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SAND2004-0914

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Printed March 2004

Reliability of Valve-Regulated Lead-Acid Batteries for Stationary Applications

A Study by the DOE Energy Storage Systems Program

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Abstract

A survey has been carried out to quantify the performance and life of over 700,000 valve-regulated lead-acid (VRLA) cells, which have been or are being used in stationary applications across the United States. The findings derived from this study have not identified any fundamental flaws of VRLA battery technology. There is evidence that some cell designs are more successful in float duty than others. A significant number of the VRLA cells covered by the survey were found to have provided satisfactory performance.

Acknowledgments

The authors wish to acknowledge the U.S. Department of Energy, Energy Storage Systems Program for the support of this work. We also gratefully acknowledge the review of this report by Garth Corey and Thomas Hund. Also, the authors acknowledge the planning of, and initial efforts for, this study by Paula Taylor and her associates at Energetics, Inc. Finally, we are indebted to Claudia Childress for the technical editing of this report.

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Executive Summary

A survey has been carried out to quantify the performance and life of over 700,000 valve-regulated lead-acid (VRLA) cells, which have been or are being used in stationary applications across the United States. This sample is estimated to constitute approximately 1.4% of the total number of cells currently in use in telecommunications, UPS, and photovoltaic sectors within the country. The performance of the cells, as determined from the survey responses, has been correlated with cell design, battery configuration and the environment in which the cells were used. A prime purpose of the project has been to establish an objective picture of the ability of VRLA cells to perform the functions required for stationary energy storage applications. A further aim has been to identify optimum design, configuration, and environmental parameters that should be adopted in order to arrive at the best possible performance from a VRLA battery system.

A majority of the cells investigated were used within recommended conditions of temperature and float voltage. For those cells not operated according to recommended conditions, no strong correlation between these parameters and the probability of good performance was identified. There is evidence that some cell designs are more successful in float duty than others. A significant number of the VRLA cells covered by the survey were found to have provided satisfactory performance; 42% of all the cells surveyed had operated for five or more years before replacement, and another 25% of all the cells surveyed had never been replaced.

The findings derived from this study have not identified any fundamental flaws of VRLA battery technology. Rather, the results of this survey suggest that the basic technology can perform well in many applications. When early failures have occurred, some end-users contributing to the survey were able to determine the cause of failure. In other cases of early failure, the battery technical community has identified design or production issues (not part of this survey), and corrections have been made that are resulting in improvements to VRLA products.

1. Introduction

Valve-regulated lead-acid (VRLA) batteries have been commercially available for more than 20 years. They have been enthusiastically embraced by users of uninterruptible power supplies (UPS) because of anticipated reductions in installation and operating costs, smaller footprint, increased installation flexibility, and fewer environmental concerns. Yet UPS applications now account for less than 23% of VRLA annual sales, which have grown from \$157 million in 1993 to \$534 million in 2000, as reflected in Battery Council International (BCI) information.¹ Telecommunications demand for emergency back-up power is primarily responsible for astronomical growth in VRLA sales, and accounts for 70% of recent sales (see Figure 1-1).

As with any evolving technology, users have encountered varying degrees of performance and reliability. Manufacturers and end users postulate that the early failures experienced at some field installations may be due to VRLA battery temperature and charging sensitivities, manufacturing quality control, or compatibility issues with particular applications. Proprietary concerns and limited data acquisition systems have constrained the amount of performance and life-cycle data that is publicly available. This has hindered the ability to evaluate premature capacity loss, which has been reported for VRLA batteries in some cases after as few as two years of service.²

¹ Battery Council International, correspondence dated July 10, 2001.

² Cantor, W.P., Davis, E.L., Feder, D. O., and M. J. Hlavac. 1998. Performance Measurement and Reliability of VRLA Batteries – Part II: The Second Generation. Proceedings of INTELEC 1998.

1.1 VRLA Reliability Study

The International Lead Zinc Research Organization (ILZRO), the U.S. Department of Energy, Sandia National Laboratories (Sandia), and the Advanced Lead-Acid Battery Consortium (ALABC) have sponsored a multi-phase project to investigate these issues. The focus of this study was 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 consisted of five 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
- Workshops for ALABC and ILZRO members and participating manufacturers to examine preliminary results
- Revision of the analysis to incorporate suggestions for improvements

Password-protected Access databases were created to contain all survey responses. Manufacturer names, cell model numbers, and end-user names were numerically coded to conceal identities. The manufacturer and end-user surveys revealed very candid descriptions of battery operation and maintenance and interesting linkages between service conditions and failure modes.

The manufacturer survey (see Appendix A) addressed differences in VRLA design and manufacturer quality control. Nine manufacturers responded to questions describing specific cells' physical, electrical, and performance characteristics (see Table 1-1).

Table 1-1. Survey Question Categories for VRLA Manufacturers

Physical Characteristics	Electrical Characteristics	Performance Characteristics
<ul style="list-style-type: none">• Exterior dimensions• Electrolyte• Separator material• Case and post sealing methods• Plate geometry• Recommended operating temp	<ul style="list-style-type: none">• Cell amp-hour capacity• Internal resistance• Monthly self-discharge• Specific energy	<ul style="list-style-type: none">• Application• Recommended float voltage• Expected yearly early failures• Cause of early failures

The end-user survey (see Appendix B) inquired about installation and operating procedures that may have contributed to the apparent success or failure of VRLA cells. Each end user was asked to respond to questions describing where they purchased and how they installed, operated, and monitored their VRLA cells (see Table 1-2).

Table 1-2. Survey Question Categories for VRLA End Users

Battery Identification	Installation Description	Operation/Monitoring
<ul style="list-style-type: none">• Type of application• Seller/installer• Receipt of installation/operating instructions• Unusual failures• Root cause of failure	<ul style="list-style-type: none">• Make/model of cells• Installation size (number of cells, modules, amp-hours)• Year installed• Indoor/outdoor and geographic location• Temperature control• Ambient temperature	<ul style="list-style-type: none">• Float voltage• Year first cell replaced• Total cells replaced• Parameters monitored and frequency

End users identified 79 different VRLA cell models, far more than the 17 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 Internet was used to research and verify model numbers and obtain product literature. Only a subset of the survey questions could be answered with the information obtained from the web.

Password-protected Access databases were created to identify VRLA battery end users and contain all data collected. Between December 1999 and May 2001, calls were made to over 350 potential respondents to seek their participation in the survey. This period coincided with significant growth in the telecommunications industry. Sales of VRLA batteries to telecommunications customers grew by 150% between 1999 and 2000. Due in part to this growth, the resources of telecommunications end users were stretched and many began outsourcing the maintenance of their batteries. As a result, it was difficult to obtain participation from telecommunications VRLA end users.

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 unmanned, underground facilities). Additional investigation was required to determine the appropriate model, number of grouped cells or monoblocks, amp-hour capacity (e.g., rated at the 8-hour rate to 1.75 volts per cell), and other parameters for calculations. Survey respondents occasionally provided incomplete model numbers, contradicting model number and amp-hour 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.

1.2 Study Results and Data Analysis

As of May 2001, 16 utilities and nine telecommunications firms had completed end-user surveys. These responses represent over 56,000 installations with more than 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 6,000 installations, while the typical utility respondent represented about a dozen installations.

Initially, this analysis was approached on a per-installation basis, assuming that the owner or operator installed all cells at the same time, maintained the ambient temperature and float voltage, monitored cell health, and made decisions regarding cell replacement. Installations varied from small, six-cell, 12-volt systems, to utility substation-scale, 750-volt facilities with hundreds of cells. However, when the installation counts were presented to ALABC members and manufacturers in May-June 2001, they suggested that cell counts be used instead of installation counts. Cell counts were available in the Access database, as well as other descriptive and operating information provided by the respondents, e.g., geographic location, installation size, temperature control, float conditions, year installed, the year the first cells were replaced, cycle frequency, and parameter monitoring.

Battery configuration is one of the most critical descriptors of the installation data. Installations consist of either:

- **Monoblocks**, i.e., two, three, or six cells housed within a single container, requiring the entire container to be replaced if a single cell fails (see Figure 1-2) or
- **Grouped cells**, i.e., single cells connected in series or parallel combinations in which single cells can be replaced, if needed (see Figure 1-3).

Manufacturers requested that the analysis address cells in monoblocks separately from cells in groups, as the two configurations probably experienced different performance, given their construction and typical use profile.

Figure 1-2. Typical Monoblock Designs

Source: Manufacturer websites

Figure 1-3. Module Containers for Grouped Cell Configuration

Source: Energetics, Inc.

Prior to June 2001, the analysis addressed either utility or telecommunications installations. Discussions with manufacturers revealed a complex situation requiring a significant change in approach:

- Most installations operating at less than or equal to 48 volts (LTE48V) d.c. are used for communications applications, whether installed by utility or telecommunications firms, and should be analyzed jointly.
- Spiral-wound monoblocks are a special class of batteries used in telecommunications and should be analyzed separately.
- UPS systems operate at or above 125 volts d.c., and should be analyzed separately.
- Batteries used with photovoltaic (PV) arrays are cycled differently, are exposed to harsher environments, and should be analyzed separately.

As a result, the data presented in this report are analyzed in four categories: LTE48V batteries, spiral-wound monoblocks, UPS batteries, and PV batteries. For certain applications, one particular configuration appears to have been predominant. For example, all of the PV installations that have been surveyed were configured as cells in groups, while all the sites where the spiral-wound cells were used had the cells deployed in six-cell monoblocks.

Throughout this report the performance data are presented for numbers of individual cells. The terms “cells in monoblocks” and “cells in groups” (or “grouped cells”) are used to describe the battery configuration and to highlight possible reasons for different performance or failure rate (see the Glossary in Appendix F for definitions of terms used in this report).

