**WHITEPAPER**

# BFVS AGM Battery Investigation

October 3, 2014

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**PURPOSE:**

This whitepaper serves as the final report for Problem Investigation (PI) MCA-111-P25R1.

**DESCRIPTION:**

This investigation was conducted under PI MCA-111-P25R1 to perform an investigation and analysis into the in-service performance characteristics of the Exide 31A925XLW Absorbed Gas Mat (AGM) battery as fielded on the Bradley Fighting Vehicle System (BFVS). An investigation of field failures of the 31A925XLW was conducted and this paper discusses field data collected under PI MCA-111-P25R0. The investigation also looked into use of tools such as the PulseTech chargers used in support of maintaining the Exide AGM batteries.

Also provided are recommendations for maintenance procedures to include any special equipment or additional tools needed. This paper makes an assessment of the Technical Manual (TM), Technical Bulletin (TB) and the PS magazine that describe the AGM/Valve Regulated Lead Acid (VRLA) maintenance procedures to see if there are any errors, and to provide any needed suggestions for update. In addition, the PI funded the receipt and limited vehicle testing of a vehicle set of product improvement batteries provided by the manufacturer.

## EXECUTIVE SUMMARY:

Field data indicates that lead acid (PbA) electrical energy storage batteries are expiring at a high rate, resulting in logistic challenges. Review of Field Service Representative (FSR) reports shows a significant percentage of the failing batteries are located in the platform's sponson. These batteries are succumbing to sulfation from being stored at less than a full State of Charge (SOC). The sponson batteries are discharged to support various turret loads, without the engine running. The platform's vehicle topology and the recharge profile of lead acid technology makes it difficult to recharge the batteries to full state without the engine running for a long period of time (greater than 6 hours) prior to storage. The vehicle electrical architecture, in particular parasitic turret loads, coupled with a low current output battery charger means that in vehicle charging operations are marginal to ineffective. Finally, the generator's voltage regulator compensates for does not account for the delta between engine compartment and battery (crew compartment) temperatures and it is likely that the batteries will charged at too high a voltage until the engine compartment temperature stabilizes.

A number of recommendations were made that include: 1) improve the vehicle charging architecture to allow a direct means of charging the sponson batteries without energizing parasitic vehicle loads, 2) change/update the chargers issued in the field that support platform Life Cycle Management Command (LCMC) operations to increase the amperage of the charger and provide the charger with temperature compensation, and 3) improve the vehicle charging system by adding temperature compensation to the vehicle charging system.

## REFERENCES:

/1/ Maintenance Information (MI) Message, TACOM Life Cycle Management Command, (TACOM LCMC) Control No. TBD, (Informational), Bradley Fighting Vehicle BUSK Battery Charging Criteria, August 2014
/2/ 80212-4274204, Revision -, Power Management/Distribution Subsystem, Block 1
/3/ TB 9-2350-395-13&P, dated June 2008, Technical Bulleting for Operator and Field Maintenance Including Repair Parts and Special Tools List (RPSTL) for Bradley Urban Survivability Kits (BUSK)
/4/ TB 9-6140-252-1, dated 31 January 2012, Technical Bulletin for Recharging Procedures for Automotive Valve Regulated Lead-Acid Batteries
/5/ TM 9-6140-200-13, dated 26 May 2011, Technical Manual Operator and Field Maintenance Manual for Automotive Lead-Acid Storage Batteries
/6/ 19207-12465518, Revision N, Performance Specification for the Infantry Fighting Vehicle (M2A3) and Cavalry Fighting Vehicle (M3A3)
/7/ Army Performance Specification; Batteries Storage: Lead-Acid ATPD 2206, Revision Number 6, dated 30 July 1999
/8/ BASS-D Modkit 57K6637 Installation Work Instructions, Revision 15, dated 9/02/2010
/9/ SAE J537, May 2011, Storage Batteries
/10/ SAE J930, May 1995, Storage Batteries for Off-Road Self-Propelled Work Machines

/11/ SAE J2185, February 2012, Life Test for Heavy-Duty Storage Batteries (Lead Acid Type only)

**BACKGROUND:**

Post Bradley Urban Survivability Kit (BUSK) upgrades (circa 2009) changed the electrical energy storage on the BFVS. Bradley vehicles' electrical storage needs are currently provided by eight (8) Group 31 AGM VRLA batteries (reference National Stock Number (NSN) 6140-01-582-5710), manufactured by Exide Technologies (reference Original Equipment Manufacturer (OEM) part number 31A925XLW). Manufacturer testing of units demonstrates a 100 Ahr nameplate energy capacity over a 20 hour discharge period. (A constant 20 hour discharge period value for battery capacity is commonly expressed as C/20.)


**Exide Group 31**
**AGM Flat Plate Battery**
**Automotive Terminals**
**P/N 31A925XLW**
**NSN 6140-01-582-5710**
**Used on the BFV**

**Figure 1 Exide Group 31 AGM Battery**

On the BFVS platform the batteries are arranged in two banks of four batteries. Each bank consists of a series string of two batteries and the two strings are electrically connected in parallel. Figure 2 provides an excerpt of the vehicle power distribution block diagram depicting this platform's organization of electrical storage (reference /2/, sheet 1). The two banks are electrically isolated from each other unless the electrical power distribution system relays are configured to place the two banks in parallel.

The two banks nominally service separate loads: the first "hull" bank, physically located beneath the floor plates of the driver's access way, is typically employed to start the engine and source power to platform accessories in the hull; the second bank is the sponson mounted location for the electronics batteries that typically service the turret loads. It should be noted that this energy storage configuration is planned to be continued in the ECP2 (A4) configuration of the Bradley platforms, but will also include a battery monitoring upgrade.

