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Performance of valve-regulated lead-acid batteries in real-world stationary applications — utility installations

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Abstract

A multi-phase project to investigate the reliability of valve-regulated lead-acid (VRLA) batteries in the field has been conducted by US industry and government research organizations. The focus of the study has been to characterize the relationships between VRLA technologies, service conditions, performance, and field failures. Two surveys were conducted: one of VRLA end users, and the other of VRLA manufacturers. Data from end users were obtained for over 56,000 telecom and utility installations representing over 740,000 cells. Seven manufacturers participated in the study. Preliminary correlations between utility end-user data, manufacturer information, and battery reliability have been developed and will be reported. Data for telecommunications installations will be reported in a separate publication when completed. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Valve-regulated lead-acid (VRLA) batteries have been commercially available for more than 20 years and have been enthusiastically embraced by users of uninterruptible power supplies (UPS) because of the anticipated reduction in installation and operating costs, smaller footprint, lighter weight, and fewer environmental concerns. However, as with any evolving technology, users have encountered varying degrees of performance reliability. Manufacturers and end users postulate that the premature failures experienced at some field installations may be due to temperature and charging sensitivities, manufacturing quality control, or compatibility issues with particular applications. Proprietary concerns and inadequate data acquisition systems have reduced the amount of performance and life-cycle data that is publicly available. This has limited the ability to evaluate premature capacity loss, which has been reported for VRLA batteries in some cases after as few as 2 years of service.

The International Lead Zinc Research Organization (ILZRO), Sandia National Laboratories (for the U.S. Department of Energy, Energy Storage Systems Program) and the Advanced Lead-Acid Battery Consortium (ALABC) have sponsored a multi-phase project to investigate these issues. The focus of this study is to characterize the relationship between VRLA technologies, service conditions, and failure modes. These organizations are impartial regarding VRLA battery choice, and their sponsorship of this effort has created an unbiased forum for evaluating VRLA product characteristics, operating conditions, field performance, and service life.

This study consists of three phases.

- Confidential survey of manufacturers of VRLA cells for stationary applications.
- Confidential survey of VRLA end users with stationary applications, primarily in the electric utility and telecommunications business sectors.
- Analysis of the two surveys to characterize the VRLA population and identify parameters of design, manufacturing, and operation that may affect VRLA performance and reliability.

As of 1 December 2000, 16 utilities and eight telecommunications firms completed surveys. These responses represent over 56,000 installations with over 740,000 cells. Many respondents completed surveys representing hundreds or thousands of installations. This was particularly true among surveyed telecom end users, who typically provided responses for over 6000 installations, while the typical utility respondent represented 13 installations (Table 1).

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Table 1
General profile of the end users that were surveyed

Application	Installations	Cells	Ah
Utility	215	15522	105040
Telecom	55992	725988	3558100
Total	56207	741510	3663140

These installations use cells produced by seven manufacturers.

In order to investigate the particular nature of the VRLA market, the two sectors had to be treated separately. The telecom market dwarfs the utility VRLA market in the USA and combined analysis would not reveal relevant information for utility operators. In addition, fundamental differences in configuration, age, operation, monitoring, and rate of failure all support distinct analyses for the two sectors. The present paper deals with the utility results; the telecom results will be described separately.

Electric utility companies use VRLA batteries as UPS systems to provide back-up power for switchgear equipment and other critical loads. Switchgear enables utilities to bypass a localized outage (e.g. failed transformer or downed cable) and to provide power to other parts of the grid. Critical loads include computer centers, banks, and other financial institutions, air traffic control centers, hospitals, critical manufacturing processes, various government agencies, and stock exchanges.

A battery provides a virtually instantaneous power source, and is sized to bridge the gap between loss of utility power and start-up of an alternate power source such as a generator. Where an alternate power source is not available, the battery is sized to allow for an orderly shutdown of critical loads. VRLA batteries are also used to support photovoltaic (PV) or other renewable energy installations in remote, grid-independent applications. In such cases, the battery is sized to provide a few days of demand.

This paper focuses on characterizing utility VRLA installations, considering:

- operating environment: geographic distribution, indoor/outdoor, temperature controlled;
- cell type: AGM/gelled electrolyte, monobloc/module, voltage;
- monitoring regime: frequency and choice of voltage, temperature, current, and/or internal ohmic measurements;
- float voltage and maximum ambient temperature;
- year installed, date first cell replaced, and contributing factors.