In order to make valid comparisons between different configurations and applications, the analysis is based on cell counts. Table 1-3 presents statistics for the data gathered from 50,911 installations where only monoblocks were deployed. On average, these installations deploy monoblocks of six cells each. Monoblock size and number of units obviously vary by application. Clearly, conclusions drawn about the performance of LTE48V batteries and spiral-wound cells (which account for almost all of the 606,263 cells in monoblocks surveyed) appear to be far more statistically significant than those for UPS applications. The total number of cells surveyed in monoblock configurations is far greater than the number of cells in groups (see Table 1-4).

Table 1-3. Surveyed VRLA Monoblock Configurations by Application

Application	Number of Installations	Number of Monoblocks	Number of Cells	Average Cells per Installation	Max. Cells at Instl.	Min. Cells at Inst.
LTE48V	14,398	58,086	345,693	24.0	36	12
Spiral-wound	36,500	43,000	258,000	7.1	12	6
UPS	13	525	2,570	197.7	360	50
PV	---	---	---	---	---	---
Total	50,911	101,611	606,263	11.9	---	---

Table 1-4. Surveyed VRLA Grouped Cell Configurations by Application

Application	Number of Installations	Number of Cells	Average Cells per Installation	Max. Cells at Instl.	Min. Cells at Inst.
LTE48V	5,221	125,229	24.0	252	12
Spiral-wound	---	---	---	---	---
UPS	123	8,983	73.0	1134	58
PV	13	2,112	162.5	360	6
Total	5,357	136,324	25.4	---	---

Grouped cell installations typically employ twice as many cells per installation. LTE48V batteries account for almost all of the 136,234 cells in groups identified by the survey. Yet cells in groups are not the dominant configuration for LTE48V battery cells, which were more likely to be installed in monoblocks. By comparison, UPS and PV installations favor cells in groups and the performance of these cells are significant for the two applications.

The 742,587 surveyed cells (see Table 1-5) represent about 1.4% of the total cells estimated to be in operation in the U.S in the year 2000, based on BCI data. This number is meaningful when compared to other random sample survey responses. The 1.4% value was derived by converting annual VRLA sales in dollars to number of cells following the analytical approach shown in Appendix D.

Table 1-5. Total Number of Surveyed Cells by Configuration

Application	Cells in Monoblocks	Cells in Groups	Total Cells
LTE48V	345,693	125,229	470,922
Spiral-wound	258,000	---	258,000
UPS	2,570	8,983	11,553
PV	---	2,112	2,112
Total	606,263	136,324	742,587

2. End-User Profiles

This section addresses the applications, locations, and installations of the VRLA batteries that are described by the survey results. The key criteria against which the surveyed cells have been analyzed are introduced. Brief profiles of the four categories of end-user applications are presented.

2.1 Applications and Installations

VRLA batteries are used in utility UPS applications to provide back-up power to operate switchgear equipment and other critical loads. Switchgear enables the utility to isolate a localized problem (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. Batteries provide a virtually instantaneous power source and are 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, batteries are sized to allow for an orderly shutdown of critical loads. Smaller systems may be incorporated into substations or other locations where batteries are needed. When the system is very large, a separate structure is usually built (see Figure 2-1).

Figure 2-1. Building for a Utility Battery System

Source: Energetics, Inc.

Figure 2-2. Integrated PV-VRLA Enclosure

Source: Endecon

VRLA batteries used to support PV applications are typically found in remote, grid-independent locations. An integrated enclosure to house the cells and power conversion system (PCS), including a PV array, can be sited on remote mountaintops (see Figure 2-2). Because PV batteries support an intermittent generation supply, they are subject to more frequent discharge cycles than the float duty typical of UPS or telecom installations. Additionally, such batteries normally are sized to provide a few days of storage.

The LTE48V and spiral-wound VRLA batteries used in the telecommunications industry provide emergency back-up or uninterruptible power to communications equipment during power outages.

Telephone networks formerly provided backup power exclusively from large central offices. However, “with cellular, wireline, and cable TV, the backup is at the end of the street.”³ As a result, telecom companies and end users are distributing batteries in a variety of housings closer to demand centers:

- Controlled-environment underground vaults
- Type 80 cabinets
- Onsite installations
- Above ground or pre-cast huts
- Cool Cell™

Controlled-environment vaults (see Figure 2-3) are waterproof, underground installations. The size and use of the vaults vary from installation to installation. The vault shown in Figure 2-3 provides telecom service to customers located within one mile of the vault.

Figure 2-3. Controlled Environment Underground Vault

Source: Energetics, Inc.

There are many different type 80 cabinets used in the telecommunications industry (e.g., type 80 A, 80 B, 80 C, etc.). The cabinet shown in Figure 2-4 is an 80 E cabinet; it contains electronics as well as batteries, and services a nearby hospital.

Industrial installations are commonly located in a room on the customer’s property. These include, but are not limited to, office buildings, hospitals, and universities.

Huts are stand-alone concrete or brick buildings. Pre-cast huts (see Figure 2-5) are, as the name implies, pre-fabricated and available in various sizes. They can be found servicing office parks and universities.

Figure 2-4. 80E Cabinet

Source: Energetics, Inc.

Figure 2-5. Pre-Cast Hut

Source: Energetics, Inc.

³ Quote from Frank Fleming of Hawker Energy Products, in Arielle Emmett, “A battery for all seasons?,” *Telephony*, 1/26/98.

Cool Cell™ installations (see Figure 2-6) come in a variety of sizes and can either be stand-alone, ground level installations or pole-mounted. These installations can hold more than 24 cells.

For cable TV applications, approximately eight hours of battery capacity is typically necessary. Multiplexers used by hybrid fiber/coaxial cable- and digital loop-carriers require two-to-eight hours of backup power.⁴ The typical duration of a telecom power outage, as described by one survey participant, is six hours. This same respondent indicated that his company requires ten hours of battery capacity per installation, allowing sufficient time to lease and start-up a generator to maintain service at the site.

Figure 2-6. Cool Cell™

Source: www.zomeworks.com/coolcell

2.2 Criteria for Analysis

There are a number of ways to analyze the survey responses. As can be seen in the survey form included in Appendix A, many questions were asked of the end users. However, respondents were unable to provide answers for all questions. In addition, some of the information did not lend itself to analysis. For example, respondents were asked to identify the state in which each installation operated. Those respondents covering thousands of small VRLA systems could not identify the exact number of installations in each state. The system locations were characterized by region instead of by state, disaggregating the Pacific region into the northern and southern Pacific regions. However, geographic analysis did not provide any insights regarding system performance. The indoor/outdoor location and the use of a fan or air conditioner were more important criteria than regional locations.

A key characteristic of VRLA cell design is the mode of electrolyte immobilization. Early in this effort, it was assumed that both gel and absorptive glass mat (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 since 1972.⁵ 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 capabilities that make them suitable for UPS and stand-by applications where charging periods are predictable and regulated.⁶ Acid stratification concerns limit the height of the cell container (or jar). Gel cells can be twice as tall as AGM cells, which are limited to about 15" in height, when used in an upright position. However, nearly all surveyed cells were of the AGM design.

⁴ Arielle Emmett, "A battery for all seasons?," *Telephony*, 1/26/98

⁵ R.H. Newnham, "Advantages and disadvantages of valve-regulated, lead-acid batteries," *Journal of Power Sources*, 52 (1994).

⁶ *Ibid.*

The survey data were analyzed according to the following key variables:

- Year installed
- Year first cell replaced
- Maximum ambient temperature
- Location (indoor/outdoor)
- Temperature control
- Float voltage
- Parameters monitored

Few of the surveyed end-users documented VRLA battery operation and maintenance at the level of accuracy needed for 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 instance, one UPS respondent reported installation of three substation battery systems in 1996-1998. This information was entered into the database as 1997 for the installation of all three systems. Midpoints were also used for float voltage, e.g., 2.25 volts per cell (vpc) was entered into the database if the respondent provided a range of 2.24-2.26 vpc.

The battery manufacturers requested that the analysis be performed at a very detailed level (by individual cells); however, few trends were apparent from this approach. Data on dates of installation, temperatures, and float voltages were grouped for analytical purposes as follows:

- Year of installation
 - 1980-1985
 - 1986-1989
 - 1990-1993
 - 1994-1996
 - 1997-2001
- Maximum ambient temperature
 - < 20 °C
 - 21-30 °C
 - 31-40 °C
 - > 40 °C
- Float voltage
 - < 2.23 vpc
 - 2.23-2.27 vpc
 - > 2.27 vpc

A measure of battery performance was created by comparing the year that the first cell was replaced against the year of installation. This measure – age at first cell replacement – is discussed in Section 3.

Respondents reporting on thousands of LTE48V and spiral-wound cells could not specify whether individual units were installed at indoor or outdoor locations. Initially, “both” was established as the answer in those cases; however, this did not contribute to the analysis of cell performance. The location of cells at indoor or outdoor facilities helps explain maximum ambient temperature exposures and resulting air conditioning use. Unfortunately, a significant portion of LTE48V and spiral-wound cells fell into the “both” category, and as a result, location did not correlate with age at first cell replacement in these applications.

The battery parameters monitored by surveyed respondents included voltage, current, charge, temperature, and internal ohmic measures. Many respondents monitored more than one parameter, albeit at different time intervals, as described in the following sections. Cell health, as monitored by these parameters, is addressed in Appendix E.

This study investigated links between monitoring regimes and age of first cell replacement. Unfortunately, it appeared that the respondents who monitored their cells more frequently were more aware of cell failures than the respondents who monitored their sites less frequently. Also, the more parameters monitored, the greater the likelihood that the cells experienced their first cell failure earlier, possibly because the operator was more aware of battery performance. A monitoring regime alone without a proactive maintenance program cannot keep VRLA batteries free of early failures.

