

Sulfation in lead–acid batteries

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Abstract

Virtually, all military land vehicle systems use a lead–acid battery to initiate an engine start. The maintainability of these batteries and as a consequence, system readiness, has suffered from a lack of understanding of the reasons for battery failure. Often, the term most commonly heard for explaining the performance degradation of lead–acid batteries is the word, sulfation.

Sulfation is a residual term that came into existence during the early days of lead–acid battery development. The usage is part of the legend that persists as a means for interpreting and justifying the eventual performance deterioration and failure of lead–acid batteries. The usage of this term is confined to the greater user community and, over time, has encouraged a myriad of remedies for solving sulfation problems. One can avoid the connotations associated with the all-inclusive word, sulfation by visualizing the general “sulfation” effect in terms of specific mechanistic models. Also, the mechanistic models are essential for properly understanding the operation and making proper use this battery system. It is evident that the better the model, the better the level of understanding.

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1. Introduction

The US military defines readiness in land vehicle systems as the ability of that vehicle to be capable of executing a predefined mission. This capability is the consequence of the successful linking of a series of probabilistic events leading to the favorable result.

The concern here is the reliability of one of the early events in the chain of events that activates the on-board power generation system. For the most part, the subsystem that determines whether or not an engine start takes place is an on-board lead–acid battery. Also, the lead–acid battery can be viewed as serving three major functions in military vehicle systems.

The first is the engine start function. In this case the battery has to provide sufficient power to accelerate the rotation of the crankshaft (or fan as the case may be) to bring about a successful engine start. Although the current draw can be very high, the time over which this draw takes place uses a very small fraction of the battery’s energy storage capacity.

In many cases the energy consumption is less than 5% of the energy storage rating of the battery.

The second function is to make up for the difference between the load power demand and the power delivered by the engine/alternator system (or perhaps an auxiliary power unit). This is an example of load leveling. An example of this is the case where the engine is idling and a large electrical load is brought on-line. The battery supplies the deficit power and continues to do it until the engine is brought throttled up or the battery exceeds its energy storage reserve.

Lastly, the battery is sometimes the only energy source available to maintain the operation of the vehicle. An example of this would be silent watch. In that case, the battery will meet the power delivery requirements of the vehicle until the energy reserve in the battery is exhausted.

Two issues are immediately evident. The battery must have a sufficiently low internal resistance such that the battery will load-follow. That is, the resistance of the load will determine the power delivered by the battery. Next, the battery must contain a sufficient state of charge whose upper limit to determined by the design capacity of the battery. It is important to understand the battery has a normally occurring but very low parasitic energy loss. In time, the battery must be recharged to make up for this energy loss as part of vehicle maintenance. In the case of passenger vehicles, the parasitic

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losses are not of any real concern because the day-to-day operation of the vehicle serves to top up the battery's energy reserve. However, in military vehicles this is not the case. Most military vehicles are kept in storage in an inactive condition. In this situation, periodic topping up of the charge reserve becomes part of the routine vehicle maintenance procedure. To clarify this a little further, the total energy battery losses are the sum of the internal self-discharge (which is a function of the environmental temperature) and the external parasitic loads imposed on the battery by the attached vehicle electrical system when the vehicle is in the "key-off" state. Many vehicle designs impose low power electrical drains on the battery to keep various subsystems in operation when the vehicle is in a stopped and in an unattended condition. Security alarms and clocks are a couple of examples. The discussion that follows relates to the failure modes of lead–acid batteries in vehicle applications.

The lead–acid battery has a long history spanning over 150 years. During that time, much folklore as well as solid technology has developed in support of battery applications. An interesting simplification is currently in vogue. That is, if one should search the internet for the word, "sulfation," a substantial search return was received having an apparent distinctive and authoritative flavor. Among the items returned are statements like "...over 80% of discarded batteries have nothing more than a curable sulfation problem..." or "sulfation is the number one cause of battery failure." It is interesting that specialized textbooks on battery technology and the discussions with technical staffs of battery manufacturers assiduously avoid the use of the term, "sulfation". It is a fair question to ask why battery experts consistently and intentionally appear to ignore the very thing that limits battery life.

Some times, it is said that "a page of history is worth a tome of logic." In the late 1800s, Bernard Drake carefully studied a large number of failed lead–acid batteries of the Faure design. "When Drake examined the failed cells, he invariably discovered that the faces of the plates had become covered with a 'hard, white enamel,' which he found to be lead sulfate. This led Drake to a most important, although quite unexpected discovery about lead–acid battery operation. This was the problem of oversulphation; a battery can be destroyed if too much sulphate forms in the active material" [1].