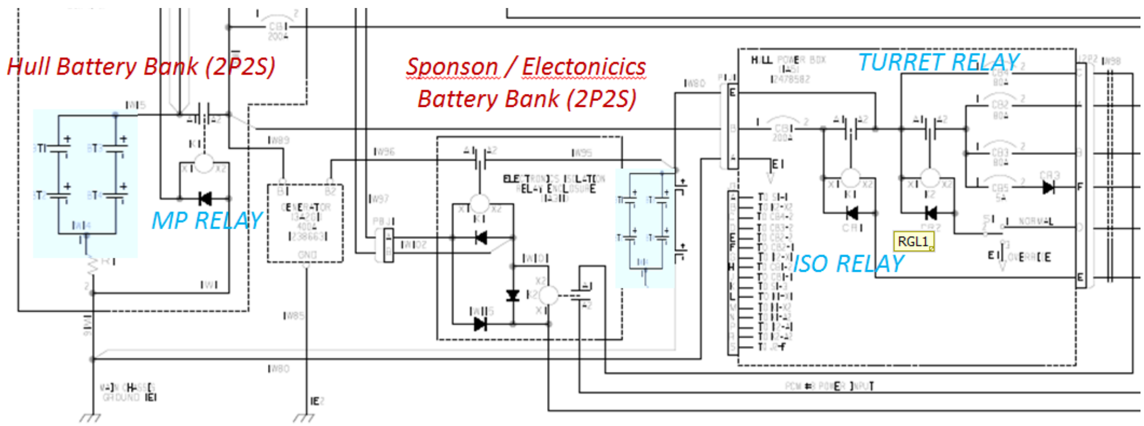


**Figure 2 Annotated Bradley Electrical Distribution System Block Diagram (/2/, Sheet 1)**

Note that in addition to the two banks of Group 31 AGM VLRA batteries, a separate 24 V flooded lead acid battery (type 4HN) is located in the turret. This turret battery functions as a ballast for the inductive motors in the turret used in weapon firing.

Since their introduction, the BUSK batteries have received praise for the increase of stored power provided to the platform and criticism for the increased logistic burden required to keep these articles in service. This paper will outline 1) current field maintenance, use and abuse, issues with maintaining the platform batteries by the Area Maintenance Support Activity (ASMA) in a fielded operations environment; 2) limitations of platform electrical architectures and support equipment requirement evaluation; 3) insufficient charging due to use of the Standard Automotive Tool Set (SATS) chargers; and 4) difficulties in quantifying and testing the requirements for the platform energy storage.

### Table I Comparison between 6TMF, 6TAGM and Group 31 AGM Batteries

**Comparison of 6TMF/ Hawker Arm safe AGM Plus and Exide 31 Properties**

| Description | Test Spec | 6TMF Specification ATPD 2206 | Hawker Armasafe 6TAGM 9750N7025 | Exide 31A925XLW Grp 31 AGM | Exide 31A925X1A Grp 31 AGM | Notes/Commentary |
|---|---|---|---|---|---|---|
| Weight [lbs/(kg) | | 75(34.1) | 86.5(39.2) | 73.0(32.9) | 71.9(32.4) | Diminished active materials historically correlates with diminished life but 18 month service life demonstrated. |
| Handle | | Below Plane top Cover | Below Plane top Cover | Deformable plastic strap. Total Height with strap is 9.4"(239mm) | Deformable plastic strap. Total Height with strap is 9.4"(239mm) | Certain platform mounting require "below cover plane design [NA in BUSK mountings] |
| Case Size (excluding handles) [in3/(l)] | | 1071.4(17.56) | | 723.9(11.86) | 723.9(11.86) | |
| Length [in/(mm)] | | 11.25 | | 12.98(329.7) | 12.98(329.7) | |
| Width [in/(mm)] | | 10.5 | | 6.55(166.4) | 6.55(166.4) | |
| Height [in/(mm)] | | 9.07 | | 8.515(216.3) | 8.515(216.3) | |
| Plates | | N/A | Pure Lead -tin 99.99% tin with tin dope (14+/15- per cell) | +:Lead Calcium-Tin : Lead Calcium (15 plates per Cell) | +:Lead' Calcium-Tin -: Lead Calcium (17 plates per cell) | |
| Internal resistance (mΩs) | | | 1.55 | 1.33 | 1.33 | sponge lead formulation enhanced in latest Exide units. |
| Initial charge | | 120 C | 132.6 | | | |
| Flame retardation | | | | per M-506 Sec01 & DR100411-00 | per M-506 Sec01 & DR100411-00 | |
| Capacity (A*hr)@C/20 to 10.5V) | | 120 | 132.6 | 100+ | 100+ | |
| Reserve Capacity (minutes) | | 200 | 132.6 | 215.7 | 221.9 | |
| Life Cycle Capacity Test (cycles) APD 2206 | | 235 | 481 | | | |
| SAE Type 1- J2185 Cycle Life | | | | 555 | 792 | |
| Storage Life Test | | 160 | 258 | | | |
| Deep Discharge Recovery | | 120 | 132.25 | | | |
| VDA AGM (9.9.4) – Deep Cycle Durability Test | | | | 50th Cycle = 75.5 Ah Final C/20 = 98.3 | 793 | Test attempts to quantify degradation to repetitive discharges (European start stop standard) |

## BACKGROUND REQUIREMENTS:

The current configuration of batteries was selected and developed during 2008-2009 and that change process was driven by enhancing the survivability of the Bradley platform.

Survivability

In response to operational needs, the BUSK upgrades were developed in 2009. These upgrades resulted in the changes to the vehicle electrical energy storage. Hull modifications in the floor provided space beneath a blast resistant seating structure that protects the driver in a blast event. The seating requires an open space to permit travel of the seating structure. These changes drove the relocation of the two (type 6T) electrical batteries that were located under the baseline driver seat and the selection of smaller batteries to fit into the space available after hull modifications were made. This resulted in selection of Group 31 batteries as they could fit in the hull space claim and also permitted installation of two additional articles in the sponson location. The Group 31 Exide batteries were already available in the logistics supply system in theater as they were used on Mine-Resistant Armor Protected (MRAP) vehicle variants. As an added benefit, the additional sponson batteries, although slightly smaller and having less electrical capacity, were able to be mounted and utilize the available space more efficiently. Thus eight Group 31 batteries represent an upgrade over a suite of six type 6T batteries in terms of total vehicle energy storage capacity.

The Exide Group 31 battery's AGM construction also provides a measure of improved survivability as when overmatched the glass mat material tends to retain the battery electrolyte inside the battery container. When a flooded lead acid battery is similarly struck, the liquid electrolyte flows from the battery more readily presenting an additional hazard to the crew. Electrically, the AGM batteries have shown themselves better than flooded cells in performance characteristics. The AGM battery's marginal additional cost was accepted as a means of reducing the acid exposure hazard.

## BUSK Impact on Silent Watch Requirement

The silent watch specification only defines loads that will be powered off, so other vehicle load remains present. Table I indicates the turret loads that are powered off in silent watch.

