Real-Time Expected Life and Capacity on VRLA and Flooded Products Unraveling the Predicting Code

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***Abstract* - A general vision of battery capacity prediction as a function of multiple non-invasive measurements is presented. The importance of quantifying the uncertainty of such predictions is underscored. A Valve-Regulated Lead Acid (VRLA) cell group is chosen to develop and examine a detailed functional relationship of capacity with conductance; particular emphasis is placed on the range of 75-105% battery capacity. It is hoped that consolidation of the vast studies conducted throughout the industry will one day lead to a robust battery state of health prediction model with reasonable confidence limits.**

I. BACKGROUND & MOTIVATION

Over the last decade, a multitude of significant studies, on a combined population of over 750,000 units, have examined VRLA batteries in operation and established that original 10-20 year product life claims were not realistic. The results indicate that actual service life tends to be in the range of 4-8 years on 20 Year Class VRLA products. Overall, similar results were obtained for various manufacturers, different discharge rates, Absorbed Glass Mat (AGM) cells, Gel cells, pre-1994 products, and post-1994 products. The newer AGM, and particularly Gel, cells on the higher end of the service life range. Also demonstrated in some studies was that capacity begins to decline after as few as 2 years in service for a large enough portion of the product to warrant concern [1][2][3][4][5][15][16].

In response to shorter than expected service life for VRLA products, the community of users employing the technology immediately turned to methods to estimate the actual state of health at a given point in time. The prospect of incurring another round of significant purchase and deployment costs for battery protection much earlier than expected left many trapped in a compromise of budgets and reliability. The search had begun for accurate and inexpensive methods to ascertain the two most critical aspects of battery health: existing capacity and remaining service life. Understandably, the battery end user would like to squeeze every last penny from the units already in service [16].

To add to the end user's plight, the industry is economizing on labor and material budgets to the point where insufficient resources remain for battery maintenance and/or record keeping. As a result the necessary battery service records are never established. This leaves end users exposed by the battery manufacturers who can do nothing to support their warranties due to the fact that the end user can not produce the required warranty records to claim their warranty credits.

Flooded cell technology has been around for more than 100 years with excellent repeatability in manufacturing processes to ensure consistent product to end users. Most end users do not have problems with managing their battery assets when it comes to flooded products, due to their predictable results based on visual inspection and standard aging over time. Most 20 year class flooded end users will replace these products at 12 to 18 years, simply based on age without any type of testing! In this paper, equations are introduced to assist flooded users in determining their capacity and remaining life.

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II. CAPACITY PREDICTION

A comprehensive, non-invasive model for predicting battery capacity is possible provided the end users follow the battery manufacturer's warranty requirements for maintenance records and establish baseline readings on all cells/units placed into field service.

There are a number of models that have been developed, but the issue is extremely complex; a myriad of variables exist, the technology is constantly evolving, and there are multiple failure modes to consider. Statistically, it would be expected that combining unique indices will increase the confidence of the predictions.

A consolidated battery "fuel gauge" approach is not a new idea, but perhaps the timing is now right to draw on the substantial research results which have been obtained industry-wide. It is easy to remain apprehensive about quantifying results, but to be truly valuable to the battery user, both the capacity prediction and associated uncertainty must be known [16].

Universal Solutions, Inc. (USI) introduced at Intelec 2002 in Montreal one of the first "Fuel Gauge Database Warehouse systems" utilizing the capacity predicting model. As seen in Model A, this model yields % of battery capacity vs. % of baseline conductance without performing invasive discharge testing.

In order to increase the confidence to predict capacity and remaining life, plus help end users administer their VRLA and flooded cell/unit warranties, additional equations must be introduced. The equations should be set-up into "SIS Test Group" Models, "Control Group" Models and "Feedback Group" Models.

The first group called "System In Service (SIS) Test Group" must yield % of capacity and % of remaining life without invasive testing. Invasive testing requires performing a discharge or *coup de fouet* on the battery string. The confidence of the prediction coming from this group should never be less than 80% accurate.

SYSTEM IN SERVICE (SIS) TEST GROUP

Item	Parameters	Invasive ?	Model	VRLA	FLOODED
				Model ID	
3.1	Ohmic vs. Capacity	No	Yes	A	A
3.2	Ohmic vs. Remaining Life	No	Yes	B	C
3.3	Temperature vs. Capacity	No	Yes	D	D
3.4	Temperature vs. Remaining Life	No	Yes	E	F
3.5	Float Voltage vs. Capacity	No	No	N/A	
3.6	Float Voltage vs. Remaining Life	No	Yes	G	H
3.7	Float Current vs. Capacity	No	Yes	I	I
3.8	Float Current vs. Remaining Life	No	Yes	J	K

The second group called "Control Group" must yield % of capacity and % of remaining life with invasive testing. The results from the control group will then be compared to the results from the test group to determine the exact accuracy of the test group models. The confidence of the prediction coming from this group should never be less than 100% accurate.