It has to be noted that Drake was a mechanical engineer by training and, further, did not have the chemical and structural analysis tools that are currently available. Based on his observations, Drake developed a hypothesis whereby the formation of this sulfate layer became the basis for a simple explanation for the observed behavior of lead–acid batteries. The hypothesis was qualitative in nature but, for the times, provided a reasonable basis for interpretation and interpreting battery behavior.

Leaping forward in time to the year 1955, BCI Technical Subcommittee on Battery Failure Modes issued a report discussing the failure modes of lead–acid batteries [2]. The

BCI presentation identified 29 causes of failure and categorized them into six major groupings. The failure modes listed were the result of observations made during the post mortem examination of the batteries. One could argue from the discussion in this report that many of the identified reasons for failure are not failure modes at all. They are actually the result or consequence of the operating failure mode. However, this depends on how one chooses to define the thing called failure. The essential point is that the study did not reveal sulfation as being of any significance in the failure of these batteries.

We shall attempt here pull these observations together to achieve a more comprehensive and integrated view of lead–acid battery failure modes.

2. Discussion

In general discussions between the technical and user community, the word, sulfation is inherently a confusing term. To illustrate this, three distinct definitions can be formulated:

Definition 1. Sulfation is the name given to the general cause that brings about failure of lead–acid batteries. It is identified empirically by observing the effects of:

- Loss of capacity.
- Loss of voltage.
- Increase in internal resistance.
- A decrease in sulfuric acid concentration.

This definition is phenomenological. That is, the term is the name given to a set of observed phenomena without inquiring into the specific reasons that bring about the consequence. It is noteworthy that such a definition does not open the door to discussions of the truth or falsity of the statement.

Definition 2. Sulfation is the recrystallization of lead sulfate into a form that is no longer electroactive. That is, it no longer participates in the charge–discharge process.

This definition identifies a discrete mechanistic effect. It is distinguished from [Definition 1](#) because it specifies the specific causal relationship. Also, it deals with the essence of the process to which one can either affirm or deny the truth of the statement.

Definition 3. Sulfation is the chemical process by which sulfates are produced.

This definition has a long established usage as a chemical process. This definition is the first impression one would get upon hearing the word, sulfation used in any context.

It is easy to see how these definitions create some immediate problems. In terms of value judgments, [Definitions 1](#)

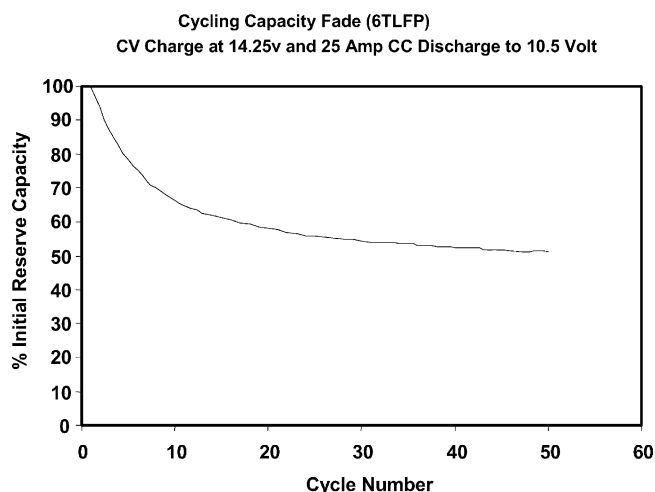


Fig. 1. Capacity loss resulting from consecutive charges and discharges.

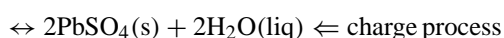
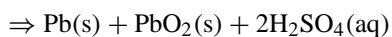
and 2 are “bad” because they diminish the life and performance of the battery. Definition 3 is “good” because it is the fundamental chemical process by which the lead–acid battery operates. Another problem is that it is difficult to distinguish which definition is being referred to from the context in which the term is used. It is necessary that a single meaning exist for any particular word or concept unless it is obvious from the context as to what the object of the reference is. This is clearly not the case for the term, sulfation.