**Table II LRUs Powered Down in Silent Watch**

| |
|---|
| GPFU – Gas Particulate Filter Unit |
| GCU – Gun Control Unit |
| IBAS Defogger |
| Turret Drive System - Drive Power |
| MRE Heater |
| Squad Leader Display |

Given that the BUSK survivability changes resulted in a significant change in the platform's electrical power storage, a validation test was performed to show that the BUSK electrical changes met the baseline silent watch requirements. Specifically the Bradley program office sponsored cold room tests at Aberdeen Proving Grounds (APG), where a test platform attempted a cold temperature silent watch profile followed by engine start with the baseline new fully charged 6T flooded PbA batteries (organized in a bank of four hull batteries and a bank of two sponson batteries). The baseline configuration test was not successful. The BUSK configuration (eight Group 31 AGM batteries) were then installed in the test asset and were able to successfully meet the test criteria (reference /6/, paragraph 4.4.4.6). Note that the testing was a single 24 hour cycle test and did not evaluate the ability to recharge or restore the batteries after the deep cycle or any long term logistical impacts of silent watch deep cycle discharge/recharge batteries on platform variants. As a result of the BUSK requirements evaluation, the Bradley energy storage was modified as shown in Figures 3 and 4 below.

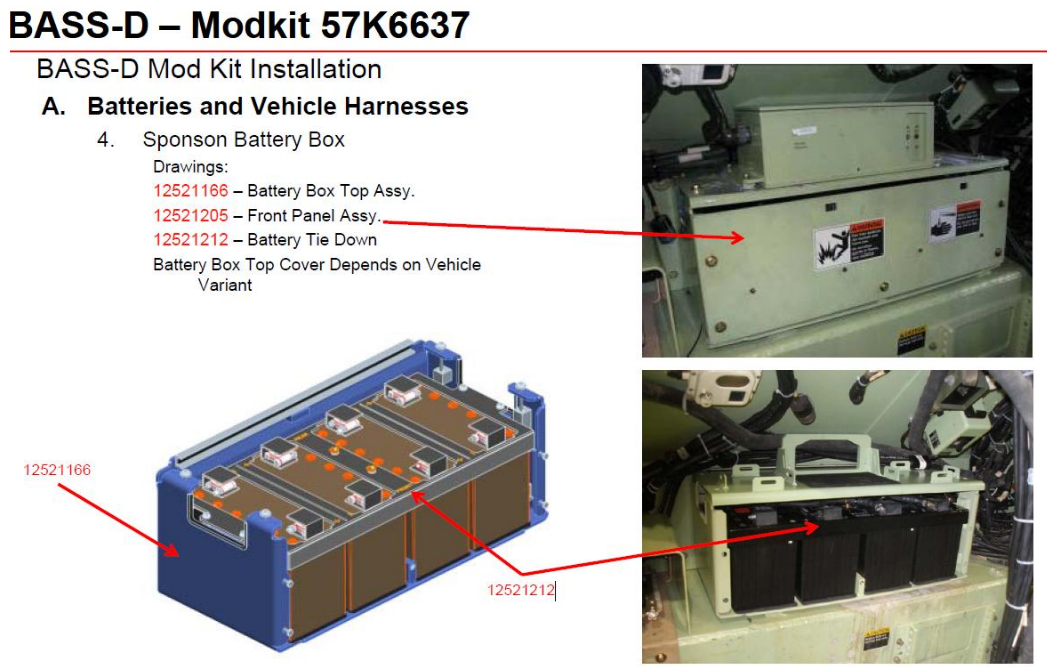


**Figure 3 BUSK Sponson Kit Installation per Reference /8/**

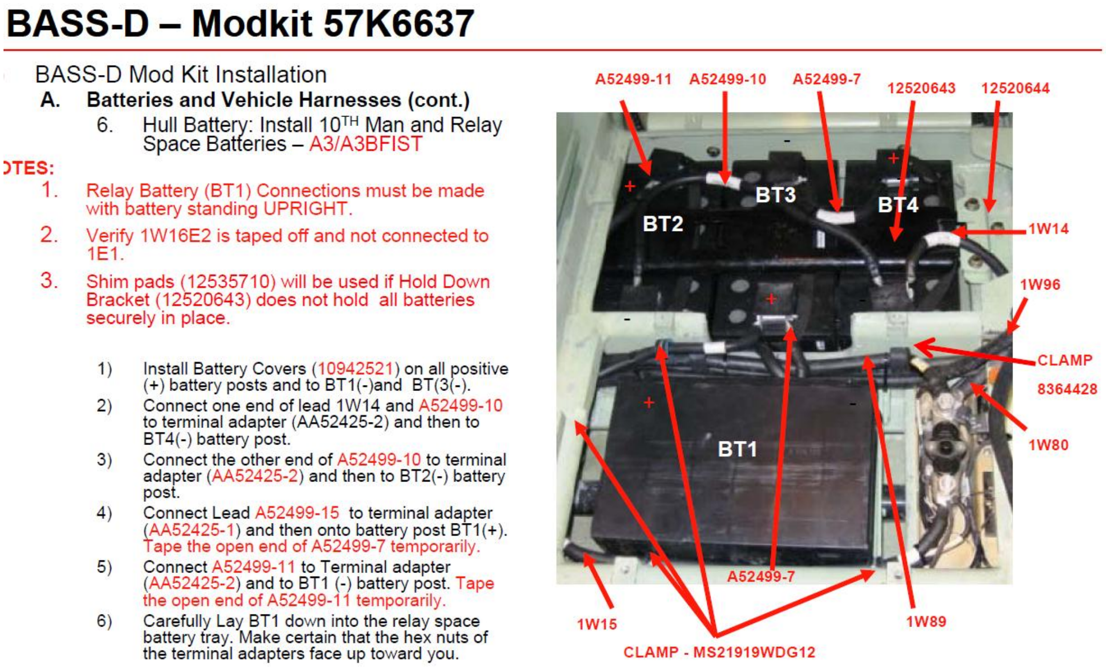


**Figure 4 BUSK Hull Kit Installation per Reference /8/ [Note attitude of BT1 mounting - requiring AGM battery for electrolyte retention]**

## ENGINEERING ANALYSIS: FIELD FAILURES

The analysis of the issues with energy storage focused in several areas: 1) study of the current field maintenance, use and abuse; 2) validation of the performance of the battery tools used to service the batteries; 3) a review of the details of the battery design, and finally 4) a system level review to see if any feature/action in one area negatively reacted with the features in another area. In focusing on the maintainer task, environment, tools and the energy storage articles themselves, a comprehensive study hoped to find causes why the batteries are continuing to affect the readiness of the platform and recommend measures or actions that might improve the situation.