CONTROL GROUP

Item	Parameters	Invasive ?	Model	VRLA	FLOODED
				Model ID	
4.1	% Time Discharge vs. Capacity	Yes	Yes	L	L
4.2	% of Trough [Coup de Fouet] Voltage vs. Capacity	Yes	Yes	M	M
4.3	% of MFG Cycles vs. Remaining Life	Yes	Yes	N	O

The final group called "Feedback Group" will provide feedback on applied overhead for these products. In order to start a battery prediction database system it becomes necessary to provide real-time results daily with or without data being entered daily. The following parameters are provided to give real-time prediction models based on historic results. These equations allow the database to update all information at the time of look up, which can include warranty dollars available if failed at time of look up. Also calculated would be the expected capacity in the event of an outage and how long until the end user needs to budget for the product's replacement.

This group will constantly change due to the feedback from larger sample sizes and improvements in technology.

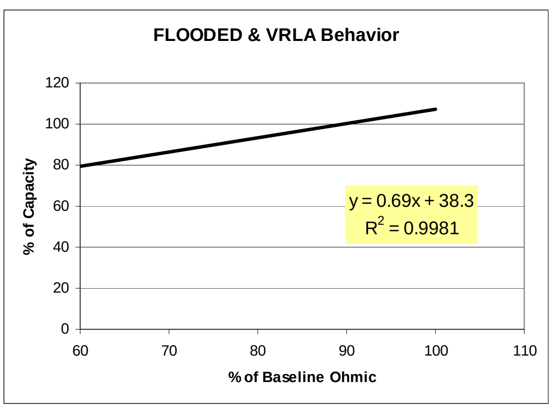
FEEDBACK GROUP

Item	Parameters	Invasive?	Model	VRLA	FLOODED
				Model ID	
5.1	% Capacity vs. Life	No	Yes	P	Q
5.2	% Remaining Life vs. Life	No	Yes	R	S

III. SYSTEM IN SERVICE (SIS) TEST GROUP

3.1 Ohmic Measurements and Capacity

Perhaps the most robust correlation with capacity has been demonstrated with the ohmic measurements of conductance, impedance, and resistance. As a battery ages, degradation in the internal plates, grids, and connections results in decreased conductance (increased resistance and impedance)[16]. This effect has been studied extensively and a strong linear correlation with ohmic measurements and cell capacity is well established [3][7][10][13][16]. Model A depicts typical behavior of a VRLA cell, examining conductance in particular due to its relative ease of measurement for the battery user.



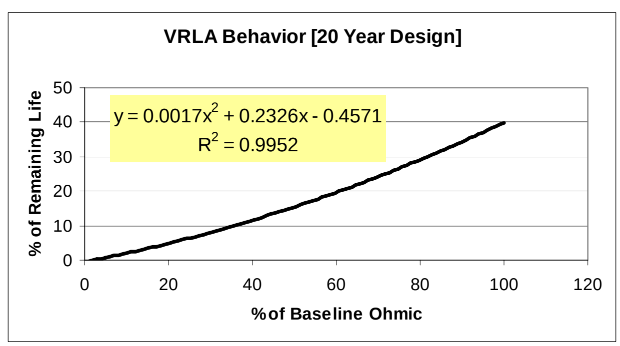
Model A
SIS Test Group – Non-Invasive - OHMIC MEASUREMENTS
% Baseline Conductance vs. % Capacity Model - Any Design

While the data speak volumes for the obvious linear correlation of capacity and conductance, it is the quality of this correlation that has sparked the most controversy. The high data scatter for higher capacity cells begs the question of how precisely capacity may be predicted, if at all, using this measure alone. It is with this in mind that a further look into the very nature of the correlation between capacity and conductance is required. For conductance to be one of a combined set of measures used to predict capacity, the uncertainty of resulting predictions must be quantified to understand whether the confidence is palatable to the battery user.