Still another problem is that whenever one suggests that sulfation is the major failure mode for lead–acid batteries per Definition 1, the immediate question is “what causes sulfation?” Often, what is heard is a mechanistic explanation based on Definition 2. That is, the inference is that the mechanism described under Definition 2 explains the effect description identified under Definition 1. This is what Drake attempted to do in his original hypothesis and it appears as a conceptual error. This error is immediately evident from the following data.

Fig. 1 shows the consequence of repetitive cycling of a maintenance-free flooded lead–acid battery. The charging was carried out at constant voltage and the discharge was performed using constant current to a voltage cutoff as specified in the figure. The 6TLFP uses a typical lead grid alloy composition for the positive and negative electrodes containing calcium and tin. The plot of the measured capacity trend diminishes and tends toward an asymptotic limit. Definition 1 would identify this effect as sulfation. However, the effect is unrelated to the mechanistic interpretation expressed under Definition 2.

To explain the actual operating mechanism, it is useful to consider the overall energy storage reaction in a lead–acid battery:

discharge process



During charging, concentrated sulfuric acid is produced at both electrodes. Sulfuric acid has a specific gravity of about 1.835. Water has a specific gravity of 1.000 and a charged lead–acid battery has a specific gravity of about 1.280. One would expect the sulfuric acid to flow downward after it is generated at the plates and collect at the bottom of the battery. This effect is well known [3,4]. This happens whenever a dense water-soluble fluid is poured into water. The denser fluid sinks to the bottom and remains there until it eventually dissipates by a diffusion process. The actual mixing using this mechanism takes a long time. Basically, the top of the battery becomes acid starved and does not permit the reaction of the solid electroactive material located at the top plates to go to completion during the discharge part of the cycle. If one makes the logical inference that stirring this solution will result in recovering the lost capacity, the result would be correct.

Fig. 2 shows the same process that produced the data in Fig. 1 except that an overcharge was periodically performed. In Fig. 2, the measured reserve capacity is shown on the ordinate axis. The effect of the overcharge generated a gaseous reaction product at the electrodes that in turn serves to stir the electrolyte. The consequence of this convective mixing process was a complete recovery of the lost capacity. This loss of capacity effect is well known and is often referred to as electrolyte stratification. The effect is unrelated to the mechanism identified under Definition 2. This demonstration shows that the cause of the effect identified under Definition 1 is not brought about by the mechanism identified under Definition 2.

In passing, Fig. 2 also shows the comparison of batteries differing in positive grid alloys. The antimonial alloy grids of the 6TL batteries are leaching out antimony compounds that are inducing additional gas evolution as the battery ages. This is both good and bad. The good part is that it reduces electrolyte stratification capacity losses. The bad part is the gassing enhances the battery self-discharge rate and a loss of water, which is the material consumed to form the gas.

Experience has shown that the identification of failure modes in lead–acid batteries is not a simple matter for three reasons [5]. First, batteries are complex systems having many operational interactions and the dominance of any particular failure mode depends on a number of environmental and construction factors. Second, batteries are long lived and testing to failure is a long and costly process. Lastly, accelerated testing of complex systems often prefers one failure mode over another. Another way of looking at this is to consider the failure mode as an equilibrium point in a chaotic process. That is, any specific failure mode constitutes a chaotic attractor. The general method for observing failure modes is to perform post mortem on failed batteries. The failure mode determination is often based on the observational skills of the person or group present during the post mortem examination. It is very rare that a failure mode is studied in a planned controlled test. An example of a failure mode that is testable in a controlled experiment is electrolyte

