LARGE FORMAT VRLA PRODUCTS FOR UNCONTROLLED TEMPERATURE ENVIRONMENTS

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VRLA PRODUCTS FOR HIGH TEMPERATURE ENVIRONMENTS

VRLA products have been installed in uncontrolled applications for many years, yet problems persist with short and variable product lives. This has lead to some networks deploying products based on different chemistries – NiCd, NiMH, lithium systems – to varying degrees of satisfaction. Large systems, particularly using large format VRLA products have predominately remained in climate controlled central offices, data centers or CEV's. The choice to provide climate control for large battery systems appears to be driven by cost factors – historically the batteries are so short lived at even moderately high temperatures that replacement costs for the large systems are higher than the initial cost and utility costs for temperature management.

Providing long, reliable, and predictable life in VRLA products in uncontrolled temperature environments has been discussed for more than ten years.[1] Recent advances in VRLA designs, however, point towards the possibility of a cost effective large format VRLA solution for high temperature applications. Providing a solution that enables large VRLA products to work at higher temperatures would reduce or eliminate the need for costly cooling equipment, reduce operating costs, and may open up opportunities to increase revenue generating equipment in conditioned environments.

BATTERY OPERATION IN HIGH TEMPERATURE ENVIRONMENTS

High temperatures offer a very challenging environment for any electrochemical system. VRLA products, however, are susceptible to deterioration at high temperatures. Principal factors include:

- **Recombination:** In flooded lead acid and other electrochemical systems some of the energy absorbed by the battery (as float current) is dissipated by venting of hydrogen and oxygen. VRLA products do not vent significant quantities of gas during normal charging operations. Nearly all of the float energy in a VRLA system is absorbed by the battery, and then converted to heat within the element by the recombination process. This raises the internal temperature of the cell over the ambient temperature.

- **Insulating Space:** In flooded lead acid and other similar "wet" systems, the interior of the cell is filled with liquid. This provides a thermal coupling between the interior of the cell wall and the battery group – enhancing heat transfer in and out of the battery. In VRLA products there is typically a gas filled gap between side of the battery cell and the interior cell wall. This prevents effective thermal transfer in this direction – which may affect half or more of the battery surface area.

- **Positive Float Current Feedback:** All electrochemical reactions are accelerated by higher temperatures, including those that drive float current acceptance (typically internal gas generation and capacity loss). As noted above, VRLA products absorb all float current energy, and are typically better "insulated" against heat loss than flooded lead acid or other technologies. This means that cell internal temperatures are higher than other technologies, driving even more float current. In its worst manifestation this positive feedback loop causes thermal runaway, which can destroy a cell in a short period of time. Thermal runaway tends to be unpredictable; resulting in quick failure of products that otherwise appeared to be normal.

Other factors are also often combined with the other harmful effects of high temperature on battery components – softening of plastic containers and covers – allowing swelling and separation of plates, accelerated aging of amorphous plastics materials (polycarbonate blends, etc) resulting in cracking, vent failure due to thermal swelling of components, etc. These too contribute to short, unpredictable product lives.

There have been traditional methods for reducing aging reactions in VRLA products at high temperatures. Previous publications [2] have recommended temperature compensation of charge voltage – reducing the charge voltage as temperature rises. This reduces float current and the damaging effects of internal cell heating and excess gassing, however, it adds costs for charger control, requires careful placement of temperature probes, and in some applications (particularly telecommunications) there are voltage limits that limit how low the charge voltage can be set while maintaining the proper system voltage. Providing a solution that does not require compensation would eliminate these complications.

DESIGNING FOR HIGH TEMPERATURES

As discussed in previous work, it is possible to design products for very long life in room temperature environments. [3] That work looked at a comparison of two different design approaches for components and cell active material design, and the product that resulted when the best aspects of both design approaches were combined. Since publication, additional work has been performed validating the life of the product at various temperatures, and investigating the contribution of components to the life of the product.