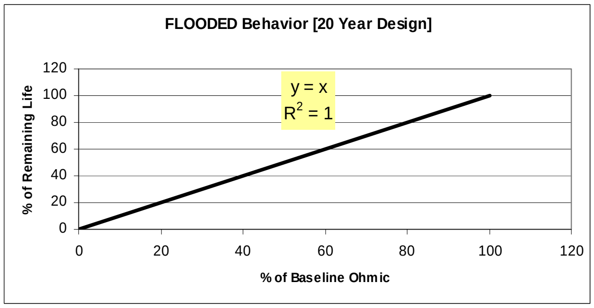
The biggest limitation of % Baseline Conductance vs. % Capacity Model is the majority of the end users who installed these 20 year class VRLA cells/units 2 to 5 years ago did not measure and collect baseline ohmic measurements when the cells were originally installed. This model deficiency may be solved with a baseline conductance/impedance value from the cells/units manufacturer if available. At this writing, the majority of the manufacturers of the 20 year class VRLA products do not publish a baseline impedance/conductance measurement in their specifications or procedures, which makes accurate capacity prediction difficult to determine without baseline measurements. Note: This model requires either conductance or impedance measurements to always be collected in the same ohmic units and if possible with the same test set during the life of those cells/units.

3.2 Ohmic Measurements and Remaining Life

Ohmic measurements are very good indicators of battery remaining life due to the fact that as the battery ages naturally in service the internal resistance is always going up because of the internal corrosion associated with Lead Acid Battery technology. As a result the Model B depicts VRLA behavior in 20 year designs and Model C depicts flooded behavior in 20 year designs. The need for two equations for this parameter is due to the difference in Design Life vs. Actual Life in VRLA Technology. The limitations of Model B and Model C include Internal Short Circuits and difficult to determine State of Charge



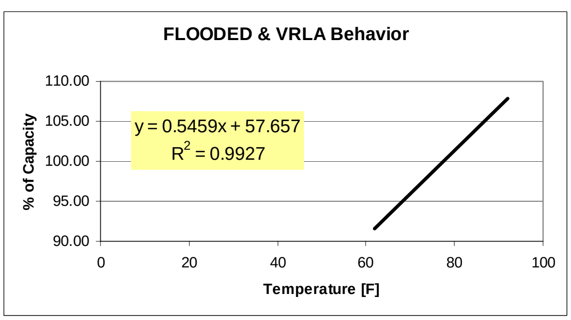
Model B
SIS Test Group – Non-Invasive - OHMIC MEASUREMENTS
% Baseline Conductance vs. % Remaining Life Model – 20 Year VRLA



Model C
SIS Test Group – Non-Invasive - OHMIC MEASUREMENTS
% Baseline Conductance vs. % Remaining Life Model - 20 Year Flooded

3.3 Temperature and Capacity

Temperature is a critical parameter of battery performance. A service temperature increase accelerates the chemical reaction within the cell, increases the available capacity, but ultimately shortens the life [7]. Unfortunately there appears to be little indication that temperature alone correlates significantly with battery capacity. Temperature changes certainly may be a precursor to a problem, but the incorporation of other indices must be combined to verify a battery fault [8]. While temperature may not be an effective indicator of capacity it is an essential quantity to consider when forecasting remaining battery life. Model D depicts Flooded and VRLA behavior. The measurement of temperature at a single point in time limits the ability of Model D to tell the entire story. End users need to evaluate average operating temperature to keep their warranty viable.

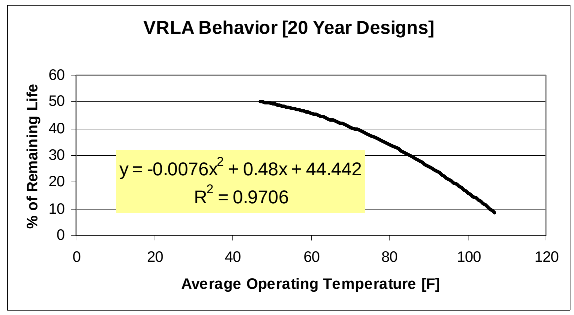


Model D
SIS Test Group – Non-Invasive – TEMPERATURE MEASUREMENTS
% Baseline Conductance vs. % Capacity Model – All Designs

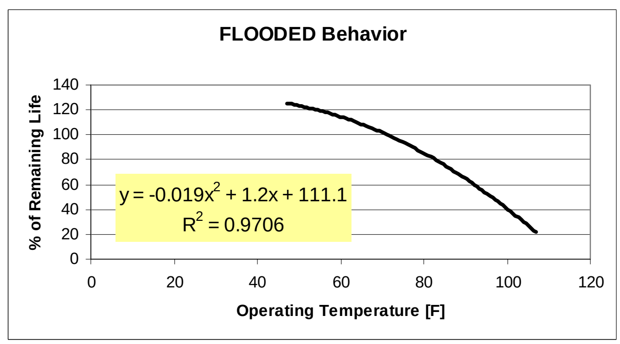
3.4 Temperature and Remaining Life

Temperature and Battery life is well documented by the majority of battery manufacturers. Typically for every 15°F above 77°F, the battery's expected life is reduced by 50%. The majority of the environments where flooded cells are utilized are normally in an HVAC protected room. However, VRLA products, because of the appeal of their small footprint application, are installed wherever they fit regardless of temperature considerations.