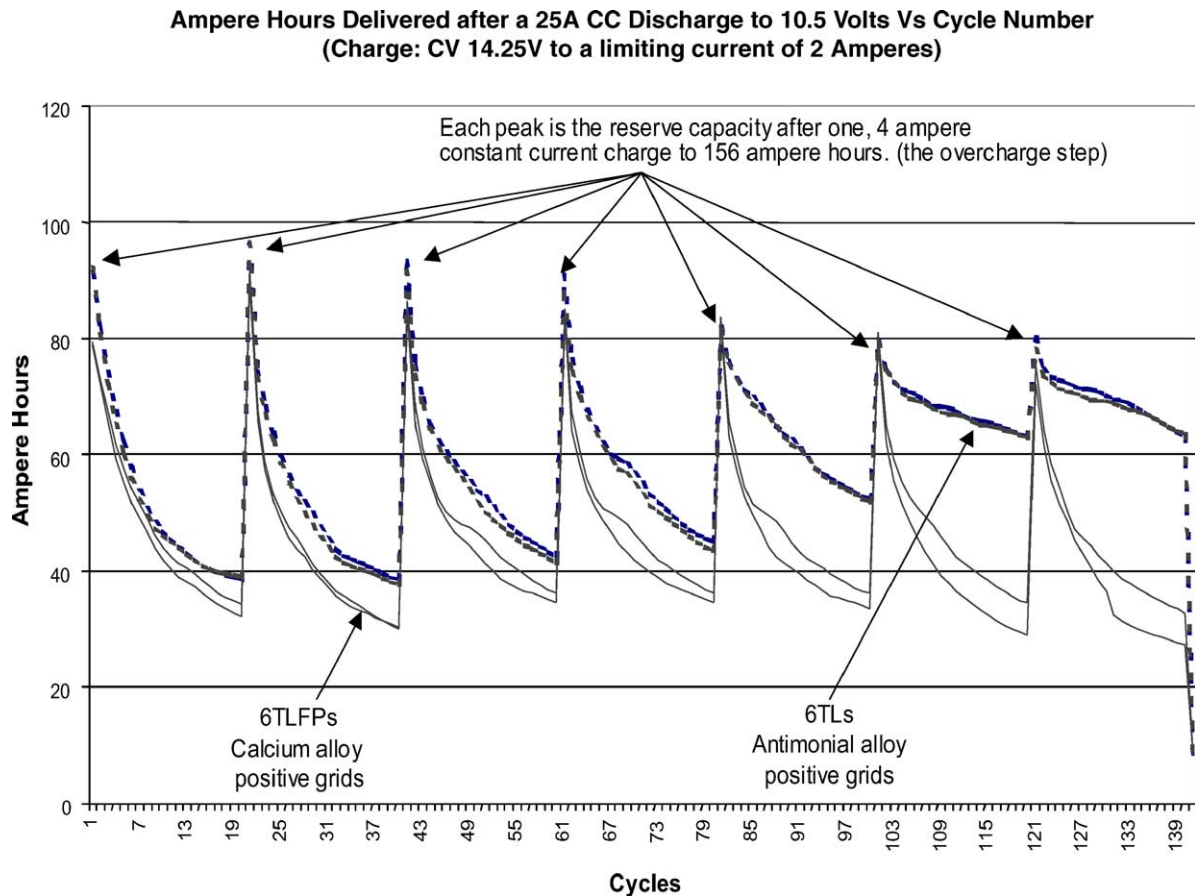


Fig. 2. Effect of induced stirring by gassing on capacity.

stratification. Nevertheless, discrete failure modes often occur in conjunction with other failure modes. There is strong empirical evidence that at higher specific gravities present at the bottom of the cells during stratification (>1.35 specific gravity) promote self-discharge and encourage “hard sulfation”. The latter term is defined and explained below.

It is to be noted that the failure mechanisms described above are to be considered our best understanding. There exist alternative mechanistic interpretations of the failure modes yet there is total agreement on the empirical observations. As an example of this, the loss of capacity in the negative electrodes has been attributed to agglomeration of finely divided lead particles. An alternative mechanism is the hard sulfation (Definition 2) of the discharged product [6]. This is testable by removing the plates and attempting to scrape the surface deposit from the plate. In our observations, the plate showed a shiny metallic appearance under the surface deposits. However, some hard sulfation will, no doubt, be present simultaneously. Additional confirmatory investigations are necessary. Unfortunately, there is little incentive to support carrying out studies of this kind. However, it is important to at least develop testable hypotheses that can be evaluated under controlled conditions to assess their adequacy.

2.1. Failure

A precise failure definition is important because it brings into focus those issues having a high operational significance. Having such a definition fosters effective communications because the persons involved become aware of the essential performance limiting issues. In addition, it also provides a basis for a common understanding of where high pay-off improvements can be made.

There are few things to consider when developing a failure definition. The definition must be concise and easily understandable. If it is not, too much room for interpretation will remain. There should be no need for interpretation. It must only address one topic. If we include too many topics, the domain of our inquiry becomes too large to manage in a practical manner.

Some common understandings of the meaning of the term, failure, in its most general sense are:

1. The condition or fact of not achieving the desired end or ends.
2. The condition or fact of being insufficient.
3. A cessation of proper functioning or performance.
4. Nonperformance of what is requested or expected.
5. A decline in strength or effectiveness.