The procedure employed for data collection and analysis is described in Section 2.

2. Procedure

The survey of manufacturers identified differences in VRLA design and manufacturer quality control. Each manufacturer was asked to respond to questions describing a specific cell's physical, electrical, and performance characteristics (Table 2).

The survey of end users was designed to facilitate responses from operators of multiple installations. For instance, one utility provided survey responses for 75 installations. Similar installations were bundled according to age of installation, manufacturer and model, voltage class, and other information specific to the application. The survey of end users attempted to reveal installation and operating procedures that may have contributed to the apparent success or failure of the VRLA cells. Each end user was asked to respond to questions describing from whom they purchased their cells, a description of their VRLA installation, and operating and monitoring regimes (Table 3).

Every effort was made to conceal the identity of participants, yet survey response was initially less than desired. End users identified 76 different VRLA cell models, far more than the number in completed manufacturer surveys. Manufacturers tended to complete surveys for new product lines, whereas end users more often identified older models, no longer produced or sold. To fill in the gaps, the authors performed research on the Internet to verify model numbers and obtain product literature. Only a subset of the survey questions could be answered with the information obtained from the web.

Two linked, password-protected Access databases were created for the VRLA battery end users and manufacturers. Manufacturer's name, cell model, and end-user name are numerically coded to conceal identities. The collected and estimated data are provided as metric measurements.

Table 2
Question categories in the survey of VRLA manufacturers

Physical characteristics	Electrical characteristics	Performance characteristics
Exterior dimensions	Cell Ah capacity	Application
Electrolyte	Internal resistance	Recommended float voltage
Separator material	Monthly self-discharge	Premature failures
Case and post-seals	Specific energy	Cause of premature failures
Plate geometry		
Recommended operating temperature		

Table 3
Question categories in the survey of VRLA end users

Battery identification	Installation description	Operation/monitoring
Type of application	Make/model of cells	Float voltage
Seller/installer	Installation size (number of cells, modules, Ah capacity)	Year first cell replaced
Receipt of installation/operating instructions	Year installed	Total cells replaced
Unusual failures	Location	Parameters monitored and frequency
Root cause of failure	Temperature and control	

Queries have been developed to interrogate the databases, with analysis performed in Excel.

None of the surveyed end users documented VRLA battery operation and maintenance at the level needed for exact numerical responses. A respondent's recall often resulted in date ranges instead of a specific year for installation or first cell replacement. Multiple-survey respondents typically provided ranges, resulting in use of the midpoint value for the installations. For instance, one utility respondent installed three substation batteries in 1996–1998; the authors set the year as 1997 for all three installations. Midpoints were also used for float voltage, e.g. 2.25 V where 2.24–2.26 V was provided.

Linking the manufacturer and end-user surveys required identifying the model used in each installation. In some cases, respondents could not remember the exact model number and could not easily visit the site (e.g. remote and unmanned, underground, or pole-mounted facilities). Sleuthing was required to determine the appropriate model, cells per module, Ah capacity (at the 8 h rate to 1.75 V per cell), and other parameters for calculations. Survey respondents occasionally provided incomplete model numbers, contradicting model number and Ah capacity, or general guidelines for dividing a bundle of installations by make and model. The measures taken to overcome the shortcomings in the gathered data are believed to have been adequate to protect the validity of the conclusions drawn from the data set.

3. Results

Utility VRLA end users responding to the survey operate 215 installations, distributed across 13 States of the USA. To conceal end-user identity, survey results are reported for four regions: northeast, midwest, south, and west. The geographic distribution of the survey sample is skewed towards the midwest and west regions. This characteristic is biased by the random nature of the survey. The VRLA cells installed in the northeast appear to be smaller in capacity than those installed elsewhere in the country.

By comparison, the south is less represented in the survey sample. While the use of VRLA cells is not promoted in very hot climates, a good portion of the south is still reasonably temperate and opportunities for VRLA applications abound. More installations are known in the south, but potential respondents were unwilling to participate. A regional map of the USA with the number of cells and estimated Ah represented by surveyed utility end users is shown in Fig. 1.