Current Field Maintenance, Use, Abuse, Issues and Documentation

1. A survey of field problem reports as well as interviews with FSR personnel was conducted. The successes/challenges of the various maintenance environments along with their recommendation of field level procedures were compiled.

2. Current maintenance guidelines described in references /4/ and /5/, as well as the PS magazine document the baseline processes being used to support the battery. Yet, the platforms still experience high mortality of platform batteries and their availability is limiting fielded platform readiness/availability.

3. The TM, TB and PS magazine prescribed maintenance procedures appear to be generic and may not be specific enough to meet the challenges of the Bradley Electrical distribution system.

4. After working a draft document, the Bradley Program office elected to reemphasize the charging algorithm prescribed in the current documentation with clarification as to the switch positions required to properly parallel the two Bradley energy storage packs.

<u>Summary of Field Issues Identified Several Challenges and Possible Solutions</u>

1. Current maintenance guidelines described in References /4/ and /5/ as well as the PS magazine still experience high mortality of platform batteries and their availability is limiting fielded platform readiness/availability. Current maintenance tools properly emphasize the need to need to check open circuit voltage (VOC) at the battery level to assess battery state of health, but they are time and manpower intensive to perform. At present, there is no platform monitoring/telemetry that facilitate the collection of the battery state of health information and drive maintainer actions.

2. FSR reports from operational units supporting training at garrisons (Fort Hood, Fort Carson) showed that the majority of battery failures occurred in the sponson/turret electronics battery bank location. Given the strong statistical inference associated with the sponson batteries, further research was conducted to identify probable causes. It was noted that in a majority of cases the anomaly was initially identified as “turret electronic fault/shutdown”. This observation suggests that activities similar to silent watch condition are being performed on battery power and thus turret bus voltage is falling below the level require to maintain electronics functionality. Probable causes developed include:

    a. Several reports show Inertial Navigation Unit (INU) faults during turret movement, indicating low turret voltage levels. This low state of charge on the sponson battery bank confirms lack of charge maintenance.

    b. The engines on the subject vehicles are not being run often or long enough to provide sufficient recharge to the sponson batteries.

    c. Condition (less than 100% SOC) of the floor batteries is probably being masked as the floor batteries provide power for hull loads, which are substantially less than turret loads. As long as the floor batteries have sufficient stored charge to provide for an engine start event they will receive little attention from the user and maintainer and will be deemed “OK”.

    d. The SATS PulseTech PRO-HD charger charge limit of 45 A was confirmed. Given the current needs to charge low SOC batteries, and the presence of “always on loads,” the capability of the charger output is exceeded. Consequently, the batteries do not charge.

e. Even if the PRO-HD charger had sufficient output capacity, the appropriate switch configurations are not being employed that would provide recharge of the sponson batteries in the vehicle via the NATO Slave. (Maintenance documentation did not specifically note the need to turn Master Power select - ON Engine Accessory Select Switch – OFF and Turret power – ON.)

f. The fleet does not employ low amperage trickle chargers (for example, solar powered or dedicated 110 VAC powered battery charger/maintainers) to keep the batteries fully charged during non-operational periods, a practice that has reported beneficial results across aviation and commercial fleets that have low periods of operation versus storage similar to a combat vehicle utilization. Applicability to combat vehicles has yet to be demonstrated.

Maintenance History in Depot Logistic Locations

Authors were able to review battery maintenance history of the Bradley population from three sites. The sites represent hot, cold and test environments.

1. 2013-2014 battery maintenance activities in Camp Arifjan, Kuwait: 41 vehicles are in preposition storage and are being maintained by the 402nd Logistic Group. The environment represents some of the warmest storage conditions for a large group of Bradleys. Excellent record keeping shows that the unit was using the SATS charger but was still removing and replacing a significant number of batteries. That replacement rate was taxing the logistic system's ability to supply replacement batteries in the required quantities. The replacements were also required across the platform population and were not concentrated in the sponson/electronics bank as was seen in the logistical history of the operations units involved in training activities. The logistics team used the NATO slave/SATS charger to perform charging monthly. When a battery was deemed bad their attempts to recover the battery did result in successfully recovering 40% of the suspect batteries. The organization also developed a unique electrical configuration that improved the effectiveness of their PulseTech PRO-HD charging operation. Specifically, they jumped the two banks together at the B1/B2 vehicle alternator outputs. In doing so they were able to avoid turning on the turret loads, thereby eliminating the parasitic loads that are incurred while charging the batteries with standard switch configuration.

   Analyzing the hot maintainer experience:

   a. Charging in hot climates continues to challenge batteries. OEM recommendations are to discontinue charging when battery temperature reaches 50 ºC (122 ºF). Research (reference /9/) indicates that dynamic charge acceptance at temperature after a period at rest facilitates anode oxidation and sulfation. Since temperature cannot be controlled by the maintainer, consideration should be given to providing the charge algorithm with the battery temperature and allowing it to decrease the target voltage when performing charge operation in elevated temperatures. The current SATS charge has no provision to accomplish this.

b. Recovery charge procedures are partially effective, but charge acceptance of the lead acid chemistry (exothermic charge acceptance properties) continues to decrease the life of these batteries.

c. The SATS charger does not provide a sufficient peak current output and/or battery temperature monitoring, thereby hampering the effectiveness of charge maintenance operation. The OEM provides for a maximum peak electrical current of 40 A across the bank strings (4 * 40 A (max) = ~160 A). The currently fielded charger has a peak output of 45 A. The following table also summarizes the recommended time to reach 100% SOC.