In the case of batteries, many definitions of failure are possible. Depending on the definition selected, one can either include or exclude various effects than might be considered failure modes.

The “catastrophic” failure occurs when the battery cannot be recovered by any process that would be part of normal maintenance. Aside from completely rebuilding the battery, the battery that has failed in this manner needs to be returned for material recycling. One example, of a catastrophic failure would be cell shorting. However, positive grid passivation would not be considered a failure mode under this definition. This effect can be reduced or entirely eliminated by changing the battery over an extended period of time.

A “graceful degradation” failure exhibits itself by a gradual but perceptible loss of performance until it reaches the point of failing to meet a minimum level of performance. An example of this is positive grid corrosion. Alternatively, electrolyte stratification would not be such a failure mode because the effect is reversible simply by stirring the electrolyte leading to a restoration of its original capacity.

For our purposes here, we shall define failure in a very pragmatic way. We shall understand that the existence of a failure occurs entirely from the user’s perspective. That is, battery failure occurs whenever the battery no longer meets the user’s intended purpose. It is important to realize that by virtue of this definition, once the battery fails to meet the user’s intended purpose, a failure has occurred even if the battery could be applied to another application in a satisfactory manner. For example, a battery whose polarization resistance is too high to permit the passage of sufficient power to initiate a vehicle engine start has failed even though it might be very able to handle another lower power application. This definition can be criticized because it is possible to declare a battery failure as a consequence of the user’s ignorance of established battery maintenance procedures. For the purposes here, we shall assume that the user is fully aware of the normal procedures necessary for maintaining batteries.

Whenever one observes a battery failure, the conclusion is that sulfation probably caused it. In this case reference has been made to sulfation as defined above under [Definition 1](#). The possible mechanisms of failure are known and can be listed. These include:

- Loss of electrolyte.
- Electrolyte stratification.
- Hydration.
- Positive grid corrosion.
- Internal shorting.
- Passivating lead oxide film formation at positive current collectors.
- Agglomeration of finely divided lead in the negative electrodes.
- Electrolyte contamination.
- External damage to case and terminals.
- “Sulfation” (as a recrystallization effect) occurring in very old batteries.
- Inter-cell connector failure.
- Positive electrode active material softening and shedding.
- Others (unique to recombinant battery systems)
 - thermal runaway,
 - hydrogen accumulation consequences,
 - lead sulfate accumulation on the negative plate.

It should be clear that these failure modes constitute the set of failure modes that have been assigned the general name of sulfation. It should be noted that one of the failure modes within the set of failure modes carries the same name, sulfation. In an attempt to distinguish it, the name “hard sulfation” is sometimes used. This is a minor failure mode that rarely appears. It is most commonly observed on batteries that have been in service for extended periods of time that have been well maintained. An example would be telephone batteries. One issue becomes abundantly clear. The name of the set is, sulfation, and one of the components of the set is also named, sulfation. This is a very bad from a scientific point of view as the confusion is readily apparent. It is very hard to solve a problem when the problem has not been clearly identified. The reasons why specialists in the technology avoid the use of the word “sulfation” is now clear. In keeping with the need to describe the discrete failure modes as a means for present and future discussion, an attempt will be made to provide a very brief discussion in mechanistic terms.

Loss of electrolyte: The loss of electrolyte eventually reduces the effective internal surface area of the battery and the consequence is an increase of internal resistance. The battery can be recovered simply by the addition of distilled water to replace that which was lost. Batteries that are sealed such as the VRLA types do not allow additional water to be added. In these batteries, this failure mode is irreversible. It should be noted that these batteries lose water at such a low rate that there is no need to add additional water throughout the life of the battery. However, since the water loss is temperature dependent, this failure mode would be most prevalent in warmer climates. Flooded battery designs allowing access to the electrolyte offer a considerable advantage here.

Electrolyte stratification: Electrolyte stratification was discussed above. It is a reversible effect but maintaining a battery in that state can encourage grid corrosion and hard sulfation. This stratification effect is unique to flooded designs. The effect is nowhere as prominent in AGM and GEL designs. This failure mode is reversible.