Location and temperature control define the operating environment of VRLA installations. Utility VRLA install-

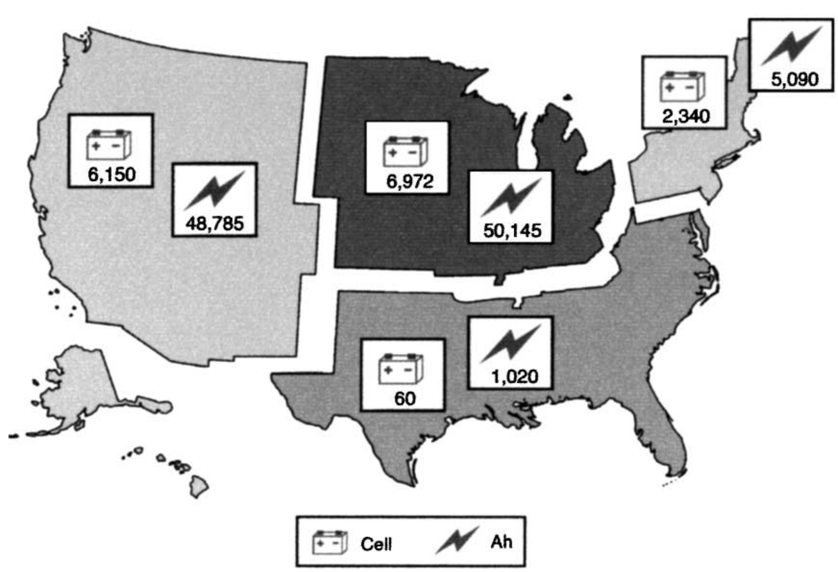

Fig. 1. Geographical distribution of utility VRLA cells and their total energy output.

ations are primarily indoor facilities; almost 90% of the surveyed installations are indoors. Not surprisingly, maximum temperature exposure is not high for the surveyed utility respondents. In fact, none of the 215 installations is operated above 40°C. Manufacturers by and large do not require temperature control. Nonetheless, almost half of the utility installations were temperature-controlled, typically by a fan or small air conditioning unit.

The manufacturer chooses a particular cell configuration to meet the customer's needs, which in turn, impacts surface area, air circulation, and stack and rack design. Utility installations are comprised of single cells, modules of three–eight cells connected in series or parallel, or monoblocs of up to six cells within a single container. Modules are the configuration of choice for the surveyed utility installations. Use of monobloc designs is also popular. A key advantage of the monobloc is a smaller battery footprint. The key disadvantage is that failure of a single cell within the block results in the replacement of the entire container and its cells.

A key determinant of cell chemistry is the mode of electrolyte immobilization. Early in this survey, the authors assumed that both gel and AGM materials would be well represented in the survey. After all, gelled-electrolyte technology has been available since the early 1960s and AGM cells have been marketed only since 1972 [1]. Gel cells experience less electrolyte stratification than AGM cells, particularly under deep cycle conditions, and typically require less overcharge to reach full state of charge. AGM cells have high-rate discharge capacities that make them suitable for UPS and standby applications where charging periods are predictable and regulated [1]. Acid stratification impacts the permitted height of the container (or jar). Gel cells can be twice as tall as AGM cells, which are limited to about 380 mm (15 in.) in height, when in an upright position.

Utility respondents indicated that only four installations used gelled electrolyte in their 476 cells, with the remaining 211 installations employing AGM. As expected, most (64%) of the surveyed utility installations operate at 125 V for substations and industrial customer sites (see Fig. 2). This group accounts for 83% of the cells employed by the surveyed utilities. A third of the installations operate at 48 V, and these are employed in a wide variety of applications.

In order to get a complete picture of the status of a VRLA battery, it is important to take account of its state of health. VRLA batteries are often closely packed in module racks or designed as monoblocs, making the measurement of individual cell voltages difficult. In addition, the spread of individual cell voltages during float service exceeds that of conventional flooded batteries, especially when the battery is new, making float voltage measurements less meaningful [2].

Monitoring temperature is important in VRLA batteries, because they are more sensitive to heat than flooded lead-acid batteries, and increased temperature can result in water loss and thermal runaway.

Since, conventional discharge tests are time consuming and expensive, many end users have taken to monitoring battery health in terms of voltage, current, temperature, and internal ohmic measurements (internal resistance, conductance, impedance). Because not all regimes are ideal for every installation, end users must decide for themselves which parameters are most effective in identifying their battery's state of health. There has been much talk of late regarding simply tracking ohmic measurements to detect faults that impact on a battery's capacity [3]. These readings measure impedance, which will increase due to loss of electrolyte or corrosion of the conducting components [2]. None of the surveyed utility participants measure internal ohmic readings alone.