2.3 LTE48V Battery Profile

The LTE48V systems provide backup power for communications for both the telecom and utility industries. Nearly 74% of the 470,922 surveyed LTE48V battery cells are installed in monoblocks (see Table 1-5). A key advantage of the monoblock 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. Key characteristics of LTE48V battery operation, as revealed by the survey, are profiled in Table 2-1.

Almost all of the surveyed LTE48V battery cells were installed prior to 1994. This does not reflect recent VRLA sales data that would indicate a greater number of LTE48V batteries installed after 1996. The participating end users used mostly monoblock configurations prior to 1994. In fact, 76% of all LTE48V battery cells installed prior to 1994 were in monoblocks. Since 1994, the cells installed by survey respondents were primarily in groups (see Figure 2-7).

Nearly all LTE48V battery cells, whether in monoblocks or groups, are equipped with some sort of temperature control device. Unlike the rest of the survey sample, the LTE48V battery cells in monoblocks were installed mostly outdoors in temperature-controlled enclosures; maximum ambient temperatures did exceed 40°C for almost half of the cells. By contrast LTE48V battery cells in groups were mostly installed indoors in temperature-controlled buildings where maximum battery room temperatures typically did not reach 40°C.

Table 2-1. Profile of LTE48V Batteries by Number of Cells in Monoblock and Grouped Cell Configurations

Description		Cells in Monoblocks	Cells in Groups	Total Cells
Year Installed	1980-1985	6,000	180	6,180
	1986-1989	228,000	48	228,048
	1990-1993	110,964	110,758	221,722
	1994-1996	234	13,163	13,397
	1997-2001	495	1,080	1,575
Maximum Temperature	20-30°C	9,426	7,221	16,647
	31-40°C	180,147	108,816	288,963
	>40°C	156,000	---	156,000
	N/A	120	9,192	9,312
Temperature Control	No Control	627	741	1,368
	Controlled	345,066	124,488	469,554
Float Voltage	<2.23 vpc	---	48	48
	2.23-2.27 vpc	343,230	124,317	467,547
	>2.27 vpc	2,463	864	3,327
Parameters Monitored	Voltage	111	708	819
	Voltage, ohmic	36	333	369
	Voltage, ohmic, temperature	6,120	6,672	12,792
	Voltage, current, temperature	230,904	180	231,084
	Voltage, temperature	522	4,176	4,698
	Temperature, current, charge	---	5,160	5,160
	Ohmic	108,000	108,000	216,000

Figure 2-7. LTE48V Battery Cells Surveyed by Year Installed and Configuration

Source: Table C3-1 in Appendix C.

The surveyed LTE48V battery cells were primarily floated between 2.23 and 2.27 vpc, which is the preferred range for VRLA cells. However, outliers did exist, both below 2.23 and above 2.27 vpc. These cases are investigated in Section 4.

The surveyed LTE48V batteries were monitored for a variety of parameters. The most popular monitoring regime for surveyed LTE48V battery cells in monoblocks included voltage, current, and ambient temperature. A large number of cells in both monoblock and grouped cell configurations were monitored for ohmic measures exclusively. The significance of monitoring regimes is examined in Appendix E.

2.4 Spiral-Wound Cell Profile

Spiral-wound cells employed in telecommunications are typically in monoblock configurations (as can be seen in Figure 2-8). The key characteristics of spiral-wound cells in monoblocks, as revealed by the survey, are profiled in Table 2-2. All 258,000 surveyed spiral-wound cells were installed during the 1980s. This results in an older sample of VRLA cells for telecommunications than is supported by BCI sales data.

Cells were installed both outdoors and indoors in environments where maximum battery room temperatures exceeded 40°C. Yet, these systems were all in temperature-controlled environments and floated between 2.23 and 2.27 vpc. These two features may help explain the excellent performance of these cells, well beyond the warranty period. Ohmic measurements were the favored means of monitoring.

Figure 2-8. Typical Spiral-Wound VRLA Installation

Source: Energetics, Inc.

Table 2-2. Profile of Spiral-Wound Cells by Number of Cells in Monoblock Configuration

Description		Cells in Monoblocks
Year Installed	1980-1985	180,000
	1986-1989	78,000
Maximum Temperature	31-40°C	180,000
	>40°C	78,000
Temperature Control	Controlled	258,000
Float Voltage	2.23-2.27 vpc	258,000
Parameters Monitored	Voltage, current, temp	78,000
	Ohmic	180,000

2.5 UPS Cell Profile

UPS installations typically require higher voltage (rated at or above 125 V), and hence, more cells. Grouped cells were the configuration of choice for the surveyed systems, as they accounted for 78% of the 11,553 surveyed cells (see Table 2-3).

Table 2-3. Profile of UPS Batteries by Number of Cells in Monoblock and Grouped Cell Configurations

Description		Cells in Monoblocks	Cells in Groups	Total Cells
Year Installed	1980-1985	---	60	60
	1986-1989	---	120	120
	1990-1993	180	4,319	4,499
	1994-1996	2,270	2,514	4,784
	1997-2001	120	1,970	2,090
Maximum Temperature	20-30°C	180	4,249	4,429
	31-40°C	230	3,420	3,650
	N/A	2,160	1,314	3,474
Temperature Control	No Control	1,790	2,808	4,598
	Controlled	780	6,175	6,955
Float Voltage	2.23-2.27 vpc	2,570	7,849	10,419
	Not floated	---	1,134	1,134
Parameters Monitored	Voltage	230	1,140	1,370
	Voltage, ohmic	60	884	944
	Voltage, ohmic, temperature	---	245	245
	Voltage, current, temperature	120	1,494	1,614
	Voltage, current, ohmic	2,160	4,500	6,660
	Voltage, temperature	---	720	720

The majority of surveyed UPS cells were installed between 1990 and 1996, which is supported by the BCI sales data. Almost all surveyed UPS cells were installed indoors. The majority of cells in groups were equipped with some sort of temperature control. However, 70% of the cells in surveyed UPS monoblock configurations were not temperature-controlled. Very few of the surveyed UPS monoblock respondents could identify the maximum ambient temperature their cells experienced. This was surprising, as monoblocks tend to experience more temperature problems because their design cannot dissipate heat as effectively as grouped cell configurations. Section 4 considers the combined impact of temperature and float voltage on system reliability. Those survey respondents who monitored battery parameters indicated that they monitored every UPS cell for voltage with the most common regime including current and ohmic measurements as well.

2.6 PV Cell Profile

The respondents using VRLA cells to support PV installations indicated installing grouped cell configurations exclusively. Key characteristics of these PV cells in groups are profiled in Table 2-4. Batteries used in PV applications are typically cycled frequently rather than floated, and this is a key difference in the applications presented here. All surveyed PV cells were installed after 1994. At the time of this survey, few cells were more than five years old. Surveyed PV cells were typically installed in controlled environments indoors, with maximum ambient temperatures not exceeding 40°C. However, 99% of all surveyed PV cells were floated above 2.27 vpc, a finding the manufacturers found unusual. It was suggested that perhaps these respondents reported the equalization charge voltage instead of the float voltage, as PV cells are typically cycled rather than floated. Surveyed respondents monitored most cells for voltage, current, and temperature.

Table 2-4. Profile of PV Batteries by Number of Cells in the Grouped Cell Configuration

Description		Cells in Groups
Year Installed	1994-1996	1,524
	1997-2001	588
Maximum Temperature	<20°C	24
	20-30°C	1,008
	31-40°C	1,080
Temperature Control	No Control	24
	Controlled	2,088
Float Voltage	<2.23 vpc	6
	2.23-2.27 vpc	24
	>2.27 vpc	2,082
Parameters Monitored	Voltage, ohmic, temperature	48
	Voltage, current, temperature	2,064

3. Cell Life-time Analysis: First Cell Replacement

VRLA technology first became available in the 1960s when the gel-cell was released to the market. Since then there have been many design changes, most significantly, the introduction of the AGM design. Manufacturers have made other improvements over the years. As with any new technology, there will be successful designs and some not-so-successful designs. The analytical approach employed in this section was to compare the age at which the first cell failed to the year the cells were installed to determine if there were any significant trends in cell reliability or early failures. Had numbers of cells replaced after the initial failure been available, a more complete view of VRLA performance would have emerged. First cell replacement was the only quantifiable measure of cell life resulting from the survey and should be interpreted within the context of warranted life, which is discussed below. It should be noted that, except for the PV application, the batteries described in this report are primarily floated, with occasional discharges. The PV application involves frequent deep discharges and must be considered within that context.

3.1 Warranted Life

Some VRLA products were initially marketed as “maintenance-free, 20-year-life batteries.” Although these claims are being reconsidered seriously by both manufacturers and end-users alike, there is still a perception in the end-user community that VRLA batteries are only successful if they require no maintenance and last 20 years. Some end-users claim that their cells hold 20-year warranties; however, most of these have a limited time for a full refund or free replacement, and then a pro-rated period. In other words, the cells initially hold a 100% warranty (100% of the value of the cells would be refunded or the cells replaced) should the cells fail within a specified amount of time (typically, about five years). After the full warranty time limit is exceeded, the refund value steadily diminishes, so that after 20 years, there would be no refund amount.

Warranties are typically negotiated for each VRLA battery sold. The warranty period and conditions are determined by the type of installation, expected float or cycle use, climatic conditions, and other factors. End-users negotiate longer warranties when their aversion to risk is high.