The relationship for VRLA Behavior in Model E is different from Flooded Behavior in Model F for Temperature due to the unrealistic life expectations for VRLA products. As a result the curve never shows greater than 50% of advertised design life.



Model E
SIS Test Group – Non-Invasive – TEMPERATURE MEASUREMENTS
Temperature vs. % Remaining Life Model – 20 Year VRLA Designs



Model F
SIS Test Group – Non-Invasive – TEMPERATURE MEASUREMENTS
Temperature vs. % Remaining Life Model – 20 Year Flooded

3.5 Float Voltage and Capacity

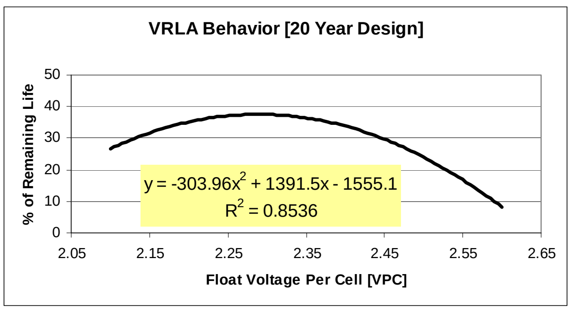
Float voltage is a measure that has received considerable attention. However, many studies have shown that it has very little ability to accurately predict battery capacity [5][8][9][10]. No relationship is presented to define these parameters for float voltage vs. capacity.

3.6 *Float Voltage and Remaining Life*

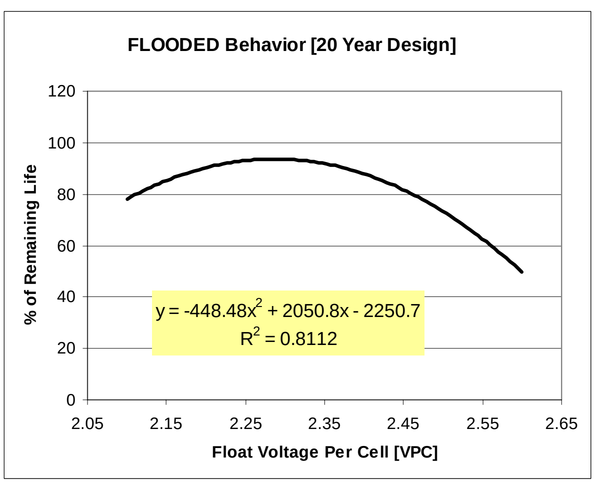
Float voltage is a measurement that the battery manufacturers require to collect on any warranty claims. The reason for this parameter to be collected is that keeping a string of cells at the incorrect float voltage can have significant impact of remaining life. Setting the float voltage too low can cause sulfation to occur on the plates. If sulfation is not treated in less than 6 months, the battery will not be able to recover to 100% health due to the sulfate acting as an insulator between the negative and positive plates.

Setting the float voltage too high can cause excessive float current into the string which can prematurely age the cells due to increased temperature and the current being converted directly into hydrogen/water loss in the electrolyte. This condition, if not corrected immediately, may cause thermal runaway because the voltage necessary to properly float a cell decreases as the operating temperature increases.

Since the advertised design life for VRLA is not true, two relationships must be presented to define this parameter. Model G depicts VRLA and Model H depicts flooded cell technology. Limitations on Model G and Model H include maintaining consistent float voltage throughout the life of the product and product selection. Battery manufacturers' processes vary and consistent float voltage throughout a string of cells is very difficult to obtain without a tank formed product.



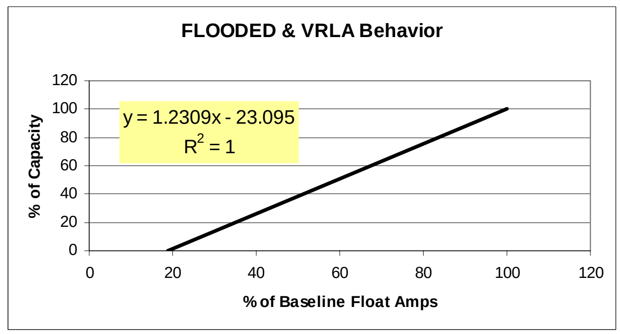
Model G
SIS Test Group – Non-Invasive – FLOAT VOLTAGE MEASUREMENTS
Float Voltage vs. % Remaining Life Model – VRLA Designs



Model H
SIS Test Group – Non-Invasive – FLOAT VOLTAGE MEASUREMENTS
Float Voltage vs. % Remaining Life Model – Flooded Designs

3.7 *Float Current and Capacity*

Float, or trickle, current appears to have some correlation with capacity, but has limitations. Since the same current passes through all cells in a given battery system, an inherent difficulty arises when trying to examine the significance of current at a cell level; the best and worst cells in a battery string will experience the same current flow. A thorough study recently examined other logistical difficulties associated with utilizing float current readings. Difficulties obtaining the measurement, appropriate concern thresholds, battery AH size, battery age, and state of charge must all be considered [8]. To assist with determining the correct float current vs. any size AH product, Model I for VRLA and flooded is introduced to assist with defining this parameter.