Our testing of long life designs focused on several aspects of the designs, and determined that there are two critical design features that allow both long life at room temperature and good performance at high temperature. These were float current control and choice of lead alloy for the positive plate. These factors were tested as individual components and as complete systems to determine contribution to product life and performance at high temperatures. Results are presented below.

Float Current Control: Our original work found that float current control was the single largest factor in determining product life at accelerated test temperatures, and by inference at room temperatures. As described in that paper, float current control is a mix of standard and proprietary technologies that keep the polarization (share of overvoltage) shared between the positive and negative plates. This is in contrast to other technologies that have very low voltages on the negative electrode, resulting in overcharge on the positive plates and high gassing and recombination rates. At the time of publication float current vs. temperature behavior was only available for two temperatures, 25°C and 70°C for the new product. Since that time testing has been underway to determine this float current behavior of the cell at intermediate temperatures. This is important for determining behavior of the cell at high application temperatures, which generally range between 30 and 50°C. The data, presented in Figure 1, show that the relationship between steady state float current and temperature is smooth and continuous. This indicates that standard methods may be used to estimate life at intermediate temperatures.

Float current control is also fundamental to prevention of thermal runaway, the self-destructive tendency of VRLA cells to increase float current with temperature, resulting in self heating and eventual product failure. Thermal runaway can be induced by high ambient temperatures, overcharging of batteries due to electronics failures or shorting of single cells resulting in higher applied voltages to the other cells in the system. The behavior of the float current with temperature shows that thermal runaway does not occur in float.

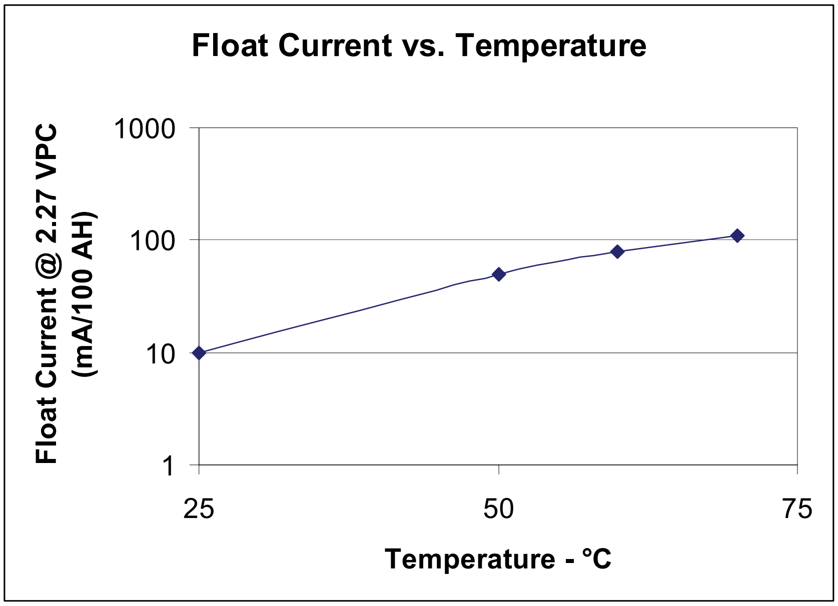

Figure 1. Float Current – Ambient Temperature Relationship

Lead Alloy Selection: The choice of lead alloy for the positive grid has traditionally been a key factor in determining product life. In a lead acid environment, the positive grid is exposed to conditions that promote conversion of lead to lead dioxide, resulting in grid growth and failure of the positive plates. Two corrosion modes occur – surface corrosion that gradually reduces the cross section of the grid elements from the outside in, and intergranular corrosion, a mode that has corrosion reactions proceeding along grain boundaries, attacking the grid members through their cross section. This type of corrosion can cause high rates of "grid growth" – expansion of the grid and plates as corrosion wedged the lead grains apart. For long lived and predictable products intergranular corrosion must be delayed or prevented altogether, as it can cause sudden and spectacular cell failure as the covers are pushed off and the jar walls are ruptured.