**Table III Exide Suggested Charge Times @ 77 °F**

| Typical Charging Time (Hours) for Single Battery | | | | |
|---|---|---|---|---|
| OCV* | SOC | Charger's Maximum Rate Setting | | |
| | | 30 Amps | 20 Amps | 10 Amps |
| 12.80 | 100% | 0.0 | 0.0 | 0.0 |
| 12.60 | 75% | 0.9 | 1.3 | 2.5 |
| 12.30 | 50% | 1.9 | 2.7 | 5.1 |
| 12.00 | 25% | 2.9 | 4.3 | 7.8 |
| 11.80 | 0% | 4.0 | 5.7 | 10.7 |

d. Running engines to effect charging was not possible due to site constraints.

e. Sites developed an alternate charging bus configuration that paralleled both sets of batteries without energizing the turret loads, thereby increasing the effectiveness of charging equipment.

The table suggests that using a 45 A SATS charger (~ 10 A per series battery string) will require a minimum of 11 hours to fully restore the vehicle battery set assuming the platform has no parasitic loads. Since the platform is not equipped with a battery management system, it is difficult to make an estimate of State of Charge beyond noting the system bus voltage, which makes the performance issue of the individual batteries difficult to properly assess.

2. 34th Division Minnesota National Guard, Camp Ripley, MN 2013 - 2014: In the past year this location experienced one of the coldest winters on record. After prolonged cold storage, the batteries were often dead. But the maintenance organization was able to disconnect the batteries from the vehicle and charging them on the SATS charger they were able to recover all but four batteries by using a prolonged 48 hour charge period. Bradley vehicles were operational and the site took advantage of the breaks in operations to proactively use the

SATS battery charger, which resulted in excellent results with minimal numbers of batteries requiring replacement.

Summarizing the cold maintainer experience:

a. Charging in cold climates was required between operational periods to recover batteries that were "dead" after storage (monthly).

b. The lack of battery failures, despite the cold, suggest that the maintenance team was able to keep the batteries unfrozen [i.e., charge greater than 75% SOC (battery electrolyte for fully charged battery freezes at ~-100 °F, while a completely discharged battery will freeze at temperatures as low as 25 °F; see figure 5, below)]. The formation of internal ice in the electrolyte can physically damage the tightly spaced plates, glass mat and separators.

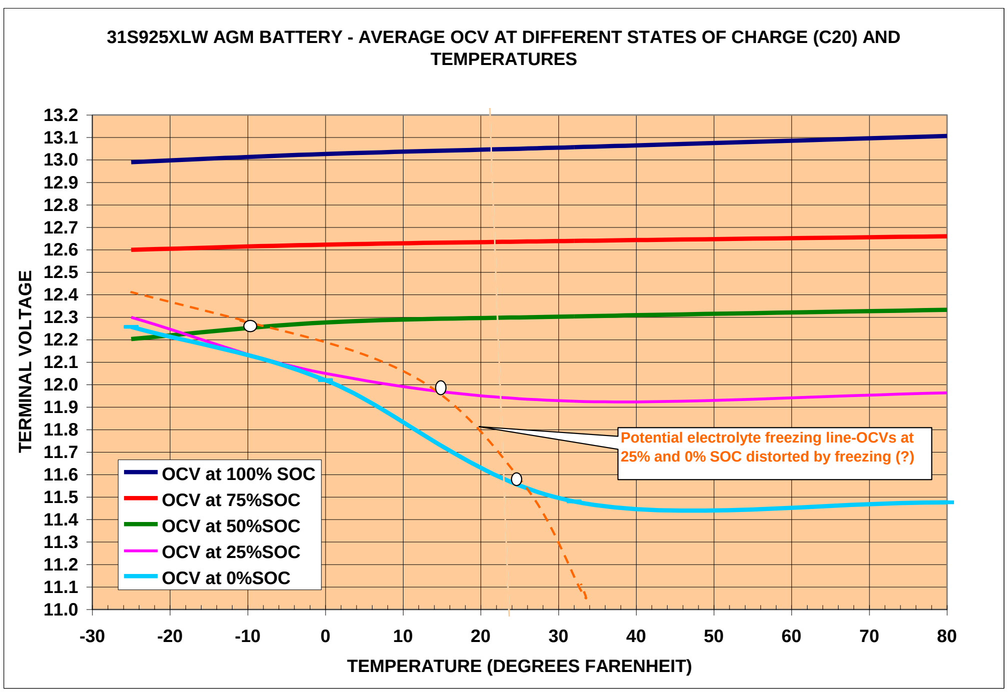


**Figure 5 Exide 31A925XLW VOC vs. Battery Temperature (with freeze line)**

3. The final case study: the Bradley platforms support software verification and validation testing in Santa Clara, California. Each of these units is located in the Vehicle Test and Integration Lab (VTIL) facility where extensive software checks are performed. In the process of performing this effort the units spend days with the vehicle electronics powered, although not all the electronics are present in all the vehicles. Each vehicle station hosts a 150 A power supply sourcing current at 28.4 VDC. The power supply is connected to the

platform via the NATO slave. The platform switches were configured to parallel both battery banks. Despite exercising a nominal population of an average of ten vehicles, no battery causalities were noted and none were replaced. It should also be noted that nominal current draw from the supply with fully charged batteries is 40 A – 45 A, which would equal the capacity of the SATS charger. This would indicate that vehicles in the field with low State of Charge batteries cannot be charged effectively. Vehicles in the VTIL are operated on power supply or the engine.

Summarizing the test maintainer experience:

a. Frequent use of a large (150 A peak) power supply to charge the batteries and support test operations (versus discharging vehicle batteries) in a moderate temperature environment resulted in no noted battery issues. Thus the test site charger also is sufficient to support vehicle engine off operations. The lack of sponson battery failures in this environment highlights the positive benefit of the larger capacity charger than the SAT's charger.

b. Industry studies [BCI International 2010] that document the reason batteries were removed from service often indicate that 1) sulfation of batteries stored at less than full state of charge, 2) operation and or charging of lead acid batteries at elevated temperatures, 3) internal temperature rise due to high C fast charging and the associated drying out (electrolysis of the electrolyte), or 4) prolonged overcharging, are identified as leading source causes for removal of batteries from service. The review of field data found strong correlation with the first cause, limited correlation with the second mechanism and little or no correlation to other casual factors.

c. Note that an AGM battery, unlike a flooded cell battery, cannot replenish the lost electrolyte. Given the high incident of AGM batteries being removed from service, the last factor, overcharging, which is typically a function of the regulator set point received further study. The battery OEM recommends a charging set point of 28.4 +/- 0.3 V for a bus supported by two batteries in series (at battery temp of 25 °C). Figure 6 provides Pacific Scientific/CE Niehoff regulator voltage output as a function of temperature.