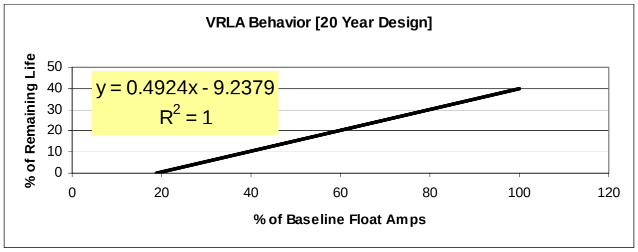


Model I
SIS Test Group – Non-Invasive – FLOAT CURRENT MEASUREMENTS
% Baseline Float Current vs. % Capacity Model – All Designs

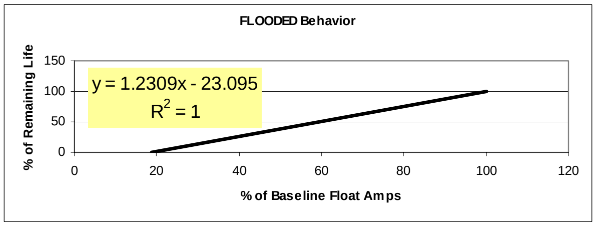
3.8 *Float Current and Remaining Life*

Float current with respect to remaining life has very useful characteristics. Typically at the end of life for both VRLA – Model J – and flooded – Model K products, they will demand a much higher current to maintain float as compared to first day in service. This is due primarily to the internal resistance increasing; in order to properly float the cells/units, a higher current is required at end of life. This parameter is also very helpful for finding early thermal runaway candidates before they self-destruct while in service.

Typically when a VRLA battery is at end of life cycle, all the current from the power plant is going to increase cell temperature with limited current available to service the load. Current is being converted into hydrogen gas which causes the internal specific gravity of the cells to increase due to less water in the electrolyte. Differentiating cell types and the state of charge limits Model J and Model K from developing one standardized equation for all operating conditions.



Model J
SIS Test Group – Non-Invasive – FLOAT CURRENT MEASUREMENTS
% Baseline Float Amps vs. % Remaining Life Model – VRLA Designs

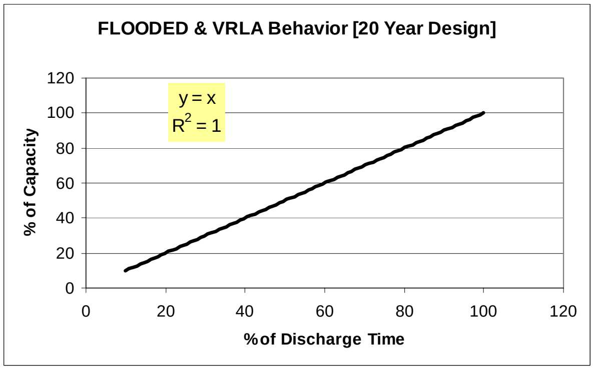


Model K
SIS Test Group – Non-Invasive – FLOAT CURRENT MEASUREMENTS
% Baseline Float Amps vs. % Remaining Life Model – Flooded Designs

IV. Control Group

4.1 *Discharge Testing and Definition of Capacity*

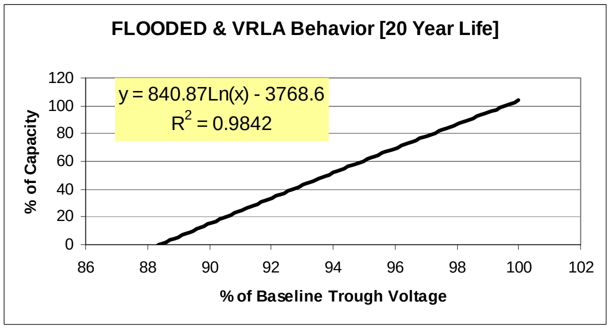
The most accurate determination - Model L - of battery state of health is a discharge test because it evaluates how the unit performs under the very condition a back-up battery is designed to accommodate. Derived from discharge results, capacity is defined as the ratio of the actual time a battery can sustain certain load conditions to the expected or designed time under the same conditions. A well recognized criterion for battery degradation is 90% capacity and for failure/replacement is 80% capacity [6]. Unfortunately, discharge testing is costly, time consuming, and most importantly invasive; removal of a battery system from the distribution plant it protects inevitably carries increased risk for service outages.



