discharge terminated when the lowest Batteries State of Charge in the String was 10%. This is a capability provided by the Ultra EMS Vehicle Power System Controller (VPSC). String 2 had the discharge terminated when the sum of the battery voltage in the string was 18V, the minimum voltage shown on a MS24532-2 Voltmeter.

The vehicle operators the key criterion is energy provided to the load.

Figure 19 show the ampere hours provided by each string. While String 2 initially provided 10% more energy than String 3 by 40 cycles the two strings provided identical energy; furthermore, by 60 cycles String 2 provided 15% less energy than String 3. String 1 provided approximately the same energy in Cycles 1 to 40 and after that began to age at the same rate as String 2.

The C20 estimates provided by the VPSC are shown in Figure 20. Note the C20 estimates for Strings 1 and 3 are balanced between the upper and lower batteries. They do age over the discharge cycles of the batteries; however they remain balanced to within 10%. Note the C20 estimate for String 2 is greatly divergent between upper and lower batteries. The upper battery decreases to 27AH at 60 cycles while the lower battery decreases to 45AH. The lower battery rate of aging is commensurate with the batteries in Strings 1 and 3 while the upper battery rate of aging far exceeds the nominal value. String 2's upper battery capacity is reflected in the terminal voltage progressing towards zero in Figure 17 .75H after the discharge started, while the lower battery voltage never crossed the 10.5V boundary.

Terminal voltage at the end of each discharge is shown in Figure 21. Note the terminal voltage for the 4 batteries in Strings 1 and 3 are balanced within .75V up till cycle 40 and there then diverges for String 1 up to 1V, String 2 exhibits markedly different behavior. While initially balanced to 1.5V at the first cycle the upper and lower battery discharge levels become divergent. The battery that is discharged to a lower potential (upper) suffers reduced capacity, leading to increased discharge. This creates a runaway effect whereby the increasing over-discharge causes capacity reduction in each succeeding cycle.

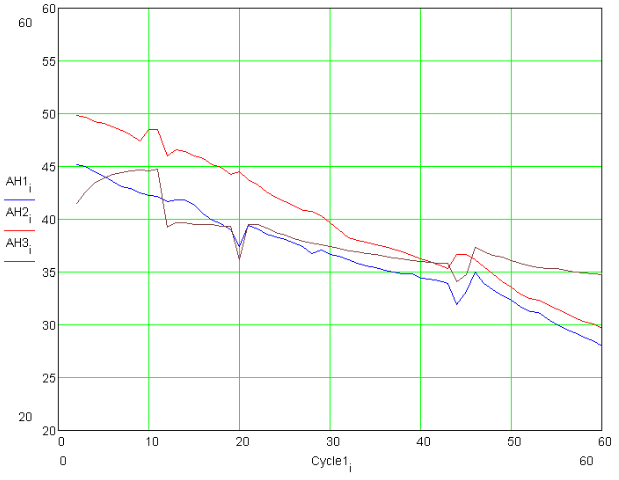

Figure 19: Ampere Hours Discharged.

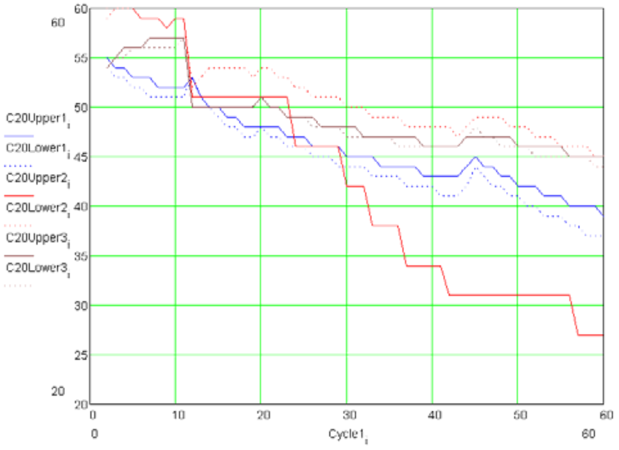

Figure 20: C20 Estimates Provided by VPSC

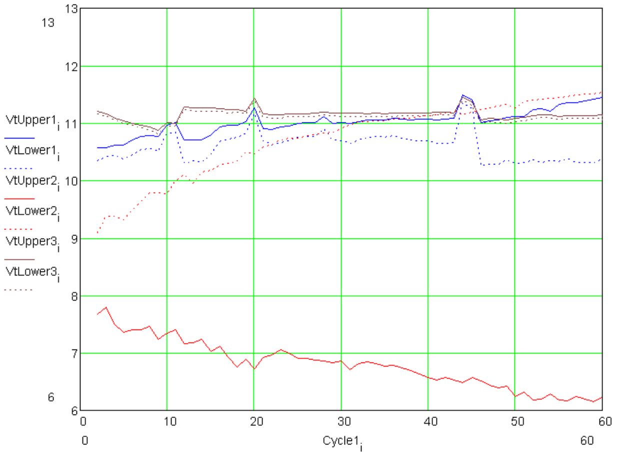

Figure 21: Terminal Voltages at End of Discharge

CONCLUSION

Combat Vehicle Voltmeters provide a means of monitoring a battery string voltage; they do not provide means to monitor individual battery voltages. With the crude meters provided operators often are forced to rely on loads to judge string voltage – when the loads shut off the batteries need recharging.

The batteries are arranged in a series configuration and may not age equally. If only string voltage is metered the 'needle may be over the line' and the users load may still function while one battery is over-discharged since only string voltage is measured.

This over-discharge is a runaway condition. The battery that is discharged to a lower potential suffers more damage resulting in increased capacity loss. The increased capacity loss then results in earlier discharge to a lower potential furthering the capacity loss.

Batteries that are monitored with modern Battery Management Systems such as the Ultra EMS VPSC detect when one battery is being over discharged. This prevents an imbalance from developing. Batteries discharged till the user's load stops functioning initially provide more energy than those whose discharge is terminated at 10% State of Charge. By 40 cycles the aging created by the over-discharge reduces the capacity of these batteries till they are equal to the capacity of SOC controlled batteries; at this point the life of the over-discharged batteries is compromised and they continue to age at a rate greater than SOC controlled batteries illustrating the utility of modern Battery Management Systems.

ACKNOWLEDGEMENTS

The author wishes to thank Military Battery Systems and Optima Batteries Division of johnson Controls for their supply of batteries used in these tests.

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