In our research lead alloys were tested as individual components by exposing test grids to accelerated corrosion conditions – immersion in sulfuric acid at 55°C with 125 mV positive polarization for 180 days. Outputs of the test were growth in area (a measure of intergranular corrosion) and loss of weight when corrosion products were stripped away (a measure of overall corrosion). The results of the testing (Figure 2) showed the accepted belief that high calcium contents promote high rates of growth, but also showed a surprising relationship between growth and high tin contents – even for alloys without any calcium. There appears to be a region of minimal growth (and intergranular corrosion) that requires both tin and calcium. This may be due to the formation of easily corrodible regions of lead tin eutectic on the outside of grain boundaries in pure lead tin alloys.

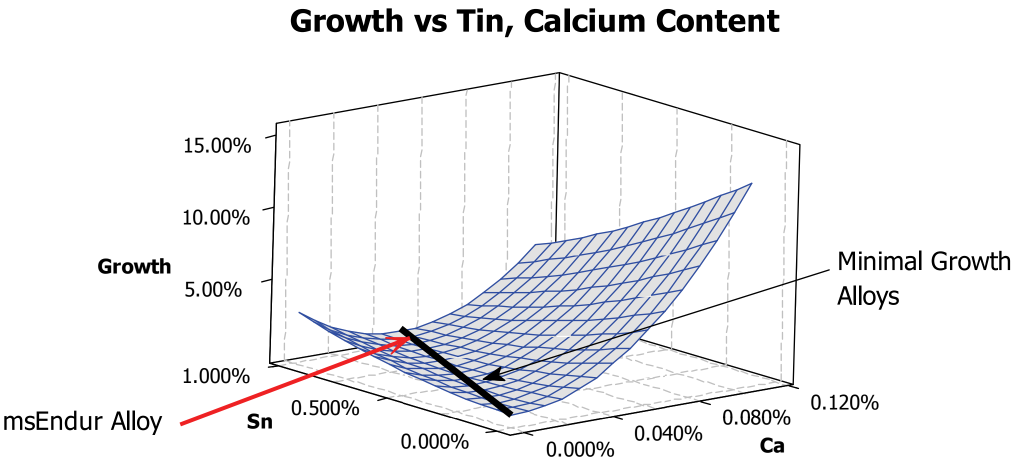

Figure 2. Growth vs. Alloy Content

While bench testing of alloys gave direction to the choice of alloys, VRLA batteries are dynamic environments, and bench testing alone could not simulate the impact of the swelling and contraction of active materials or the other conditions that exist in cells. To determine the ultimate impact of the calcium level reduction testing in actual products was required. Large format VRLA cells were chosen as a test bed for the testing. Both calcium and tin contents varied widely between the alloys as shown in Table 1.

Element	Alloy 1	Alloy 2
Calcium	0.08%	0.045%
Tin	2.20%	0.90%

Table 1. Test Alloy Formulation

As with the bench testing, there were differences in performance of cells using the two alloys. Testing according to the procedures in SR-4228 [4], using 70°C test temperature. Results are shown on Figure 3. There was a clear cut difference in behavior between the two alloys. Alloy 2 had half the calcium content of Alloy 1, and twice the life at high temperature. Tin appeared to have little beneficial effect – Alloy 1 had twice the tin content, and much shorter life. Teardowns of these batteries showed little plate growth for either alloy (less than 2% in any direction).

The test data show that with proper attention to alloy content lead calcium tin alloys can be formulated with the same functional corrosion resistance as pure lead. This has several implications for battery design, particularly for revisiting the relationship between battery life and plate thickness. This will be discussed in the testing results section.