The end-user survey included a question on the length of warranty on batteries. Half of the respondents claimed that their cells held 20-year warranties, yet, they operated a mere 3% of the total cells identified in the survey (see Table C2-2). An assumption that had been made was that longer warranties were more popular initially and that the owners/operators of older cell models would report holding 20-year warranties, however, this was not the case. These 20-year warranted cells accounted for less than 1% of the total cells installed prior to 1990. Most of the 20-year warranted cells were installed between 1990 and 1996, which is when the bulk of the surveyed facilities were installed. No apparent trend exists between the year the cells were installed and the warranty reported by the participating end-users. Most cells surveyed held five, seven, or ten-year warranties.

The LTE48V installations predominantly held five-to-ten-year warranties (see Figure 3-1). Five-year warranties predominate for LTE48V monoblocks, but not for grouped-cell configurations. This suggests that battery manufacturers have limited the warranty for monoblocks, limiting their exposure to five years and expecting that there will be scheduled replacements after that time.

The same is true of spiral-wound monoblocks; all surveyed cells had limited warranties up to seven years. The situation is the same for grouped cells in cycling use at remote, off-grid, PV installations (see Figure 3-2). Manufacturers typically limit their exposure to five years when more frequent, deeper-cycle discharges are required.

Figure 3-1. Warranted Life of Surveyed Cells in Communications Applications

Source: Table C2-1 in Appendix C.

Figure 3-2. Warranted Life of Surveyed Cells in PV and UPS Applications

Source: Table C2-1 in Appendix C.

Surveyed UPS cells in monoblocks appear to follow the same pattern with ten-year warranties predominating. By contrast, UPS cells in groups are the only application in which longer warranties dominate: 85% of the surveyed cells in groups held 20-year warranties.

3.2 Calculation of Age at First Cell Replacement

The VRLA end-user survey results analysis was handicapped in terms of the type of information needed to develop a complete picture of cell performance. This was primarily because:

- VRLA cell replacements and unusual experiences were not well documented by the 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 or she can only venture a guess as to when cells first failed. Many respondents answered this question as a range, i.e., 1994-1995. Midpoints were used in the database to enable analysis.
- The age at which the first cell was replaced could be derived from the answers provided by the survey respondents. The age of the second and third cell replacements would also be of great interest and could be incorporated into subsequent survey designs. However, given the number of installations and cells covered by a single respondent, it is unlikely that those questions could be answered accurately.

With the above caveats, all surveyed end-users were able to provide the year of installation and the year the first cell was replaced. The age of first cell replacement was calculated by subtracting the year the cells were installed from the year the installation experienced its first cell replacement.

Initially, the age of first cell replacement was calculated in terms of the installation counts. When the basis of analysis was changed to cell counts, certain assumptions were made to estimate the total number of cells replaced when a failed cell was removed from service. Any monoblock-type installation experiencing a first cell replacement meant that two, three, or six cells were replaced, depending on the monoblock design. For grouped cell configurations, the number of cells replaced varied by installation size and application. When not specifically answered by the survey respondents, the number of cells replaced, along with a failed cell, was:

- One cell was assumed to be replaced in small LTE48V and PV installations
- Two percent of all cells were assumed to be replaced in larger UPS installations⁷

These assumptions were used to estimate the total number of cells replaced for a given installation identified as experiencing a first cell replacement.

The ages of the first cells to be replaced are expressed in whole years. The analysis initially was undertaken on the basis of individual years, but the data were too spread out and did not show any patterns. Therefore, for analytical convenience, the age of first cell replacement was bundled into six different categories:

- <1 year
- 1-2 years
- 3-4 years
- >4 years (assumed to be scheduled replacements)
- None replaced pre-1997
- None replaced in or since 1997

Cell failures within the first year of service are typically due to manufacturer defects, and are usually covered by warranty. Installations experiencing first cell replacements within the first four years of operation were considered to be early cell failures.

Initially, those cells that were replaced after four years of service, or never replaced at all, were included in a single table. However, after meeting with VRLA manufacturing representatives, it was decided that many end-users were following a pre-determined replacement schedule to change out cells after five years of service to ensure system reliability. As a result, cells replaced after four years of service were assumed to be scheduled replacements.

The age of first cell replacement is analyzed later in this section in terms of a variety of parameters, such as the year the cells were installed, the float voltage, maximum ambient temperature, and the existence (or not) of temperature control. First, however, the cells that were not replaced are discussed.

⁷ Derived from anecdotal information provided by surveyed UPS respondents.

3.3 Installations with No Cell Replacements

Over 186,000 cells operated in surveyed VRLA installations in which no cell had been replaced as of the time of the survey. These cells represent 25% of the 742,587 cells surveyed. Each application has a distinct distribution of these cells by year installed and configuration (see Table 3-1 and Figure 3-3). For example, LTE48V batteries had the most cells replaced as a percentage of total cells installed. Prior to 1990, by which time 234,000 LTE48V monoblock cells were installed, at least one monoblock had been replaced in every installation (see Table 3-1). This experience is a major contributor to the fact that less than 1% of all surveyed LTE48V cells in monoblock installations have had no cell replacements (see Table C3-2).

Spiral-wound batteries appear to have had the longest experience without cell replacements – none of the 180,000 cells installed before 1986 has ever been replaced (see Table C4-2). This group of cells has a strong impact on the survey results. If the experience of all 492,408 surveyed cells installed in the 1980s was excluded from the analysis (see Table 3-1), then installations with no cell replacements account for 2.5% of all surveyed cells installed since 1990 ($6,150 \div 250,179$).

Table 3-1. Surveyed VRLA Cells in Installations by Application, Configuration, Year Installed, and Replacement Experience

Year Instl'd.	Installations With	LTE48V		Spiral- Wound	UPS		PV	Total
		Cells in Monoblocks	Cells in Groups	Cells in Monoblocks	Cells in Monoblocks	Cells in Groups	Cells in Groups	
Pre- 1990	No Cells Replaced	---	204	180,000	---	60	---	180,264
	Some Cells Replaced	234,000	24	78,000	---	120	---	312,144
	Subtotal	234,000	228	258,000	---	180	---	492,408
Post- 1990	No Cells Replaced	2,487	1,380	---	110	1,921	252	6,150
	Some Cells Replaced	109,206	123,621	---	2,460	6,882	1,860	244,029
	Subtotal	111,693	125,001	---	2,570	8,803	2,112	250,179
Total		345,693	125,229	258,000	2,570	8,983	2,112	742,587

Figure 3-3. Percent of Surveyed Cells in Installations Experiencing No Cell Replacements by Year Installed and Application

Source: Calculated from tables C3-2, C4-2, C5-2, and C6-2 in Appendix C.

Having no cells replaced could indicate that a battery was recently installed, e.g., within the past three years. Almost 37% of all cells installed after 1996, regardless of application, did not experience any failures. For older installations, having no cells replaced means the battery was performing well. 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. In subsequent sections, discussions of cells not yet replaced will address cells installed in or since 1997 separately from older, pre-1997 cells.

3.4 LTE48V First Cell Replacements

Almost every surveyed LTE48V battery experienced some cell replacements; however, none of the cells was replaced within the first year of service. In fact, very few were replaced within the first two years of service. LTE48V battery cells in groups were typically replaced at three-to-four years of service. Lasting a few years longer, LTE48V battery cells in monoblocks were typically replaced after four years of service (see Figure 3-4).

The 5,175 LTE48V battery cells in groups that required replacement represent only 4% of the total LTE48V grouped cells installed. Nearly all of these cells were replaced within four years of installation.

The 85,698 surveyed LTE48V battery cells installed in monoblock configurations lasted longer but experienced a higher percentage of replacements (25% of total LTE48V monoblock cells) than the surveyed LTE48V grouped cells. However, two-thirds were assumed to be scheduled replacements after four years of service, and one-third lasted three-to-four years.

Those LTE48V battery cells in groups installed prior to 1990 tended not to experience early failures, as none of those installed between 1980 and 1985, and 50% of those installed between 1986 and 1989, had been replaced at the time of the survey (see Table C3-2). Nearly all of the

cells replaced in grouped cell configurations were installed between 1990 and 1993, and replacement occurred after three years of service.

Over 66% of the surveyed monoblock cells requiring replacement were installed between 1986 and 1989 ($57,000 \div 85,698$). However, those were assumed to be scheduled replacements, and end-users were assumed to have instituted a policy to replace VRLA cells after five years of service.

3.5 Spiral-Wound First Cell Replacements

The 258,000 surveyed spiral-wound cells were installed in the 1980s. They were extremely successful as 70% of the cells had not been replaced at the time of the survey and some were 20 years old (see Tables C4-1 through C4-3). Of the remaining 78,000 cells, half of these (or 15% of the total number of spiral-wound cells) were replaced after five years of service, suggesting that they were scheduled replacements. These 258,000 cells were used in 36,500 installations operated by two survey respondents.

3.6 UPS First Cell Replacements

None of the surveyed UPS cells installed between 1980 and 1985 had needed replacement at the time of the survey. This excellent experience continued for UPS cells installed through the 1990s, with very few of the cells requiring replacement (see Tables C5-2 and C5-4).

The 186 UPS cells that did require replacement primarily were installed after 1990, with the majority being in groups. They represent less than 2% of all 11,553 surveyed UPS cells. The distribution of these cell replacements by configuration, year installed, and age of first cell replaced is shown in Figure 3-5. Only 23 of the cells installed in UPS installations failed in their first year of service, suggesting the cause was due to manufacturing defects (see Table C5-3).

A large fraction of the replacements (121 of the total 186 cells) occurred between three and four years of service, while 36 cells were replaced after five years of service, indicating possible scheduled replacements (see Table C5-3).

3.7 PV First Cell Replacements

Over 250 PV cells (of the 2,112 total surveyed cells) were operating in installations that had no cells replaced as of the time of the survey, and 43% of those were at least four years old (see Table C6-2). Only seven cells required replacement; three replacements occurred within the first year of life, indicating probable manufacturing defects. The remaining four cells were replaced within two years of installation (see Table C6-3).