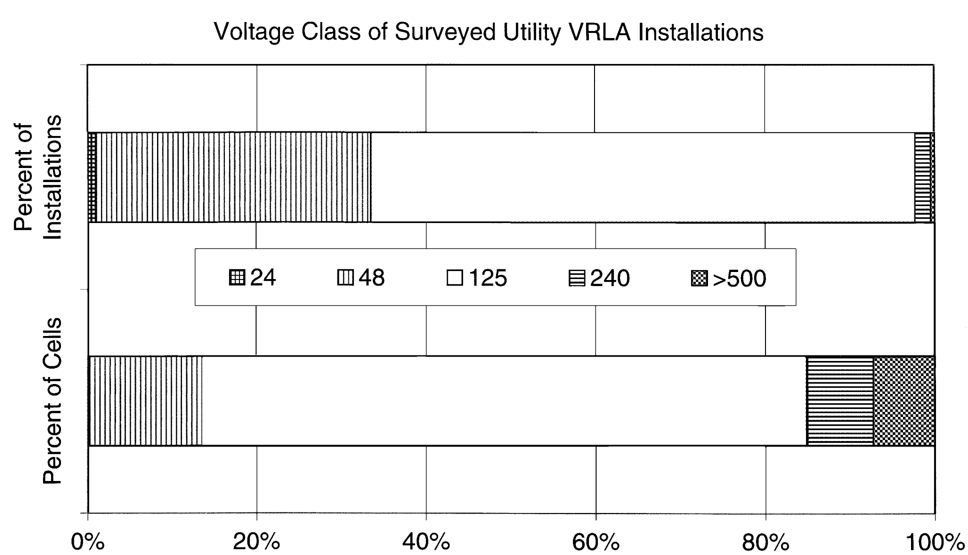

Fig. 2. Voltage of utility VRLA installations and the cell groups surveyed.

Table 4
Parameters monitored by utility installations

Installations	Cells	Parameters			
		Voltage	Temperature	Current	Ohmic measurements
38	3990	×	×	×	
21	653	×	×		×
6	720	×	×		
81	6660	×		×	×
29	1313	×			×
40	2186	×			
215 (total)	15522 (total)				

There were six different sets of parameter combinations used by utility respondents (Table 4). Two-thirds of the participating utility installations included monitoring three parameters in their regime. None of the end users monitored all parameters. Voltage, current, and internal ohmic measurements were the favored combination, monitored at 43% of all surveyed cells. None of the utility respondents indicated visually checking their cells for cover, case, and post-integrity.

Every utility installation surveyed measured voltage, 84% of the installations monitored it at the cell level, thus impacting 88% of all surveyed utility cells. For only 31% of the installations was the battery room's ambient temperature monitored. Internal ohmic measurements were taken on 55% of all cells, and although only two regimes included monitoring current, 69% of all surveyed cells are impacted by this measurement.

Not only must companies monitor their cells, they must do it consistently to assess battery health accurately. Only 7% of cells surveyed were monitored on a daily basis, and voltage, current, and ambient temperature were checked. While a quarter of the utility VRLA cells are monitored monthly, over half of the cells are monitored semi-annually for voltage, current, and internal ohmic measurements.

The life of the lead-acid battery is dependent on the choice of positive plate geometry, positive grid alloy and thickness, processing parameters, electrolyte, and other design variables. Each battery manufacturer sets operational limits for warranties, e.g. involving ambient temperature, float voltage, normal and equalization charges, depth of discharge, etc. When operating conditions fall outside specified limits, customers are given guidelines for compensating the difference to maintain the design life of the product.

A fully charged cell in a standby condition has a predictable voltage determined by its chemistry and temperature. Overcharging cells can lead to them drying out. In order to prevent this, the recommended float voltage for the majority of VRLA cells surveyed is 2.26 V per cell. If the cells are exposed to ambient temperatures above 25°C, manufacturers recommend temperature compensation to reduce unwanted aging effects.

- Too high a float voltage will lead to accelerated corrosion and water loss.
- Too low a float voltage will lead to self-discharge and, potentially, sulfation of the negative plates.

Some manufacturers suggest reducing the float voltage by 2.5–3.25 mV for each degree above 25°C. The float voltage for VRLA cells operated at 35°C would then be reduced to 2.24 V. As seen in Table 5, most of the utilities surveyed float their VRLA cells at 2.24–2.25 V. However, there are 22 installations that float their 2600 cells above 2.28 V.