Model L
Control Group – Invasive – DISCHARGE MEASUREMENTS
% Discharge Time vs. % Capacity Model – All Designs

4.2 *Coup De Fouet and Capacity*

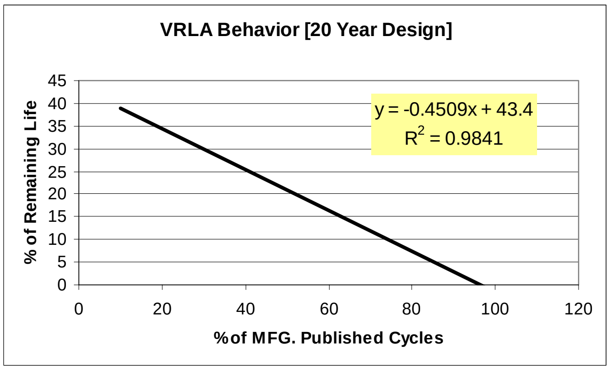
Encouraging correlations are found between capacity and the initial - Model M - highly transient voltage behavior manifested upon application of a load; this phenomenon is more commonly referred to as coup de fouet. While measurement of this parameter still requires invasive discharge activity, the time required on discharge to obtain the information is usually on the order of a few minutes rather than a few hours required for a traditional discharge test. Studies have shown reasonably strong linear correlations with either trough voltage or subsequent plateau voltage to capacity. Typically, a lower voltage corresponds to lower battery capacity. There are, however, significant contributions to the results from external operating conditions which detract from knowledge of the condition of the battery itself. Discharge rate, prior time on float charge, and float voltage all have an influence on the results. Some preliminary correction factors have been developed to minimize the effect of these external operating conditions in order to gain a true depiction of the performance of the cell. However, these correction models are still preliminary and under development [11].



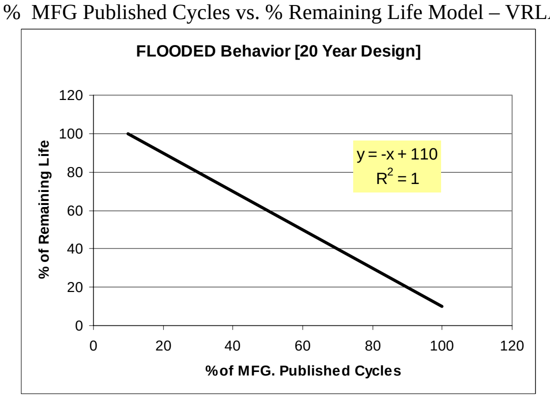
Model M
Control Group - Invasive – INITIAL DISCHARGE MEASUREMENTS
% Baseline Trough Voltage vs. % Capacity Model – All Designs

4.3 *Manufacturer's Cycles vs. Remaining Life*

Cycles consumed during life can be a very good indication of remaining life provided that you can track Depth of Discharge [DOD]. While many power plants possess cycle counters not many provide a depth of discharge correlation between # of cycles and remaining life. If the actual # of discharges and DOD were known in each event, the remaining life would be very easy to predict. However, in the field the DOD is always different for each service outage event. As a result a relationship as depicted in Model N and Model O are required to normalize this relationship.



Model N
Control Group – Invasive – CYCLE MEASUREMENTS
% MFG Published Cycles vs. % Remaining Life Model – VRLA Designs

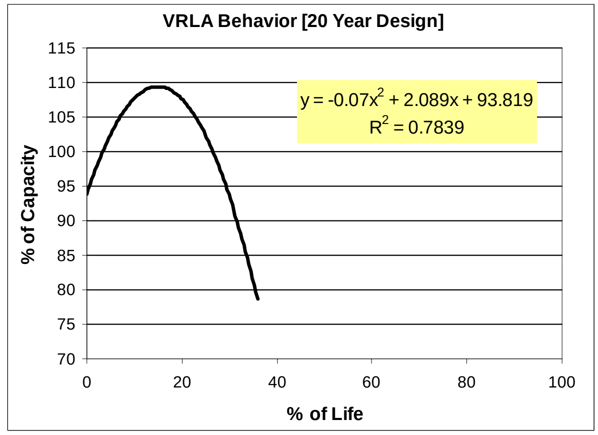


Model O
Control Group – Invasive – CYCLE MEASUREMENTS
% MFG Published Cycles vs. % Remaining Life Model – Flooded Designs