Hydration: This failure mode was a severe problem in military batteries. Hydration comes about in battery designs where the sulfuric acid is the limiting reagent. That is, the limiting reagent is that component which determines when the chemical reaction has gone to completion. Whenever sulfuric acid is the limiting reagent, the electrolyte in a lead–acid battery approaches that of pure water when the

battery is fully discharged. This is a common occurrence in military vehicles because of the long storage times. In this case the natural self-discharge completely discharges the battery. This is rarely the case in commercial and passenger vehicle applications. The result of this hydration condition is that lead sulfate is dissolved as lead solubility increases considerably in the low specific gravity electrolyte. The problem arises when one attempts to pass a current through this solution. There is a tendency for dendrites to form creating high resistance shorts in the battery. These dendrites find their way through the pores of the separator resulting in micro-shorts between the plates. The observed effect is that these batteries cannot hold a charge for extended periods of time. Two solutions can be used to avoid the hydration effect. The first is to add excess sulfuric acid to the electrolyte. The other is to add a supporting electrolyte (for instance, sodium sulfate) to the battery electrolyte to ensure that the ionic strength of the electrolyte never reaches that of pure water. This failure mode is not reversible.

Positive grid corrosion: The existence of lead dioxide (the positive electrode active material) in contact with metallic lead (the current collector in the positive electrode) results in a situation where the reaction is thermodynamically spontaneous. The reaction product is a divalent lead salt. Fortunately, the reaction is kinetically very slow. Two important observations follow immediately. First, the life of lead–acid battery is finite because the positive lead alloyed grids will eventually disappear by natural corrosion. Second, all reasonable measures must be taken to minimize the rate of corrosion throughout the life of the battery. It has been observed that the rate of corrosion increases as the acidity of the electrolyte decreases [7]. In other words, a charged battery has a longer life expectancy than a battery that is maintained in a discharged state. This is a permanent failure and cannot be reversed.

Internal shorting: Separators and proper packaging of the electrodes eliminate the possibility of producing short circuits within a cell by material shedding. However, in normal battery cycling, the physical volume of the active material changes. This action stresses the packaging and separator material. In time these materials may degrade and, sometimes, electrical contact is made between the positive and negative electrodes in a cell. Whenever this occurs, the effect is often irreversible.

Passivating lead oxide film formation: The positive electrode current collector (i.e., the grid) forms a passive film that serves to reduce the corrosion rate. As this film becomes thicker, a lead–acid battery exhibits an increase in internal resistance. This film formation is minimized when using antimony alloy grids. However, calcium alloy grid tends to exhibit this effect much more prominently. The passivation layer grows thicker when the battery is allowed to stand for long periods of time at low states of charge. If the resistance is measured or the battery discharged at high rates, the influence of this film is readily evident. However, charging

the battery at constant voltage over a period of time destroys the film. The observed current rises slowly until the battery returns to its original operating condition. This effect is often reversible. The thickness of the film and the extent of grid corrosion can limit the recoverability of the battery.

Agglomeration of finely divided lead at the negatives: Pure metals are known to undergo a contact fusion at a temperature well below their melting point. This effect is most prominent when finely divided metallic powders are produced. To stabilize the powder, a foreign material is introduced to intentionally contaminate the surface and thus prevent the contact fusion. In the case of batteries, this contaminant is called an expander. If this expander is insufficient or destroyed during the normal cycling, a capacity fading is observed by virtue of this agglomeration of the finely divided lead. The consequence of this effect is observed by attempting to polish the plate after a post mortem battery disassembly. The agglomerated lead is evident. This effect is irreversible.

Electrolyte contamination: The standard instruction to battery users is that distilled water is to be used to replace lost water during normal use of lead–acid batteries. However, experience has shown that available water is the most common source of the make-up water. Available water has unknown mineral content and serves to increase the self-discharge of the battery. The self-discharge can grow to such a level that the battery can accept no charge at all. In some cases this effect is reversible. A strong argument can be made that it is sometimes better not to add water and accept battery failure from water loss. This is plausible when the water loss occurs at such a low rate that water loss failure and failure from other causes are about the same. In that case, a sealed battery makes sense. It is to be noted that other performance compromises must be tolerated to achieve a fully sealed environment.

External damage to case, cover and terminals: Ordinarily, one does not associate sulfation (Definition 1) with external damage. However, if the external damage is not detected upon casual inspection, sulfation is the most convenient explanation for the battery failure. The effect is usually irreversible but if the damage is detected and simple corrective action is possible, the battery can sometimes be returned to service.