Figure 3-5. Age of First Cell Replacements in Surveyed UPS Installations

3.8 First Cell Replacements in Summary

Overall, the results of the analysis of first cell replacement data indicate positive end-user experience with VRLA batteries. Certain applications and cell configurations had better outcomes than others; these were addressed earlier in the section. Table 3-2 identifies the number of cells in installations that experienced early cell replacements, scheduled replacements, or no cell replacements. These results can be summarized to describe the replacement experience of the VRLA cells surveyed:

- 25% of all surveyed cells were installed at facilities that never experienced any cell replacements
- 42% of all surveyed VRLA cells were in operation for more than five years before being replaced, probably due to scheduled maintenance
- 33% of all surveyed cells were located at installations in which some cells were replaced early, i.e., within the first four years of operation.

Table 3-2. Surveyed VRLA Cells in Installations by Application and Replacement Experience

Installation Replacement Experience	LTE48V	Spiral-Wound	UPS	PV	Total
No Cells Replaced	4,071	180,000	2,091	252	186,414
Assumed Scheduled Replacements* (>=5 yrs)	229,002	78,000	1,680	---	308,682
Early Replacements* (<5 yrs)	237,849	---	7,782	1,860	247,491
Total	470,922	258,000	11,553	2,112	742,587

*The number of cells listed includes all cells in installations that experienced cell replacements, i.e., the values include both the number of cells replaced and the number not replaced in each installation.

4. Float Voltage and Temperature Effects

The life of a lead-acid battery is dependent on the choice of positive plate geometry, positive grid alloy and thickness, processing parameters, electrolyte concentration, and many other design and operating variables. Each battery manufacturer sets operational limits for warranties, e.g., operation over a range of ambient temperatures, float voltage, normal and equalization charge conditions, depth of discharge, etc. When operating conditions fall outside specified limits, sometimes customers are given guidelines for compensating certain control parameters to maintain the design life of the product.

Charging, and particularly overcharging, can lead to VRLA cell dry-out. In order to prevent cell dry-out, the recommended charging voltage for the majority of VRLA cells surveyed was 2.26 vpc. If the cells are exposed to ambient temperatures above 25°C, many manufacturers recommend temperature compensation to reduce unwanted aging effects. Some manufacturers recommend that float voltage be reduced as ambient temperature rises.

Because VRLA cells are very sensitive to temperature and float voltage, the age at first cell replacement was analyzed against the maximum ambient temperature and float voltage to determine if any trends existed between these operating conditions and time of first cell replacement. Ideally, the analysis should address the percentage of time each year that the maximum temperature was experienced in addition to considering the average temperature and minimum temperature. Unfortunately, none of these parameters was consistently provided by the end-users, leaving only the maximum temperature to analyze against float voltage. In addition, the existence of temperature control devices (e.g., HVAC, fans, or Cool Cell™) and the age of the installation were addressed where relevant.

The survey results indicate that almost all of the 742,587 VRLA cells were floated within the 2.23 and 2.27 voltage window (see Table 4-1). The column “N/A” in Table 4-1 and other tables describes the number of units of the specified type for which detailed data (e.g., operating temperature) was not available. The range of temperature exposures is wide, with maximum ambient temperatures typically above 30°C. In fact, 234,000 cells were exposed to maximum ambient temperatures above 40°C (though it is not known for how many hours each year) yet the float voltage was not reduced to compensate for the high temperatures. In other words, there appears to have been no temperature compensation of float voltage among the surveyed respondents. The remainder of this section will look into the impact this may have had on early cell replacements.

A number of outliers do exist, both in terms of float voltage and maximum ambient temperature. These are examined relative to the application and cell configuration of the affected cells in order to see if early cell replacements resulted.

Table 4-1. Number of Surveyed VRLA Cells (all types) by Maximum Ambient Temperature and Float Voltage

Float Voltage	<20°C	20-30°C	31-40°C	>40°C	N/A	Total
<2.23	---	54	---	---	---	54
2.23-2.27	---	18,580	471,758	234,000	11,652	735,990
>2.27	24	3,450	1,935	---	---	5,409
Not Floated	---	---	---	---	1,134	1,134
Total	24	22,084	473,693	234,000	12,786	742,587

Source: Calculated from Tables C7-1, C8-1, C9-1, and C10-1 in Appendix C

4.1 LTE48V Battery Cells - Float Voltage and Temperature

Almost all of the surveyed LTE48V battery cells were floated between 2.23 and 2.27 vpc (see Table 4-2). A maximum ambient temperature between 31 and 40°C was experienced by most of the cells in groups and monoblocks. Outliers do exist:

- 156,000 cells in monoblocks were exposed to maximum temperatures above 40°C
- 2,463 cells in monoblocks and 864 grouped cells were floated above 2.27 vpc
- 48 cells in groups were floated below 2.23 vpc

Yet, from these data, surveyed respondents do not appear to be temperature-compensating the float voltages of their LTE48V cells.

Table 4-2. Total Number of LTE48V Battery Cells Surveyed by Float Voltage and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks					Cells in Groups				Total
	20-30°C	31-40°C	>40°C	N/A	Subtotal	20-30°C	31-40°C	N/A	Subtotal	
<2.23	---	---	---	---	0	48	---	---	48	48
2.23-2.27	7,026	180,084	156,000	120	343,230	7,101	108,024	9,192	124,317	467,547
>2.27	2,400	63	---	---	2,463	72	792	---	864	3,327
Total	9,426	180,147	156,000	120	345,693	7,221	108,816	9,192	125,229	470,922

Source: Table C7-1 in Appendix C.

The low and high float voltage outliers are interesting in that all of these cells operate in installations that have not replaced any cells (see Table 4-3). This is a somewhat unexpected outcome, especially in view of the age of the installations. One might expect float voltages outside the manufacturers' recommended range to result in early failures; however, almost all were equipped with some sort of temperature control device and installed before 1997. This data does not explain why these cells performed considerably better than cells floated within the recommended range. One possible explanation for this performance is the initial degree of separator saturation in the cells. If cells were delivered with separators saturated with electrolyte, they might hold enough moisture to allow the cells to operate successfully under high float voltage and high temperature conditions for a prolonged period of time.⁸

⁸ Jones, W.E.M and D. O. Feder. 1995. Float Behavior of VRLA Cells: Theory vs Reality. Proceedings of INTELEC 95, pp. 154 – 160.

Table 4-3. Replacement Experience of LTE48V Battery Cells by Configuration and Float Voltage

Installations With	Cells in Monoblocks		Cells in Groups			Total
	2.23-2.27 vpc	>2.27 vpc	<2.23 vpc	2.23-2.27 vpc	>2.27 vpc	
No Cells Replaced	24	2,463	48	672	864	4,071
Some Cells Replaced	343,206	---	---	123,645	---	466,851
Total	343,230	2,463	48	124,317	864	470,922

Source: Tables C7-1 and C7-2 in Appendix C.

Float voltage and maximum ambient temperature conditions do not explain the lack of cell replacements or premature cell failures. Almost all of the surveyed installations with monoblock and grouped cell configurations floated their cells between 2.23 and 2.27 vpc, had temperature control devices, and experienced first cell replacements (see Table 4-4). The LTE48V battery cells in monoblocks had a very different replacement experience than the LTE48V battery cells in groups. One quarter (85,698) of the 345,693 cells in monoblocks were replaced, which is the highest replacement rate of all the surveyed cell types. This group of first cell replacements was assumed to be scheduled monoblock replacements, probably triggered by warranty conditions.

Table 4-4. Number of Surveyed LTE48V Battery Cells Replaced by Age of First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks					Cells in Groups				Total
	2.23-2.27 vpc				Subtotal	2.23-2.27 vpc			Subtotal	
	20-30°C	31-40°C	>40°C	N/A		20-30°C	31-40°C	N/A		
1-2	1,635	12	---	30	1,677	5	1	---	6	1,683
3-4	---	27,003	---	---	27,003	310	4,500	321	5,131	32,134
>4	18	18,000	39,000	---	57,018	1	---	37	38	57,056
Total	1,653	45,015	39,000	30	85,698	316	4,501	358	5,175	90,873

Source: Table C7-4 in Appendix C.

Of those presumed scheduled replacements, most were exposed to maximum ambient temperatures greater than 40°C. This suggests that the end-users were aware that these cells were in jeopardy of developing problems related to the thermal conditioning and preferred to replace them regularly to ensure reliable power.

Only 1,635 of the LTE48V battery cells in monoblocks failed within the first two years of service. What is counter-intuitive is that these cells were kept cool, with maximum ambient temperatures never exceeding 30°C. Cells in this configuration exposed to higher temperatures appear to last longer:

- Three to four years for 27,003 cells
- More than four years for 57,018 cells

LTE48V battery cells in groups, on the other hand, were primarily replaced after three years of service with maximum temperature exposures limited to 40°C. The 5,175 cells replaced represent only 4% of the total number of the 125,229 LTE48V battery cells in groups.

4.2 Spiral-Wound Cells - Float Voltage and Temperature

All spiral-wound cells were floated within the recommended range of 2.23 and 2.27 vpc (see Table 4-5). None of the 180,000 cells exposed to maximum temperatures of 31-40 °C required first cell replacements in 20 years. This is probably the result of a combination of factors, including temperature control in the cabinets, redundant cells for emergency use, and infrequent monitoring of cell health.

Only the 78,000 cells operated outdoors at maximum ambient temperatures above 40 °C required first cell replacements. Even though all spiral-wound cells were temperature-controlled (see Table 2-2), approximately 50% of the 78,000 cells operated outdoors were replaced. Most of these installations were small, typically consisting of two monoblocks. These were assumed to be scheduled replacements, probably in anticipation of potential problems due to exposure to elevated temperatures.