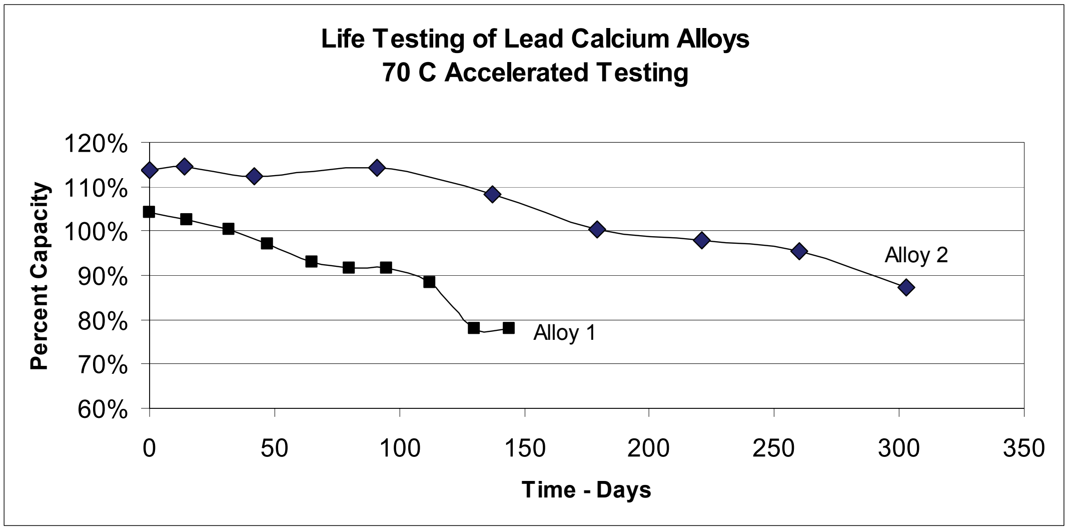

Figure 3. Life Test Results for Alloys

PRODUCT TESTING RESULTS AND DISCUSSION

Single point life testing at 70°C was used during the initial development of the msEndur product, and factors provided in SR-4228 were used to convert time on test to expected life. While it is possible to use the factors provided in SR-4228 or other standards for predicting life at temperatures other than 25°C, good engineering practice requires that the temperature-life relationship be developed more fully, especially when predicting life at intermediate temperatures. The standard practice for this is to test at temperature intervals, such as 50, 60, and 70°C.

The testing protocol for the product was as follows:

1. **Baseline Characterization**: Basic battery information (weight, OCV, ohmic values), float at 2.26 VPC for 72 hours, followed by a capacity test at the published C/8 rate.

2. **Elevated Temperature:** Batteries were placed in temperature chambers in standard modules. Temperatures were set at 50, 60, and 70°C, and controlled to ±2°C. Relative humidity was controlled to 20% as per specification. Charging was done by constant voltage float at 2.26 VPC, the midrange of the recommended field voltage setting. (Voltage compensation was not permitted under the SR-4228 specification.)

3. **Capacity Testing:** At regular intervals the batteries were removed from the temperature chambers and allowed to cool for a minimum of 24 hours on float. Capacity testing was then performed using the baseline method. After capacity testing the batteries were float recharged, and returned to the testing chamber. Testing ended when the battery capacity fell below 80%.

At the conclusion of each test the cells were disassembled to determine cause of failure. The data collected included water loss, ending specific gravity, plate growth and grid corrosion.

Testing began soon after the introduction of the msEndur in 2004, and continues to this day, involving more than 100 cells. Results to date for the product are shown in Figure 4.