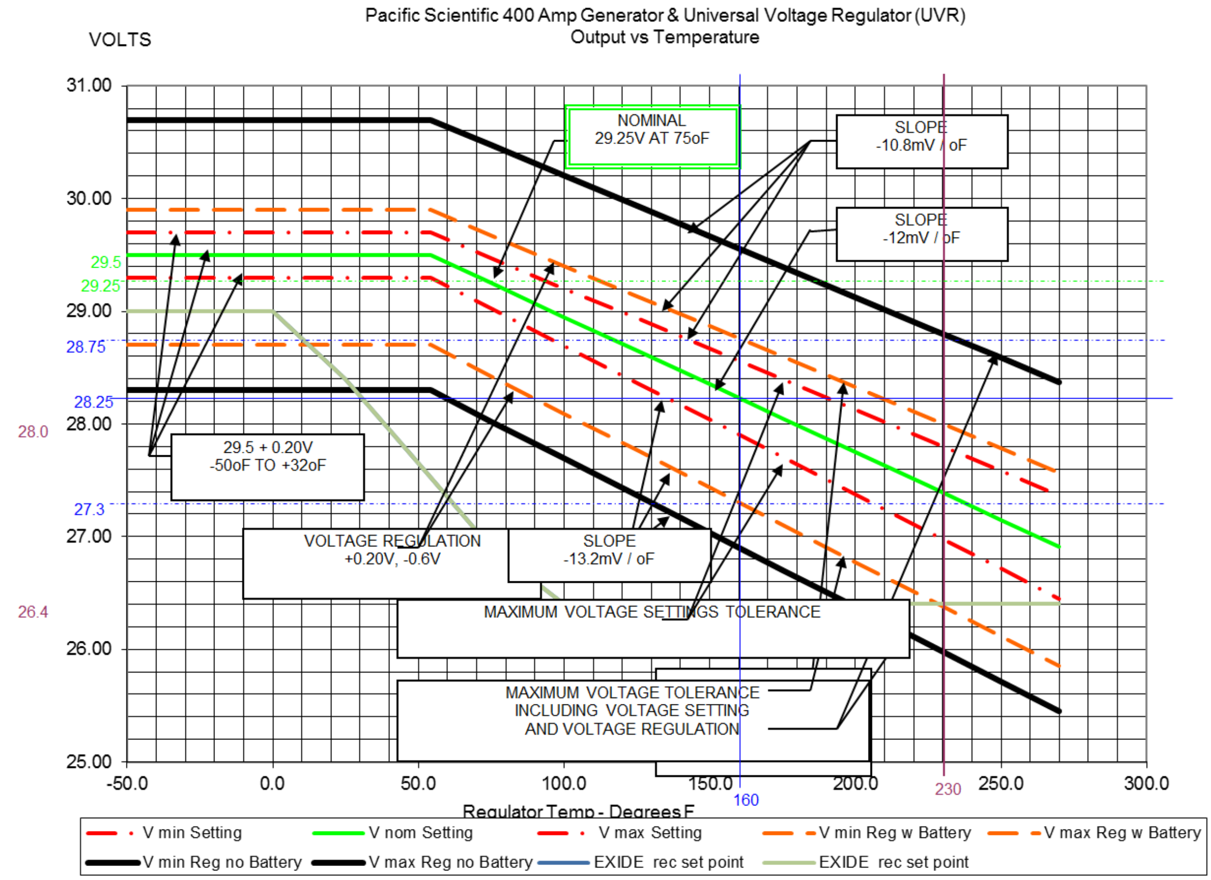


**Figure 6 A3 BFVS Output Regulator Curve**

Thus at start, the voltage set point is approximately 1 volt higher than the recommend float voltage. As the regulator temperature (located in the engine compartment) rises, the voltage decreases until it settles in the recommended range. This open loop relationship for engine based recharge over time achieves the desired set for the nominal battery temperatures. But the lack of data to validate that this relationship is valid leads to a recommendation that the actual battery temperature be measured, via a Battery Monitoring System (BMS), and used by the regulator to eliminate charge voltage uncertainties. This vehicle voltage data was presented to Exide during development of the 31A925XLW and their engineering staff felt this charge compensation was adequate for their battery.

## PI MCA-111-P25R0 Testing Results

In a tangentially related effort, Exide has identified an improved version of its Group 31 product line. The new production configuration has retained the same OEM part number. The manufacturer's changes to the 31A925XLW are form, fit and function equivalent, with the exception that the mass of the updated article is 0.5 kg less that the initial article (improvement).

The improved articles were received, installed and tested at BAE Systems' Santa Clara facility. The batteries performed as expected, as they had passed the OEM nominal testing and qualification program [electrical, mechanical and vibration testing per SAE 537 and SAE 930, VDA AGM Specification 2009, section 9.9.4]. In discussion with the OEM, the alterations to the improved version were identified as:

1. Altered the cathode chemistry for deep cycle events

2. Introduced thinner plates while increasing the total number of plates per cell from 15 to 17 to improve transport of oxygen between the anodes during charging

3. The batteries are externally identical but the date lot code will allow the articles with the changes to be identified (that is, not changing part numbers).

Supplemental track vibration screening on a Bradley operating at Camp Roberts, California:

The OEM supplied 11 new batteries to BAE Systems and a "piggyback" test was conducted on a tracked platform to screen for any possible vibrational environment issues with the new plate configuration. Tracked vehicle vibration spectrum is different than the J930 vibration profile. The results of the 10 day test with 1 hour silent watch operations were nominal, with no battery failures. Testing summary of the Exide 31A925XLW batteries down at Camp Roberts 7 Jul – 18 Jul found that over the 294 miles of travel across road and cross country courses one reportable event occurred that was not related to the new Exide Batteries.

<u>Battery Management Tools</u>

A study was conducted of the effectiveness of organizational battery chargers and the role if any that they contribute to battery maintenance success. The current charger was widely fielded at the same time as AGM batteries entered the force. Bradley electrical power architecture complexities and the electrical demand require active maintenance to maintain the platform energy stores.