Other manufacturers do not insist on temperature compensation between 5 and 35°C. Temperature-compensated float voltages are required for outdoor installations, where the range of operating temperatures can be large [2]. Without temperature control, many indoor installations may also need temperature-compensated float voltage.

The survey of end users focused on VRLA cell performance and premature failure. However, the survey was somewhat handicapped in obtaining this information because of the following reasons.

- VRLA cell replacements and unusual experiences are not well documented by utility operators. Rather, the survey had to depend on respondent recall, which is both subjective and inexact.
- VRLA cells are typically installed at remote, unmanned locations. If the owner/operator does not have a data acquisition system with remote access or a regular monitoring program to track cell health, he can only guess as to when the cells first failed.

Table 5
Maximum temperatures and float voltages found in the surveyed utility installations

Float voltage per cell	Maximum temperature		Unknown	Total
	20–30°C	30–40°C		
<2.24		1		1
2.24–2.25	83	30	26	139
2.26–2.27	23	29		52
2.28–2.29	1			1
>2.29	3	18		21
Unknown			1	1
Total	110	78	27	215

Table 6
Age of first cell when replaced within the utility installations surveyed

Year installed	<1 year	1–3 years	4–5 years	>6 years	None replaced	Total
1980–1985					10	10
1986–1989		2				2
1990–1993		61	30	3	14	108
1994–1996		42	6		8	56
1997–2000	4	3			32	39
Total	4	108	36	3	64	215

- The age at which the first cell was replaced is used as a proxy for premature cell failure. The age of the second and third cell replacements would also be of great interest and could be considered for subsequent surveys.

Despite these shortcomings, it is believed that the major conclusions of the analysis are reasonable. Cell failures within the first year of operation are typically due to manufacturing defects, usually covered by the warranty. Given the negative publicity surrounding VRLA performance, the authors expected to find a large number of failures within the first year. However, only four utility installations had their first cells replaced within the first year. The range of ages for first cell replacement naturally broke at 1–3 years, 4–5 years, and more than 6 years. The remaining category is ‘‘None Replaced’’, the most desirable condition for end users.

Having no cells replaced could easily indicate that the battery was recently installed, e.g. since 1997. For older installations, having no cells replaced means the battery has performed as expected. This could be due to any number of conditions, e.g. the end user’s preventive maintenance program, a particular product’s technical superiority, very little use, or no method of checking the capacity of the cells. To provide a more complete appreciation of the age of the installation at first cell replacement, the year installed is included (particularly for those installations with none replaced). The year installed parameter has been grouped for analysis purposes: 1980–1985, 1986–1989, 1990–1993, 1994–1996, and 1997–2000.

Half of the utility respondents had their first cell replaced within 3 years of installation (Table 6). Another 36 installations replaced their first cells after the fourth or fifth year. Three installations waited for 6 years. One interesting feature of this table is the number of installations where no cells were replaced. Half of the 64 installations where no cell has been replaced were installed prior to 1997. One operator reported that he has never replaced any cells at 10 facilities installed prior to 1985. This skews the analysis into suggesting that older models performed better than newer designs. This may not be a reliable conclusion, however, since only 12 of the 215 surveyed utility installations were delivered prior to 1990. Considerable changes in VRLA cell design have occurred during the past decade.

Unfortunately, this survey cannot test the impact of those design improvements. Subsequent survey efforts should increase the number of respondents with installations dating back before 1985 in order to permit a more complete appraisal of the performance of earlier VRLA cell designs.

Batteries installed between 1990 and 1996 constitute the largest portion of utility installations surveyed. These limited data suggest that there is a 56% probability that a VRLA battery installed by utilities between 1990 and 1993 will

Table 7
Profiles of the 125 and 48 V surveyed utility installations

Description	125 V installations	48 V installations
Year installed		
1980–1985	1	9
1986–1989	2	0
1990–1993	75	32
1994–1996	42	9
1997–2000	18	20
Maximum temperature		
20–30°C	74	35
30–40°C	55	18
Unknown	9	17
Outdoor configuration		
Monobloc	1	2
Module	8	11
Indoor configuration		
Cell	6	0
Monobloc	13	25
Module	110	32
Temperature controlled		
Controlled	85	24
Not controlled	53	46
Float voltage		
<2.25 V	105	33
>2.25 V	33	37
Parameters monitored		
Voltage	23	17
Voltage, ohmic	12	15
Voltage, ohmic, temperature	4	17
Voltage, ohmic, current	81	0
Voltage, current, temperature	12	21
Voltage, temperature	6	0