“Sulfation” (second definition): This is the oldest and most discussed failure mode in lead–acid batteries. Essentially, lead sulfate crystal growth takes place over extended periods of time. Since lead sulfate is non-conductive, the crystalline mass tends to become passive to further electrochemical activity. If one measures the loss of battery capacity over time, the effect is indeed consistent with hard sulfation (and, at the same time, a number of other mechanisms). Teardown studies do reveal the presence of hard sulfation but it is usually not the failure mode for that battery. (1) This hard sulfation effect is considered to be irreversible but substantial discussion suggests that the conversion might be

possible. However, battery failure is usually brought about for other reasons. In this connection, it has been observed that after a certain period of time under a deep discharge conditions, the recrystallization of lead sulfate could create a situation that makes it difficult to recharge the battery, if not impossible, with the usual charging method. This problem becomes more important as vehicles are equipped with electric motors and demand additional power. The new generation of vehicles with new start-up functions will probably increase the number of batteries “sulfated” as the additional power requirements act to discharge the battery during idle periods.

Inter-cell connector failures: Often modern batteries use “through the wall” welding to connect cells on mono-block battery cases. These are blind welds that are well tested before final battery assembly and shipment. In a relatively small number of cases, bad welds do occur. Failures of this kind are latent and may appear late in battery life. The failure is irreversible.

Positive electrode active material softening and shedding: This is caused by a change in the active material crystal morphology (usually a consequence of excessive cycling) which leads to the shedding of the active material from the positive grid. The positive grids are normally encapsulated using a porous envelope that serves both as a separator and confines the particulate matter shed from the positive electrodes. This failure is irreversible.

Others: It is a hopeless task to list all possible battery failures for complex systems. The best one can do is to identify the major failure modes because by doing that corrective action is effective. The discussion below mentions three failure modes that tend to be most prevalent in VRLA batteries. However, since VRLA batteries are minor variants of the flooded design, the effects can also be found in flooded systems but their occurrence is much less likely.

Thermal runaway is a prevalent failure mode in recombinant batteries. It is observed whenever a battery is taken out of service because the battery gets hot during constant voltage charging. This heating is the consequence of the rapid exothermic recombination of oxygen at the negative electrodes. Under normal conditions, constant voltage charging of lead–acid batteries shows a decrease in current approaching an asymptotic limit at a very low current. In the case of the thermal runaway, the current can rise to the limit of the power supply delivering the current. The Joule heating can boil the electrolyte resulting in a venting of steam. After a time, cell dry out occurs.

Hydrogen accumulation effects: Recombinant batteries are designed to generate oxygen on overcharge. The recombinant mechanism then scrubs the oxygen out of the gas space in the battery. However, the lead–acid battery also produces hydrogen during the self-discharge process. This hydrogen is not efficiently recombined in the battery and is accumulated in the gas space in the battery. The presence of this accumulated hydrogen is occasionally vented out

of the battery through a disk that prevents a back propagation of a possible nearby flame. Rarely, a condition is achieved, perhaps during a thermal runaway, where the hydrogen and oxygen undergo a chemical recombination inside the battery. The resulting pressure wave acts to swell the battery case and the effect is very evident. Note that the above-mentioned mechanism has a low probability of occurrence.

Lead sulfate accumulation on the negatives: This is the natural consequence of hydrogen evolution from the negative plates that eventually vents out of the batteries. This loss of hydrogen results in a charge imbalance between the positive and negative electrodes. Since the batteries are sealed and an equalization overcharge is not easy to do, this effect will result in a gradual loss of capacity and eventual failure.

3. Conclusion

Ultimately, the readiness of military vehicles requires an understanding of the operating system to a degree sufficient for anticipating and diagnosing situations that can potentially lead to system failure. Achieving this requires a high degree of skill and experience on the part of the system and maintenance crew. A first step toward achieving that objective is proper training on the basic principles of system operation. One aspect of that achievement is a basic understanding of the battery subsystem. An awareness of the failure modes associated with battery failure is a first step toward reducing operating and sustainment costs in addition to enhancing system readiness.

The term, “sulfation”, should be used only to describe the recrystallization of lead sulfate causing the failure of the battery to perform the function requested, but not to collectively describe other failure modes that could produce lead sulfate as a consequence of the discharge, neither to other mechanical (like broken connectors or physical damage) or electrochemical (corrosion, active material shedding, etc.) that has little to do with the chemical conversion of lead or lead oxides into lead sulfate.

Because of the increased sophistication of modern vehicles, those who design these vehicles must take full advantage of the latest knowledge and available technology available on batteries and the associated electronic subsystems to minimize the impact on battery failure and enhance battery useful life.

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