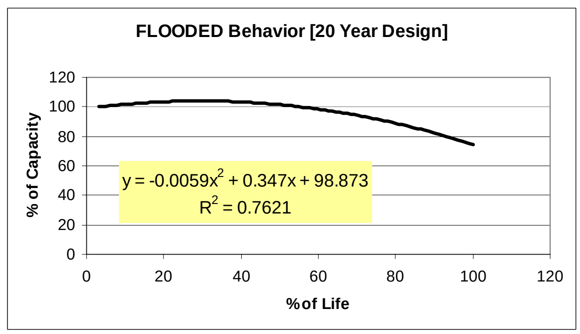
V. Feedback Group

5.1 *Design Life and Capacity*

While Actual Design Lives for 20 year class VRLA products have been well documented not to meet published design lives, the problem still exists how to get up to date capacity prediction without the presence of any new data points or remote monitoring. The Design life vs. % Capacity parameter is outlined in Model P for VRLA and Model Q for flooded cells. The requirement to have a separate relationship for flooded compared to VRLA is due to the fact that the VRLA do not meet 50% of design life. Model P and Model Q are not effective at determining poor capacity in early stages of life



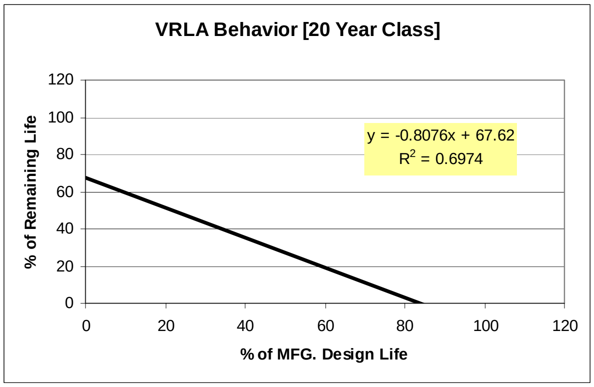
Model P
Feedback Group – Non-Invasive – DESIGN LIFE MEASUREMENTS
% Life vs. % Capacity Model – VRLA Designs



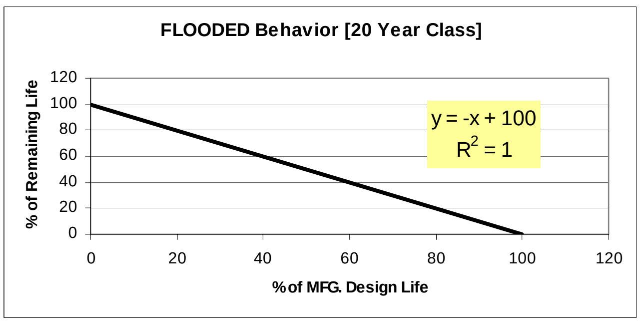
Model Q
Feedback Group – Non-Invasive – DESIGN LIFE MEASUREMENTS
% Life vs. % Capacity Model – Flooded Designs

5.2 *Design Life and Actual Remaining Life*

The last parameter to be introduced is the design life vs. remaining life. Model R depicts the VRLA behavior and Model S depicts the flooded behavior with respect to remaining life. Model R and Model S are not effective at determining poor remaining life in early stages of a product's history.



Model R
Feedback Group – Non-Invasive – DESIGN LIFE MEASUREMENTS
% MFG Design Life vs. % Remaining Life Model – VRLA Designs



Model S
Feedback Group – Non-Invasive – DESIGN LIFE MEASUREMENTS
% MFG Design Life vs. % Capacity Model – Flooded Designs

VI. TEST METHODS AND SAMPLE DESCRIPTION

To further develop and test a functional model for capacity and remaining life prediction, a sample of VRLA AGM battery strings currently in operation in various temperature controlled communications centers was selected. The sample consists of four 1200 AH, -48V strings (96 cells) with a service life of 2 years that had accurately collected all "TEST GROUP" parameters including baseline measurements from ready for service date which included float voltage, float current, ohmic measurements, temperature and baseline data points for the correct battery type. These tested cells were in service for 2.5 years. The VRLA battery strings are twenty year class products and represent two different manufacturers.

The cells were left to float without any further testing for more than 2.5 years. Prior to discharge testing all strings had been on float for a minimum of 72 hours, intercell resistance readings were taken and connections checked for tightness, float voltage was recorded at the cell and string level, and float current was recorded. Additionally, conductance readings were taken while on float since state of charge significantly affects readings. The same Midtronics Micro-Celltron Conductance Tester was used for each measurement, being careful to ensure the probes had direct contact with the cell post lead. Each string was then placed on open circuit and constant current discharge testing was conducted in accordance with IEEE 1188 guidelines [6]. The temperature corrected 3, 4, or 8 hour discharge rate to end voltages of either 1.75 or 1.86 volts per cell was used. Computerized data logging equipment was used to record current and voltage readings every 2 seconds for the first few minutes, every 10 minutes for the majority of the test, and every 1 minute after the voltages began falling quickly. Cell capacity was calculated based on test performance.