Table 4-5. Number of Spiral-Wound Cells Surveyed by Float Voltage, Temperature, and Replacement Experience

Age of Replacement	Cells in Monoblocks		Total
	2.23-2.27 vpc		
	31-40°C	>40°C	
>4 yrs	---	39,000	39,000
Total Not Replaced	180,000	39,000	219,000
Total	180,000	78,000	258,000

Source: Table C8-2 in Appendix C.

4.3 UPS Cells - Float Voltage and Temperature

The cells at one large surveyed UPS installation were not floated. All other surveyed UPS cells were floated between 2.23 and 2.27 vpc, and none were exposed to extreme ambient temperatures (above 40°C or below 20°C). Approximately 30% of the cells (including those not floated) did not have recorded maximum temperatures (see Table 4-6).

Table 4-6. Number of UPS Cells Surveyed by Configuration, Float Voltage, Maximum Ambient Temperature, and Replacement Experience

Installations With	Cells in Monoblock			Cells in Groups				Total
	2.23-2.27 vpc			2.23-2.27 vpc			Not Floated	
	20-30°C	31-40°C	N/A	20-30°C	31-40°C	N/A	N/A	
No Cells Replaced	---	110	---	181	1,740	60	---	2,091
Some Cells Replaced	180	120	2,160	4,068	1,680	120	1,134	9,462
Total	180	230	2,160	4,249	3,420	180	1,134	11,553

Source: Tables C9-1 and C9-2 in Appendix C.

An interesting outcome is that half of the UPS cells operated at maximum ambient temperatures of 31-40°C did not require cell replacements. This finding is surprising, as it is true for cells in both monoblock and grouped configurations, and most of the cells that were not replaced were installed before 1993.

As with LTE48V batteries, it appears that colder maximum ambient temperatures may have increased the likelihood of failure (see Table 4-7). The most cell replacements (81) occurred in UPS grouped cell installations with maximum ambient temperatures between 20 and 30°C. However, most cells requiring replacement in UPS monoblock configurations occurred at installations where the end-user did not know the temperature, suggesting that the end-user was not proactive in preventing potential thermal issues from occurring. As most of the surveyed UPS cells were located in indoor installations, it is difficult to determine whether a trend exists between cell failure and cell housing.

Table 4-7. Number of Surveyed UPS Cells Replaced by Age of First Cell Replacement, Configuration, Float Voltage and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks				Cells in Groups					Total Replaced
	2.23-2.27 vpc			Subtotal	2.23-2.27 vpc			Not Floated	Subtotal	
	20-30°C	31-40°C	N/A		20-30°C	31-40°C	N/A	N/A		
<1	---	---	---	0	---	---	---	23	23	23
1-2	---	4	---	4	---	---	2	---	2	6
3-4	---	---	36	36	51	34	---	---	85	121
>4yrs	6	---	---	6	30	---	---	---	30	36
Total Replaced	6	4	36	46	81	34	2	23	140	186

Source: Table C9-4 in Appendix C.

4.4 PV Cells - Float Voltage and Temperature

Cells at surveyed PV installations were mostly floated above 2.27 vpc (see Table 4-8). This is probably an equalization charge parameter since PV batteries are more often cycled than floated. All the cells floated below 2.27 vpc performed well, even 24 cells that were not temperature-controlled.

Table 4-8. Number of PV Cells Surveyed by Float Voltage, Maximum Ambient Temperature and Replacement Experience

Installations With	<2.23 vpc	2.23-2.27 vpc	>2.27 vpc			Total
	20-30°C	20-30°C	<20°C	20-30°C	31-40°C	
No Cells Replaced	6	24	24	198	---	252
Some Cells Replaced	---	---	---	780	1,080	1,860
Total	6	24	24	978	1,080	2,112

Source: Tables C10-1 and C10-2 in Appendix C.

Installations with 780 cells operating at maximum temperatures of 20-30°C and installations with 1,080 cells operating at 31-40°C required first cell replacements. These were all located in indoor, controlled environments. The first cells replaced were three in the first year and four after the first year (see Table 4-9). It is assumed that more cells subsequently were replaced, but the survey did not address the number of cells replaced the second or third time.

Table 4-9. Number of Surveyed PV Cells by Age of First Cell Replacement, Configuration, Float Voltage and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Groups		Total
	>2.27 vpc		
	20-30°C	31-40°C	
<1	3	---	3
1-2	1	3	4
Total Replaced	4	3	7

Source: Table C10-4 in Appendix C.

4.5 Float Voltage and Temperature in Summary

No strong trends were found in the analysis of the survey data. However, cooler temperatures seemed to correlate with early replacements. In addition, temperature compensation was not used in most installations.

5. Findings

Analysis of the performance of the cells in all the different sets of circumstances reviewed during the survey leads to some tentative conclusions about the way VRLA technology must be deployed in order to ensure good performance. Some factors, which were expected to exert an important influence, did not show up strongly. Others, which perhaps had not been expected to feature, did emerge as significant.

The main findings drawn from this project are as follows:

- A significant number of the VRLA cells covered by the surveys proved to be reliable;
 - 42% of all the cells surveyed had operated for five or more years before being scheduled for “first cell replacements” (see Section 3.8).
 - 25% of all the cells surveyed had never been replaced (see Section 3.3).
 - About 33% of all the cells surveyed were replaced within four years of installation (see Section 3.8, Table 3-2).
 - There is a large spread in the range of life expectancy for utility VRLA cells: from five to twenty years. (see Section 3.1).
- Spiral-wound cells appear to have provided a long life (in telecommunications applications) even under adverse temperature conditions (see Section 4.2). A caution on this observation is that, although it is based on a large number of cells, the information all comes from two respondents.
- Analysis of the influence of float voltage did not reveal a clear correlation with cell failure. Indeed, for cells in LTE48V batteries, the only cell failures were those within the voltage window of 2.23 to 2.27 volts (see Section 4.1, Table 4-3).
- Neither was any strong correlation found between high maximum temperature and particularly short life. In the case of cells in LTE48V monoblocks, there was a group of early failures for units experiencing a maximum temperature of only 20 - 30°C, while for the majority of units that experienced a maximum temperature above 30°C, a longer life was achieved (see Section 4-1, Table 4-3). Thus, there is some indication that VRLA cells on float operate better at temperatures above 30°C than at temperatures below 30°C.
- In UPS applications, temperature control appears to be effective in reducing early cell failures for monoblock installations but not for grouped cells (see Section 4.3).

The findings derived from this study have not identified any fundamental flaws in VRLA battery technology. Rather, the results of this survey suggest that the basic technology can perform well in many applications. When early failures have occurred, some end-users contributing to the survey were able to determine the cause of failure. In other cases of early failure, the technical community (not part of this survey) has identified design or production issues and corrections have been made that are resulting in improvements to VRLA products.

Appendix A. VRLA Manufacturer Survey

The manufacturer survey effort was initiated in 1998 but encountered problems with low response rate and incomplete surveys. The 1998 survey effort obtained 16 surveys from six different VRLA manufacturers.

When contacting each of the manufacturers, the identities of the sponsors - Advanced Lead Acid Battery Consortium (ALABC), International Lead Zinc Research Organization (ILZRO), and Sandia National Laboratories (SNL) - were immediately disclosed. All the manufacturers surveyed were members of ALABC. They agreed to share business-sensitive information as long as a standard non-disclosure agreement was signed. To further protect the identity of all VRLA manufacturers, all data is stored in a secure, limited-access database.

None of the manufacturers participating in the 1998 survey effort provided information on all of the cells identified by the end users. As a result, the survey was revised (see next page) and the analysts initiated a thorough Internet search and phone survey in 2000. Manufacturer specifications sheets on each cell model were readily available on the Internet. These sheets provided data on:

- Cell dimensions
- Weight
- Electrolyte
- Number of plates
- Recommended float voltage
- Current ratings
- Charging temperature

The phone and Internet surveys succeeded in obtaining information on 79 different cells from eight manufacturers that were identified by the end-user survey participants. Information for 58 of the cells came from the Internet, manufacturers completed 17 surveys, and information on two cells was obtained from both the Internet and personal contacts.

Stationary Valve-Regulated Lead-Acid Battery Manufacturer Survey

Manufacturer Identification	
Company: _____.	
Respondent Name: _____.	
Phone Number: _____.	
Email: _____.	
Survey Date: _____	Interviewer _____.

Physical Characteristics
Cell's exterior dimensions (cm) Length _____ Width _____ Height _____.
Electrolyte contained by ____ Absorbed glass mat ____ Thixotropic gel
Separator material and thickness (mm) ____. ____ Polyvinylchloride ____ Polyethylene ____ Porous rubber
Specific gravity of electrolyte in new cell _____.
Cell case material and thickness (mm) ____. ____ Polyvinylchloride ____ Polypropylene Polycarbonate
Process used to seal the case ____ Ultrasonic weld ____ Asphalt ____ Hot plate ____ Bead mash heat ____ Epoxy ____ Other
Post-to-case seal made by ____ Weld ____ Epoxy ____ Other _____.
Allowable valve opening/reseal points (psi) Open _____ Seal _____.
Plate geometry (flat, tubular, other) Positive plate _____ Negative plate _____.
Designed cell orientation ____ Plates horizontal ____ Plate vertical ____ Either/both
Nominal stack compression (psi) _____.
Case ribbed for thermal efficiency? ____ Yes ____ No
Recommended operating temperature (°F) Minimum _____ Maximum _____.
Air conditioning/fans required? ____ Yes ____ No

Market and Sales
VRLA cell types you manufacture? _____.
Cell make/model addressed in this survey _____.
Where do you manufacture this product? ____ North America ____ South America ____ Asia ____ Western Europe ____ Eastern Europe
these cells sold each year: _____ as individual cells _____ in modules
these cells sold each year by application: ____ Telecom ____ Utility substation ____ Industrial UPS ____ Motive power

Electrical Characteristics
Cell capacity (Ah) _____.
Cell's internal resistance (mΩ) _____.
Cell's monthly self-discharge (%) _____.
Cell's specific energy at rates (Wh/kg) C/20 _____ C/8 _____ C/2 _____.