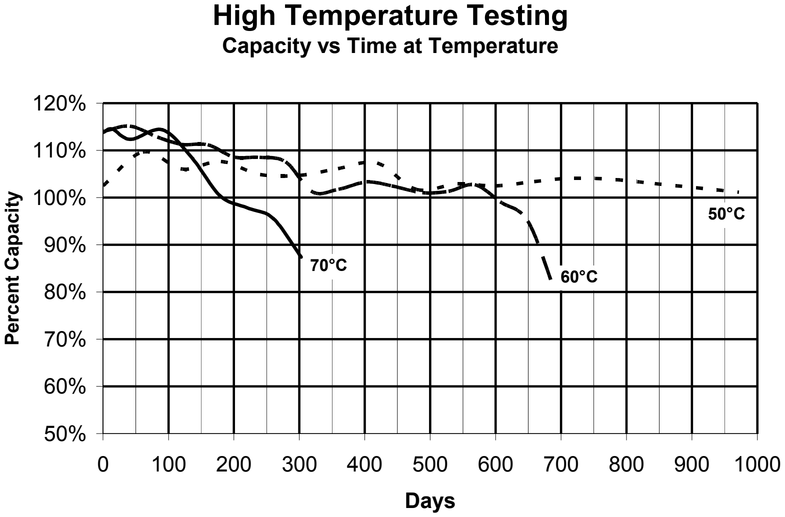

Figure 4. Capacity vs. Test Time

The results showed that the battery has a typical Arrhenius life relationship – life was roughly doubled by a temperature reduction from 70°C to 60°C. It also shows that testing at all temperatures is incomplete – testing at 50°C has exceeded 2.5 years of actual test time, without any indication of capacity loss or impending failure. Failure analysis of all tested cells showed that the mechanism was failure of the polycarbonate-ABS plastic. This allowed oxygen infiltration into the cell, resulting in depolarization of the negative plates and eventual capacity failure.

The Arrhenius relationships for the tests that have run to 80% capacity (70 and 60°C) are shown on Figure 5. Two lines were developed – one for the data from the accelerated testing, and one based on the SR-4228 acceleration factors. As shown, the msEndur has higher activation energy (steeper slope) than the SR factors. This has several implications for operation of this product at higher temperatures, most important of which is that it is capable of longer life at moderately high temperatures – such as those found in uncontrolled environments.

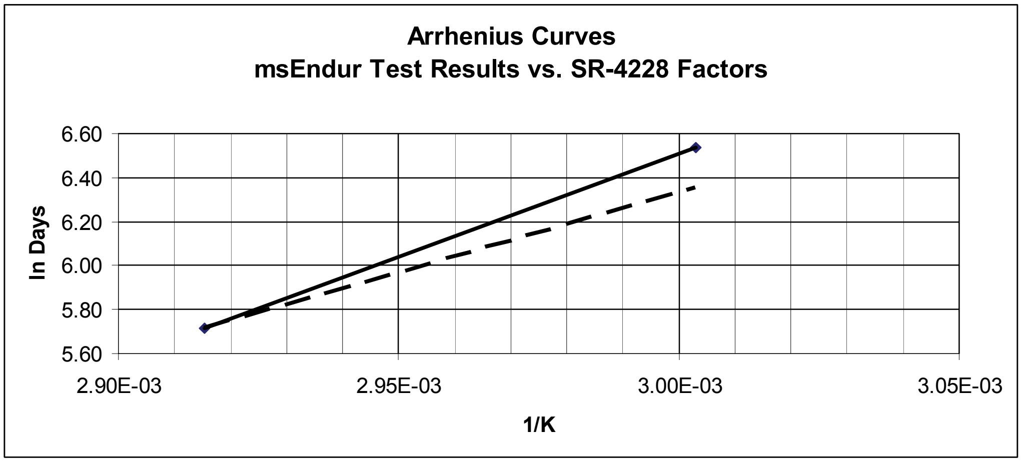

Figure 5. Arrhenius Relationship

POTENTIAL APPLICATIONS

As shown by the accelerated test results product designs featuring low float current acceptance and corrosion resistant alloys are capable of long life at high application temperatures. The product has demonstrated actual product life of 23 months at 60°C, and continued product life at 50°C of more than 2.5 years without any failures. This proven longevity has been demonstrated in few, if any, commercial electrochemical power storage systems. More importantly, the Arrhenius relationship demonstrates that the product will be capable of meeting most customer life requirements at much higher ambient temperatures than other batteries or systems.