VII. TEST RESULTS AND CORRELATION MODEL

7.1 Capacity Prediction Model Using Conductance

Conductance is well accepted as an excellent tool for trending the capacity of a cell over time by comparing previous readings. To expand beyond trending and address capacity prediction raises questions of effectiveness. Because the test group includes different products with different nominal conductance values, measurements were normalized using a baseline to facilitate comparison of the results. For the purpose of this study, the Midtronics published conductance was used as the baseline, but there are a variety of approaches for obtaining such a value when an average value was not established at the start of service life [13]. A conductance decline of 20-30% from baseline value is typically considered cause for concern and an indicator that cell performance may be declining quickly [6]. In recognition that most battery users are concerned about capacity in the acceptable range of performance, approximately 75-105%, a prediction model will be developed using test data from that same range.

7.2 Prediction Model Interpretation

Figure 1 depicts the results from the Test Data yield the following results compared to the results of the control group which had an invasive IEEE discharge. The correlation between the test group and the control group is more than 90% accurate.

RESULTS FROM TESTING THE MODELS

Parameter	SIS Test Group	Control Group	Feedback Group
String A	90% Capacity	98% Capacity	99% Capacity
String B	92% Capacity	100% Capacity	99% Capacity
String C	69% Capacity	75% Capacity	99% Capacity
String D	98% Capacity	99% Capacity	99% Capacity

Figure 1 – Test Group vs. Control Group

VIII. Conclusions

1. All models may be added to, removed and modified as more data becomes available.

2. Accuracy of Test Group is over 90% compared to Control Group. This allows end users to gain excellent prediction models with only manufacturer's maintenance records required and no invasive discharge testing.

3. Customers who want 99.999% reliability from their networks must look at the weakest link in their network. Battery maintenance and record collection is a low priority to most end users, yet they all are trying to differentiate their services from each other and the only difference in most cases is the reliability of their batteries.

4. The "FEEDBACK GROUP" will always be a dynamic set of parameters due to improvements in battery technology and results from larger sample sizes of data sets.

5. End users need to find a way to maintain better records to ensure they get the most for their asset dollar. A database system which collects the "SIS TEST GROUP" in required intervals will satisfy most major manufacturers' requirements for warranty documentation.

6. A limitation to battery prediction is not properly measuring, recording and archiving baseline measurements at the time of 'ready for service' to compare against future battery measurements. The battery manufacturers need to start publishing ohmic baseline measurements in conductance and impedance units with an acceptable +/- range.

7. The approach used to develop the capacity prediction model based upon "SIS TEST GROUP" measurements is applicable to other linearly related measurements. A model specific to a battery type, battery age, or any desired distinguishing feature for that matter, may be developed by choosing the test group appropriately.

8. Accurate and consistent data collection of the "SIS TEST GROUP" in required intervals is critical to compare with baseline values to obtain valid predictions.

9. As a large size of data is collected for the parameters listed above, new and/or revised models will emerge to provide higher accuracy of predictions.

10. The weight assigned to each model when more than one model's measurements are available will vary depending on which models are available at time of prediction.

IX. Recommendations for Future Work

1. Expand the capacity and conductance correlation model to include more data and a slightly broader range of concentration. Results drawing on a broader sample will help determine if prediction uncertainty may be significantly reduced.

2. Work with test set manufacturers to develop equipment that will be able to capture all data in the field and allow easy download into a database system for record collection management.

3. Work with <u>ALL</u> battery manufacturers to accept a standardized web-enabled database system with all required data parameters to satisfy manufacturers' requirements for warranty documentation.

4. Develop quantifiable battery capacity prediction models based upon other non-invasive measurements. Consolidate individual models into one comprehensive model.

5. Approach battery remaining life prediction models in a similar manner to that proposed for capacity prediction. A complete battery state of health prediction will need to consider both elements.

6. Ultimately, results from a battery state of health prediction model could be incorporated into a monitoring algorithm to provide the battery user real time visibility of potential problems.

7. Work with battery end users and manufacturers to start data warehousing their maintenance records in order to provide the most cost efficient solutions with respect to proactive management of warranty, cost to perform work, improving battery technology and most importantly reliability of the end user's networks.

8. Publish the weight equations for events when more than one model's measurements are available at time of prediction.

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