Table 8
Probability of first cell replacements within the 125 and 48 V surveyed utility installations

Age of installation	125 V batteries installed (%)				48 V batteries installed (%)			
	1990–1993		1994–1996		1990–1993		1994–1996	
	<2.25 V	>2.25 V	<2.25 V	>2.25 V	<2.25 V	>2.25 V	<2.25 V	>2.25 V
1–3 years	46		82	25	100	100	100	25
4–5 years	49		16					
>6 years	2	14						
None replaced	3	86	3	75				75

experience its first cell failure within the first 3 years of operation. The odds increase to 75% for batteries installed by utilities between 1994 and 1996. Examining the possible reasons for this situation, the authors investigated 125 and 48 V installations separately. Recall that almost two-thirds of the surveyed utility installations operate at 125 V and another one-third operate at 48 V (Fig. 2). Analysis of these two voltage classes helps to quantify differences in operation and monitoring that these two types of installations experience. Table 7 profiles the two groups.

Over 85% of the 125 V batteries surveyed were installed in 1990–1996. The 125 V batteries are mostly modules installed indoors, with over 61% temperature-controlled even though not required by the manufacturer. The float voltage is below 2.25 V for three-quarters of the cases and almost 60% of the installations monitor voltage, current, and internal ohmic measurements.

By contrast, over 58% of the 48 V batteries surveyed were installed in 1990–1996. The 48 V batteries are either modules or monoblocs, primarily located indoors. These units are typically not temperature-controlled. Slightly over half of the 48 V installations float their cells above 2.25 V. Owners of 48 V batteries monitor either voltage, voltage and ohmic measurements, voltage, ohmic and temperature, or voltage, current and temperature.

Do certain operational characteristics increase or decrease the probability of early first cell replacements? Table 8 examines the year installed, age of installation at first cell replacement, and float voltage of the 125 and 48 V batteries in an attempt to tackle this question. The 125 V batteries installed in 1990–1993 and floated below 2.25 V had a 46% chance of experiencing their first cell replacement within 3 years. Another 50% experienced the first cell replacement by fifth year. The batteries in this voltage category that were floated above 2.25 V lasted longer than 6 years or had never had cells replaced.

For 125 V batteries installed between 1994 and 1996 and floated below 2.25 V, the probability of early cell failure worsened, with 82% of the installations replacing their first cell within the first 3 years of operation. The likelihood of no cell replacements was slightly less for the 125 V batteries installed between 1994 and 1996 and floated above 2.25 V compared to those installed between 1990 and 1993.

On the other hand, over half of the 125 V batteries installed between 1990 and 1993 operated beyond 3 years before replacing their first cell. It is possible that the operators monitored these installations more closely than the 24 and 48 V facilities, since these were more likely to be located on utility property.

The 48 V batteries installed between 1990 and 1996 and floated below 2.25 V universally experienced first cell replacements within 3 years. The 48 V batteries installed in 1990–1993 and floated above 2.25 V also experienced first cell replacements within 3 years. This situation improved slightly for the 48 V batteries installed in 1994–1996, with 75% yet to replace any cells.

A tentative conclusion for both categories (125 and 48 V) would be that the greatest concentration of first cell replacements occurs for the batteries that have float voltages below 2.25 V. This would be consistent with a failure mechanism involving self-discharge, aggravated by the difficulties of maintaining all of the cells in a long string at a sufficiently high voltage.

4. Conclusions

Even though the surveys are still in the process of being analyzed, a number of important conclusions are worthy of note.

- A significant number of the VRLA cells covered by the surveys are lasting for 5 or more years. The 28% of the utility installations have cells lasting more than 5 years, with another 15% installed in the past 3 years without any cell replacements.
- There is a large spread in the range of life expectancy for utility VRLA cells, from 1 to 16 years.
- In some cases, it appears that adjusting float voltage may enhance battery life. Inadequate float voltage may be an important life-limiting factor for VRLA cells in float duty.
- A vigorous monitoring program does not appear to extend the life of VRLA cells without an equally proactive cell maintenance program. Every installation measured voltage and 81% of the utility installations measured one or two more parameters regularly.

Further analyses of the data and feedback from manufacturers are needed before drawing additional conclusions.

Acknowledgements

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