Performance Characteristics
Designed for which application? ____ Float ____ Deep cycle ____ Shallow cycle
Cell's recommended float voltage _____.
Float service warranty (years) _____.
Expected early failures each year (under full warranty): # cells _____ % cells sold _____.
Prevalent cause of premature cell failures Float _____. Deep Cycle _____. Shallow Cycle _____.

Identify elements in:	Positive plate	Negative plate
Plate grid alloys (antimony, tin, calcium, other)		
Grid pastes (antimony, tin, calcium, other)		
Post alloys (lead, copper, cadmium, antimony, silver, other)		

VRLA Battery Manufacturer Survey conducted by Energetics on behalf of
Advanced Lead-Acid Battery Consortium, International Lead Zinc Research Organization,
and Sandia National Laboratories

Return to Energetics, Inc., 501 School St. SW, suite 500, Washington, DC 20024, 202-479-2748, fax 202-479-0229
Email to Jennifer Dunleavy at jdunleavy@energeticsinc.com

revised 5/1/00

Appendix B. End-User Survey

At the onset, it was assumed that manufacturers would willingly share the names of their customers, particularly those with the best performance history. However, only one provided this information. As a result, lists of potential end-users of VRLA batteries for stationary applications were compiled from various technical papers, trade conferences, organizations, and word-of-mouth.

The initial survey of end-users in 1998 was hindered by a process that required too much effort on the part of the respondents: a mailed survey with three pages of questions that assumed data could be provided on each VRLA installation owned or operated by the end user. This was addressed with a significant revision of the survey, condensing it to one page that was compatible with email or fax transmission to potential end-users. In addition, the structure of the questionnaire permitted respondents to provide data on multiple groups of like installations on a single survey form (see next page). This enhancement increased the response rate.

In early 2000, an intensive phone survey was undertaken over a three-month period. Four attempts were made to contact each potential end-user. These attempts included making direct contact, leaving a voice message, or emailing. Of the 350 potential end users, 242 were successfully contacted. There were 78 users of VRLA batteries for stationary applications identified. Fifteen were from the telecommunications industry, 42 from the utility industry, and the remaining 21 were from other various industries.

The identities of the sponsors were immediately disclosed to every end-user, however, most were unfamiliar with these organizations. Forty-three end-users agreed to participate in the study, and 28 successfully completed the survey. Two of the contacts were unable to participate due to company policy and 16 were unresponsive after receiving the survey. Most participants were willing to share business-sensitive information and only one end-user required signing a non-disclosure agreement. To further protect the identity of the end-users, all responses were stored in a secure, limited-access database.

Not all of the end-user participants were able to identify the exact VRLA cell model number used in each installation. As a result, the appropriate model numbers were determined through a detailed analysis of the installation size (Ah or kWh), the total number of cells, modules, and strings at the installation, and the manufacturer cell data. This analysis impacted 29% of the installations and 44% of the total cells represented in the survey.

The participants answered most questions. This survey does not claim that all questions were answered with complete accuracy, as many responses drew on the participants' recall over the past ten years, which is far from an exact science. Table B-1 provides a comparison of the percentage of cells by application (LTE48V, spiral-wound, UPS, and PV) for which responses were provided.

Stationary Valve-Regulated Lead-Acid Battery End-User Survey

User Identification	Battery Identification
Company/Organization: _____ Respondent Name: _____ Phone Number: _____ Survey Date: _____ Interviewer _____ Willing to share data or be visited? _____ # stationary battery installations represented by this response? _____	Who sold and installed the batteries? _____ VRLA Manufacturer _____ Original Equipment Manufacturer _____ Vendor/distributor _____ Other Did you receive installation and operating specifications? Yes _____ No _____ Have you had any unusual failures? _____ How many? _____ _____ VRLA Manufacturer _____ In-house _____ Vendor/distributor _____ Consultant What were the root causes of failure?
Application(s): _____ Utility (U) _____ Emergency Back-up (B) _____ Telecom (T) _____ UPS _____ Industry (I) _____ Peak-shaving (PS) _____ Remote PV/wind (PV) _____ Frequency/voltage reg (F)	

Battery Installation Description(s) Use columns to describe installations of similar type			
Installation application(s)			
Make/model of VRLA cells			
Installation size (kWh, amp)			
# modules/# cells			
No. of similar installations			
Year installed or age (yrs)			
Warranted Life (yrs)			
Geographic location (state)			
Indoor/outdoor installation			
Air conditioning or fans?			
Battery room temp.			
Min/Max/Avg. (°C or °F)			
% year at maximum temp.			

Battery Operation/Monitoring Continue description of similar installations type in columns below			
Spec. float voltage (Volt/cell)			
Spec. current during float (amp)			
# Cycles/year average			
Are cycle intervals regular?			
If yes, interval length (time)?			
If no, random or clustered?			
Year first cell replaced?			
# cells replaced to date?			
Keep log in print or electronic?			
Parameters monitored?			
Temp, volts, amps, other ¹ ?			
Cell, module, string?			
Weekly, monthly, other?			

¹ Internal ohmic measurements, e.g., conductance, resistance, or impedance

VRLA Battery End-User Survey conducted by Energetics on behalf of
 Advanced Lead-Acid Battery Consortium, International Lead Zinc Research Organization,
 and Sandia National Laboratories

Return to Energetics, Inc., 501 School St. SW, suite 500, Washington, DC 20024, 202-479-2748, fax 202-479-0229
 Email to Jennifer Dunleavy at jdunleavy@energeticsinc.com

Table B-1. Response Rates by Question

End-User Survey Question	Response Rate
Maximum temperature	98.3%
Minimum temperature	98.3%
Average temperature	45.7%
Percent of year at maximum temperature	43.1%
Year installed	100.0%
Year first cell replaced	74.9%
Geographic location by region	100.0%
Geographic location by state	2.8%
Temperature control	100.0%
Specified float voltage	99.8%
Specified float current	42.3%
Supplier known (manufacturer, distributor, etc.)	58.3%
Installer known	58.3%

The response rate was calculated as a percentage of the total cells for which each question was answered.

Appendix C. Data Tables

Table C1. VRLA Battery Annual Sales in U.S., 1993 – 2000 (Million Dollars)

Application	1993	1994	1995	1996	1997	1998	1999	2000	Total
Telecom	77	114	143	152	194	204	242	373	1,499
UPS	46	52	70	62	68	73	101	122	595
Other/PV	34	35	33	29	34	39	41	39	282
Total	157	200	245	243	296	317	384	534	2,376

Source: Battery Council International

Table C2-1. Number of Surveyed Cells by Warranty and Configuration

Warranted Life (years)	LTE48V		Spiral-Wound	UPS		PV	Total
	Cells in Groups	Cells in Monoblocks	Cells in Monoblocks	Cells in Groups	Cells in Monoblocks	Cells in Groups	
5	5,328	158,490	78,000	---	---	2,064	243,882
7-8	---	72,000	180,000	1,134	---	---	253,134
10	109,080	108,612	---	---	2,160	---	219,852
12-15	24	---	---	185	---	---	209
20	10,281	6,591	---	7,664	410	48	24,994
NA	516	---	---	---	---	---	516
Total	125,229	345,693	258,000	8,983	2,570	2,112	742,587

Table C2-2. Percent of Surveyed Cells by Warranty and Configuration

Warranted Life (years)	LTE48V		Spiral-Wound	UPS		PV	Total
	Cells in Groups	Cells in Monoblocks	Cells in Monoblocks	Cells in Groups	Cells in Monoblocks	Cells in Groups	
5	4.3	45.8	30.2	---	---	97.7	32.8
7-8	---	20.8	69.8	12.6	---	---	34.1
10	87.1	31.4	---	---	84.0	---	29.6
12-15	0.0	---	---	2.1	---	---	0.0
20	8.2	1.9	---	85.3	16.0	---	3.4
NA	0.4	--	0.0	---	---	---	0.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table C3-1. Total Number of Surveyed LTE48V Battery Cells by Year Installed and Configuration

Year Installed	Cells in Monoblocks	Cells in Groups	Total
1980-1985	6,000	180	6,180
1986-1989	228,000	48	228,048
1990-1993	110,964	110,758	221,722
1994-1996	234	13,163	13,397
1997-2001	495	1,080	1,575
Total	345,693	125,229	470,922

Table C3-2. Surveyed Installations with LTE48V Battery Cells Not Yet Experiencing Any Cell Replacements by Year Installed and Configuration

Year Installed	Number of Cells Not Replaced ⁹			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1980-1985	---	180	180	---	100.0	2.9
1986-1989	---	24	24	---	50.0	0.0
1990-1993	2,400	72	2,472	2.2	0.1	1.1
1994-1996	24	780	804	10.3	5.9	6.0
1997-2001	63	528	591	12.7	48.9	37.5
Total	2,487	1,584	4,071	0.7	1.3	0.9

Table C3-3. Age of Surveyed LTE48V Battery Cells at First Cell Replacement by Year Installed and Configuration

Year Installed	Cells in Monoblocks				Cells in Groups				Total
	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	
1980-1985	1,500	---	---	1,500	---	---	---	0	1,500
1986-1989	---	---	57,000	57,000	---	---	1	1	57,001
1990-1993	75	27,003	---	27,078	---	4,575	37	4,612	31,690
1994-1996	30	---	18	48	6	510	---	516	564
1997-2001	72	---	---	72	---	46	---	46	118
Total	1,677	27,003	57,018	85,698	6	5,131	38	5,175	90,873

Table C3-4. Surveyed LTE48V Battery Cells Replaced by Year Installed and Configuration

Year Installed	Number of Cells Replaced ⁹			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1980-1985	1,500	---	1,500	25.0	---	24.3
1986-1989	57,000	1	57,001	25.0	2.1	25.0
1990-1993	27,078	4,612	31,690	24.4	4.2	14.3
1994-1996	48	516	564	20.5	3.9	4.2
1997-2001	72	46	118	14.5	4.3	7.5
Total	85,698	5,175	90,873	24.8	4.1	19.3

⁹ Please note that the number of cells in these tables does not include un-replaced cells in installations that have experienced first cell replacement; therefore, entries in Tables C3-2 and C3-4 cannot be added to equal the total number of cells identified in Table C3-1.