1. PulseTech Chargers

   Two deployed systems (pallet and vehicle):

   a. PRO-HD PulseTech 12/24 V Pulse Charger and Battery Recovery Unit. (See Figure 7)
      - Part number: 746X800
      - Model number: PRO-HD
      - Charge and recover any type of lead-acid battery - flooded cell, sealed, VRLA and AGM
      - Smart technology automatically switches between 12 and 24 volts. Patented pulsing prevents battery gassing. Very flexible, low resistance battery power leads attach the unit to the battery by conventional alligator clamps or special

external heavy duty plug used by some equipment (NATO slave). Comes with built-in cable and tool storage.
- NSN 6130-01-500-3401

**Figure 7 PulseTech PRO-HD**

b. There is lack of evidence that the use of the TARDEC "PulseTech PRO-HD" designed charge system is recovering batteries.

- At 45 A peak output, the charger is be under powered to effect charging of the four battery strings in the presence of parasitic vehicle loads in a timely manner.
- Charger performs no temperature compensation of the charge voltage that is recommended by all AGM battery vendors. This may be a contributing factor to overcharge casualties in hot environments.
- The charger executes a program charge algorithm that reports to minimize sulfation and recover sulfated (low VOC < 12.6 V) batteries.
- The FSR depot maintenance evidence supports that some recovery is possible, but that it typically must occur apart from the vehicle electrical bus. This suggests that the inductance and capacitance of the load on the power supplies minimize the effectiveness of a high frequency charging regimen.

2. The battery maintenance tester (Midtronics MDX-650) used in conjunction with the battery testing, requires the operator to enter in a battery parameter (Cold Cranking Amps (CCA)). Technical Bulletin /3/ directs the use of 1100 A for this parameter. The BUSK Exide battery has a rated CCA of 925 A. The 6T AGM are larger batteries and have typical CCA at or in excess of 1110 A. The testing asset then performs a battery impedance measurement and evaluates the tested battery health. The tester provides a Go/No Go determination to the maintainer. As the tester algorithm is unpublished, uncertainty exists that use of a CCA parameter that is 20% larger than the battery being tested will report false negative battery health estimations. The maintainers could be discarding serviceable batteries.

3. Battery Monitoring Function (battery balancing is not currently implemented on the A3)

**FINDINGS AND CONCLUSIONS:**

1. Strong evidence suggests installed energy stores get exercised without complete effort to fully recharge the batteries. All PbA batteries require lengthy charge to reach maximum SOC and batteries at lower SOCs are affected by higher rates of sulfation at both anode and cathode.

2. Operational/maintenance processes employ the sponson batteries and leave them in a low SOC resulting in sulfation and item mortality. Higher incidence of sponson versus hull battery failures has the following possible causes or combinations of causes:

    a. Operational activities (without the vehicle's engine running) run down the batteries in the sponson and leave batteries in a reduced SOC without attempting to return the batteries to full SOC for extended periods of time.

    b. The current SATS charger (PulseTech PRO-HD) lacks sufficient output current to perform a timely in-vehicle charging of the battery sets, particularly when 'always on' loads (primarily associated with the turret) are reducing the effectiveness of the charge process.

    c. The electrical distribution system requires switch configurations to permit the sponson batteries to charge alongside the hull batteries.

3. The SATS charger does not monitor or allow input to target battery temperature, thus hot charges will likely exceed the OEM recommendation of maximum battery temperature. This is of importance to AGM batteries as there is no means of replacing electrolyte that is lost during hot charging.

4. The SATS charger assumes the battery in each string is approximately the same state of charge. There is no battery balancing in the current system to assure this assumption is correct.

5. When batteries are replaced, the maintainers do not measure the replacement batteries' state of charge and perform a 'top off charge' consistently.

6. Current regulators in the low voltage power generation architecture have no means of temperature compensating the voltage set point to avoid overcharging AGM batteries. The overcharge mechanism is associated with "drying out" loss of AGM battery electrolyte from heating and electrolysis. (Note that water cannot be added to AGM batteries as is done in maintenance of flooded lead acid batteries.)

   The voltage set point of the regulator is locally measured at the regulator (engine compartment temperature) and without a battery monitoring system that feeds temperature data to the regulator, a period of overcharging exists. The A3 BFVS generator's voltage regulator compensates for temperature based on measurement of the engine compartment temperature, but the batteries are resident in crew space and this scheme does not account for the delta between engine compartment and battery (crew compartment) temperatures. Thus, the subsystem does not compensate for local climatic condition, and it is likely that the batteries will be strongly charged until the engine compartment temperature stabilizes. If AGM batteries are overcharged, they will loss electrolyte to localized heating and higher electrolysis rate that overcome the measure taken to retain Hydrogen and Oxygen in the battery. While this response to overcharge is the same in flooded PbA batteries, specific gravity checks can be performed and water added if indicated.

7. The maintainers may be discarding serviceable batteries either because of misinterpretation or inaccuracy of tester readings, or because the removed battery has not been given an opportunity to recover charge using a SATS charger.

**RECOMMENDATIONS:**

Definition of constraints and customer input is needed to refine the following recommendations, but they are offered to initiate discussion for possible follow on efforts. Further funding will be needed to generate the specific design details and recommended approach. Specific recommendations are focused on the goal of maintaining the batteries at a full state of charge and include:

1. Update of the platform electrical architecture to permit more effective maintenance:

   a. Need to modify vehicle electrical design to permit direct charging of the sponson batteries.

   b. A dedicated harness and/or manual by-pass switching to the sponson batteries that by-passes the vehicle electronics would simplify and facilitate efficient charging with the available chargers in the field.

2. Use a higher current battery charger to affect battery charging in the vehicles in a timely manner via the NATO slave. If high output chargers are not available consider isolation of the batteries from the always on system loads to effect timely charging.

3. Temperature compensation of battery charging. The generator charging voltage should be set according to sensed battery temperature not engine compartment temperature in order to meet the battery manufacturer's charging profile. Similarly, the cart based charging could benefit as the current the PulseTech PRO-HD charger has no means of adjusting battery charge voltage based on temperature.