Table 2 shows the estimated product life using both the SR factors and the higher activation energy demonstrated in testing.

		Life Estimate - Yr	
Temp °C	Temp °F	Testing	SR-4228
30	86	20+	13.8
35	95	18.6	9.3
40	104	11.4	6.4
45	113	7.1	4.4
50	122	4.5	3.1

Table 2. Life Estimates using Test Results or SR-4228 Factors

The life estimates at moderately high temperatures allow more freedom to users to install the large format VRLA product in applications that were previously not cost effective. It also offers users several options for reducing operating costs. Some options are:

- **Operation in uncontrolled environments**: Maeda, et al ^{5} have shown that the average temperature in typical telecommunication environments tops out at ~40°C in mid-summer, and for much of the year is less. At these average temperatures the estimated product life is the same as competitive products in conditioned (25°C) environments. Operating the product in outdoor environments would free space in conditioned central offices, and would reduce replacement/maintenance costs in existing uncontrolled installations.

- **Remote Sites:** Remote sites demand reliable operation in uncontrolled environments. Current VRLA offerings with lives of 2-5 years in outdoor environments would require very frequent maintenance on the sites to assure continued reliable operation. Installing products with double the current available life, and no risk of sudden failure due to thermal runaway would greatly reduce the frequency of service visits to the sites, and thus the operating costs of the sites.

- **Energy Conservation**: One unusual benefit would be reduction in energy costs. Most controlled sites are cooled simply to extend battery life – the electronics are rated at 40°C or higher. Herrlin[6] describes savings of up to $4000 annually per central office (at 1996 energy costs), by using a wider temperature control band (13-29°C vs. 20-25°C). In addition to operational savings equipment costs would be reduced by using smaller capacity cooling equipment. A battery capable of handling these higher temperatures makes these savings possible. As an added bonus, the warmer temperatures actually increase battery capacity, offering either more power or extended run times.

In addition to these direct benefits to end users, the long life technology also offers increases in power output and material efficiencies through new internal designs. The extreme corrosion resistance of the lead alloys and low float current technology allow reduction in plate thickness without loss of real application life.

CONCLUSIONS AND FUTURE WORK

Lead acid battery technology has often been derided as ancient and outdated, yet it remains the most cost effective solution for most standby power applications. Development of long life designs and elimination of unexpected failure modes has provided an opportunity for lead acid batteries, particularly large format VRLA, to remain competitive with other technologies on a life and performance basis.

Future work on this technology will continue with improvements in material efficiencies and elimination of weak aspects of the design. In particular, we found that choice of jar/cover materials had a profound effect on total product life, prompting product development efforts to improve these materials. Future work will also focus on matching formats to customer needs – extending capacities up and down the scale and providing form factors that match customer requirements.

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[1] A battery for all seasons? Telephony Online January 26, 1998

[2] Jergl, Cole, Purcell “Real World Effects on VRLA Batteries in Float Applications” Telecommunications Energy Conference 1996 INTELEC

[3] Malley, Williamson “Development Of A Long Lived Wide Plate Format VRLA Cell” Battcon 2005

[4] Bellcore SR-4228 VRLA Battery String Certification Levels Based on Requirements For Safety and Performance, Issue 1, 1997

[5] Maeda, M. et al. Battery Dev. Center, Japan Storage Battery Co. Ltd, Japan" Remote data collection of VRLA batteries at BellSouth Distributed Power Sites" Telecommunications Energy Conference, 2002 INTELEC.

[6] Herrlin, M. Economic Benefits of Energy Savings Associated with: (1) Energy-Efficient Telecommunications Equipment; and (2) Appropriate Environmental Controls”, Telecommunications Energy Conference 1996 INTELEC