4. A battery monitoring or management system that can balance the batteries in a string and monitor charging temperatures should be considered. (The A4 BFVS is implementing a BMS provided by Merlin Power Systems, Inc.) Improved monitoring and management of the batteries would provide the following benefits by such a system:

    a. Battery state of charge and state of health would be available to the operator/maintainer that presently can only be obtained via manual checks during logistic availabilities.

    b. Battery heath and state of charge information would be able to address battery imbalance were it to be implemented, resulting in elimination of overcharging (greater than 107% discharge) of the higher SOC battery in a series pair (string).

    c. Temperature compensation is handled by the BMS. For example, the A4 BFVS generator system has a temperature compensated voltage regulator that is tailored to the needs of the Exide AGM batteries. Battery temperature is sensed by the BMS and charging voltage from the generator is set to meet the battery manufacturer's charging profile.

    d. An active battery management system could provide some incremental improvement to battery reliability and life over a batter monitoring only system. For example, a battery management system will seek to equalize the charge on all batteries and has the ability to limit overcharge, which would improve reliability

5. It should be re-emphasized to the maintainers that replacement batteries should have their state of charge measured before installation in the vehicle and if required the charge should be "topped off" to 100% SOC.

## APPENDIX A: ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| A | Ampere |
| AGM | Absorbed Glass Mat |
| Ahr | Amp Hour |
| Amp | Ampere |
| APG | Aberdeen Proving Ground |
| BFVS | Bradley Fighting Vehicle System |
| BMS | Battery Monitoring System |
| BUSK | Bradley Urban Survivability Kit |
| C/"x" | Capacity as measure by current discharge at nameplate/x (c/1 is one hour test) |
| CCA | Cold Cranking Amperage |
| DC | Direct Current |
| FSR | Field Service Representative |
| LCMC | Life Cycle Management Command |
| MI | Maintenance Information |
| MRAP | Mine-Resistant Armor Protected |
| NATO | North Atlantic Treaty Organization |
| NSN | National Stock Number |
| OEM | Original Equipment Manufacturer |
| Pb | Lead |
| PbA | Lead Acid |
| PI | Problem Investigation |
| SATS | Standard Automotive Tool Set |
| SOC | State of Charge |
| TB | Technical Bulletin |
| TM | Technical Manual |
| V | Volt |
| VAC | Volts Alternating Current |
| VDC | Volts Direct Current |
| VOC | Volts Open Circuit |
| VRLA | Valve Regulated Lead-Acid |
| VTIL | Vehicle Test and Integration Lab |

## APPENDIX B: LEAD ACID BATTERY CHEMISTRY AND SELECTION

While there are performance variations among the various manufactures of lead acid batteries, all lead acid batteries share similar weaknesses and strengths. The single biggest strength is availability at a reasonable cost. In addition, the lead acid chemistries tend to be available in a wide variety of sizes and alternative electrical interfaces. Because of their high penetration in the transport market, there is also a strong familiarity with the products and the products themselves are relatively mature. The development of sealed units has reduced maintenance of the batteries. Gel (furic silica added to the electrolyte) and AGM variations have been increasing in popularity as they reduce handling and also increase safety by reducing the potential for exposure to the liquid electrolyte (typically a 5 molar $H_2SO_4$ acid solution). Indeed, the ability to mount the unit in different attitudes and the control of the electrolyte reduced exposure to electrolyte in overmatch are strengths.

But all current lead acid chemistries share the same weaknesses. A sulfation and corrosion process that limits life when batteries are maintained at less than 100% state of charge (SOC) along with repeated deep discharge cycles are reasons why this chemistry has failed to make significant inroads into grid storage applications. The basic charge acceptance of the chemistry is poor since $H_2O$ splits into in composite gases and these gases must move in the electrolyte between anode and cathodes (see Figure B-1). This is the primary reason this chemistry performs poorly in the silent watch scenarios. Charge acceptance also becomes worse at lower temperatures. After each partial discharge period the battery requires a lengthy recharge time (almost as long) of engine operation to return the energy storage to full SOC. The repetitive nature of silent watch events across a combat or training day do not provide the recharge time necessary to support the needs of the lead acid battery.

If a flooded PbA acid battery is employed, the specific gravity of the electrolyte can be restored by adding water to the cells after loss during strong recharge events. AGM PbA batteries do not have this benefit and must rely on management charging operation to avoid outgassing events.

The Silent Watch use case represents a poor approximation to the discharge and depletion routines of industry standards. Industry standards that test the performance of PbA batteries are focused on deep discharge followed by a lengthy recharge period and rest period on a 24 hour cycle.

Finally, all lead acid chemistries suffer performance issues at temperature extremes. Partially discharged batteries can freeze resulting in internal damage, while heat from the charge process (and or external ambient environment) causes loss of electrolyte.

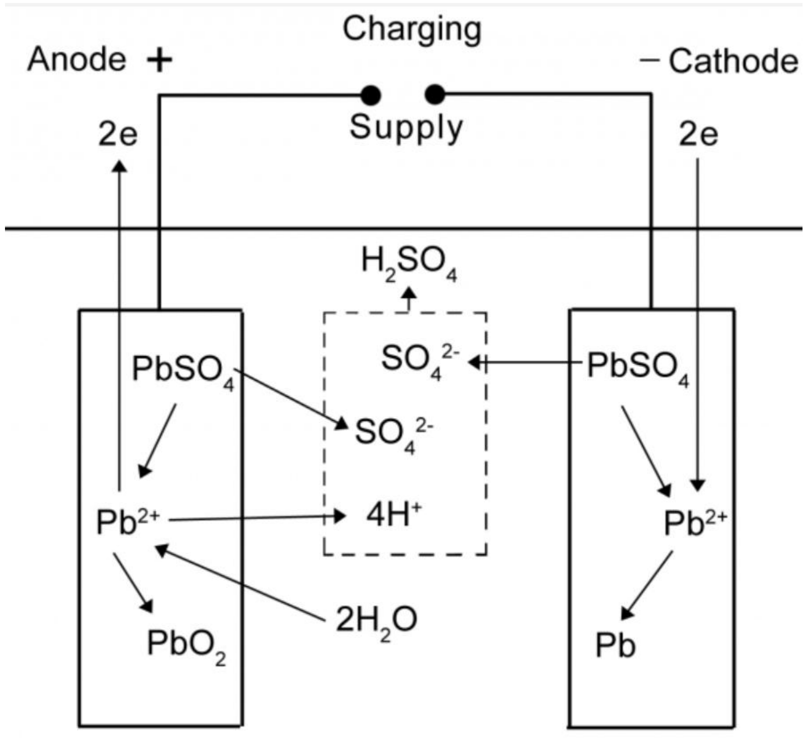


**Figure B-1 Diagram of Lead Acid Chemistry during charge**