Table C4-1. Total Number of Surveyed Spiral-Wound Cells by Year Installed and Configuration

Year Installed	Cells in Monoblocks	Cells in Groups	Total
1980-1985	180,000	---	180,000
1986-1989	78,000	---	78,000
Total	258,000	0	258,000

Table C4-2. Surveyed Installations with Spiral-Wound Cells Not Yet Experiencing Any Cell Replacements by Year Installed and Configuration

Year Installed	Number of Cells Not Replaced ¹⁰		Percentage of Total Cells	
	Cells in Monoblocks	Cells in Groups	Cells in Monoblocks	Cells in Groups
1980-1985	180,000	---	100.0	---
1986-1989	---	---	---	---
Total	180,000	0	70.0	0.0

Table C4-3. Age of Surveyed Spiral-Wound Cells at First Cell Replacement by Year Installed and Configuration

Year Installed	Cells in Monoblocks					Cells in Groups					Total
	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	
1980-1985	---	---	---	---	0	---	---	---	---	0	0
1986-1989	---	---	---	39,000	39,000	---	---	---	---	0	39,000
Total	0	0	0	39,000	39,000	0	0	0	0	0	39,000

Table C4-4. Surveyed Spiral-Wound Cells Replaced by Year Installed and Configuration

Year Installed	Number of Cells Replaced ¹⁰			Percentage of Total Cells		
	Cells In Monoblocks	Cells in Groups	Total	Cells In Monoblocks	Cells in Groups	Total
1980-1985	---	---	0	---	---	0.0
1986-1989	39,000	---	39,000	50.0	---	50.0
Total	39,000	0	39,000	15.0	0.0	15.0

¹⁰ Please note that the number of cells in these tables does not include un-replaced cells in installations that have experienced first cell replacement; therefore, entries in Tables C4-2 and C4-4 cannot be added to equal the total number of cells identified in Table C4-1.

Table C5-1. Total Number of Surveyed UPS Cells by Year Installed and Configuration

Year Installed	Cells in Monoblocks	Cells in Groups	Total
1980-1985	---	60	60
1986-1989	---	120	120
1990-1993	180	4,319	4,499
1994-1996	2,270	2,514	4,784
1997-2001	120	1,970	2,090
Total	2,570	8,983	11,553

Table C5-2. Surveyed Installations with UPS Cells Not Yet Experiencing Any Cell Replacements by Year Installed and Configuration

Year Installed	Number of Cells Not Replaced ¹¹			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1980-1985	---	60	60	---	100.0	100.0
1986-1989	---	---	---	---	---	0.0
1990-1993	---	845	845	---	19.6	18.8
1994-1996	110	240	350	4.8	9.5	7.3
1997-2001	---	836	836	0.0	42.4	40.0
Total	110	1,981	2,091	4.3	22.1	18.1

Table C5-3. Age of Surveyed UPS Cells at First Cell Replacement by Year Installed and Configuration

Year Installed	Cells in Monoblocks					Cells in Groups					Total
	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	
1980-1985	---	---	---	---	0	---	---	---	---	0	0
1986-1989	---	---	---	---	0	---	2	---	---	2	2
1990-1993	---	---	---	6	6	---	---	39	30	69	75
1994-1996	---	---	36	---	36	---	---	45	---	45	81
1997-2001	---	4	---	---	4	23	---	---	---	23	27
Total	---	4	36	6	46	23	2	85	30	140	186

Table C5-4. Surveyed UPS Cells Replaced by Year Installed and Configuration

Year Installed	Number of Cells Replaced ¹¹			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1980-1985	---	---	0	---	0.0	0.0
1986-1989	---	2	2	---	2.0	2.0
1990-1993	6	69	75	3.3	1.6	1.7
1994-1996	36	45	81	1.6	1.8	1.7
1997-2001	4	23	27	3.3	1.2	1.3
Total	46	140	186	1.8	1.6	1.6

¹¹ Please note that the number of cells in these tables does not include un-replaced cells in installations that have experienced first cell replacement; therefore, entries in Tables C5-2 and C5-4 cannot be added to equal the total number of cells identified in Table C5-1.

Table C6-1. Total Number of Surveyed PV Cells by Year Installed and Configuration

Year Installed	Cells in Monoblocks	Cells in Groups	Total
1994-1996	---	1,524	1,524
1997-2001	---	588	588
Total	0	2,112	2,112

Table C6-2. Surveyed Installations with PV Cells Not Yet Experiencing Any Cell Replacements by Year Installed and Configuration

Year Installed	Number of Cells Not Replaced ¹²			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1994-1996	---	108	108	---	7.1	7.1
1997-2001	---	144	144	---	24.5	24.5
Total	0	252	252	0	11.9	11.9

Table C6-3. Age of Surveyed PV Cells at First Cell Replacement by Year Installed and Configuration

Year Installed	Cells in Monoblocks					Cells in Groups					Total
	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	<1 yr	1-2 yrs	3-4 yrs	>4 yrs	Subtotal	
1994-1996	---	---	---	---	0	---	3	---	---	3	3
1997-2001	---	---	---	---	0	3	1	---	---	4	4
Total	0	0	0	0	0	3	4	0	0	7	7

Table C6-4. Surveyed PV Cells Replaced by Year Installed and Configuration

Year Installed	Number of Cells Replaced ¹²			Percentage of Total Cells		
	Cells in Monoblocks	Cells in Groups	Total	Cells in Monoblocks	Cells in Groups	Total
1994-1996	---	3	3	---	0.2	0.2
1997-2001	---	4	4	---	0.7	0.7
Total	0	7	7	0.0	0.3	0.3

¹² Please note that the number of cells in these tables does not include un-replaced cells in installations that have experienced first cell replacement; therefore, entries in Tables C6-2 and C6-4 cannot be added to equal the total number of cells identified in Table C6-1.

Table C7-1. Total Number of Surveyed LTE48V Battery Cells by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks					Cells in Groups				Total
	20-30°C	31-40°C	>40°C	N/A	Subtotal	20-30°C	31-40°C	N/A	Subtotal	
<2.23	---	---	---	---	0	48	---	---	48	48
2.23-2.27	7,026	180,084	156,000	120	343,230	7,101	108,024	9,192	124,317	467,547
>2.27	2,400	63	---	---	2,463	72	792	---	864	3,327
Total	9,426	180,147	156,000	120	345,693	7,221	108,816	9,192	125,229	470,922

Table C7-2. Number of LTE48V Battery Cells in Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks			Cells in Groups				Total
	20-30°C	31-40°C	Subtotal	20-30°C	31-40°C	N/A	Subtotal	
<2.23	---	---	0	48	---	---	48	48
2.23-2.27	---	24	24	72	---	600	672	696
>2.27	2,400	63	2,463	72	792	---	864	3,327
Total	2,400	87	2,487	192	792	600	1,584	4,071

Table C7-3. Percentage of LTE48V Battery Cells in Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks			Cells in Groups				Total
	20-30°C	31-40°C	Subtotal	20-30°C	31-40°C	N/A	Subtotal	
<2.23	---	---	0	100.0	---	---	100.0	100.0
2.23-2.27	---	0.0	0.0	1.0	---	6.5	0.5	0.1
>2.27	100.0	100.0	100.0	100.0	100.0	---	100.0	100.0
Total	25.5	0.0	0.7	2.7	0.7	6.5	1.3	0.9

Table C7-4. Number of Surveyed LTE48V Battery Cells Replaced by Age of First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks					Cells in Groups				Total
	2.23-2.27 vpc				Subtotal	2.23-2.27 vpc			Subtotal	
	20-30°C	31-40°C	>40°C	N/A		20-30°C	31-40°C	N/A		
1-2	1,635	12	---	30	1,677	5	1	---	6	1,683
3-4	---	27,003	---	---	27,003	310	4,500	321	5,131	32,134
>4	18	18,000	39,000	---	57,018	1	---	37	38	57,056
Total	1,653	45,015	39,000	30	85,698	316	4,501	358	5,175	90,873

Table C7-5. Percentage of Surveyed LTE48V Battery Cells Replaced by Age of First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks					Cells in Groups				Total
	2.23-2.27 vpc				Subtotal	2.23-2.27 vpc			Subtotal	
	20-30°C	31-40°C	>40°C	N/A		20-30°C	31-40°C	N/A		
1-2	23.3	0.0	---	25.0	0.5	0.1	0.0	---	0.0	0.4
3-4	---	15.0	---	---	7.9	4.4	4.2	3.5	4.1	6.8
>4	0.3	10.0	25.0	---	16.6	0.0	---	0.4	0.0	12.1
Total	23.5	25.0	25.0	25.0	25.0	4.5	4.2	3.9	4.1	19.3

Table C8-1. Total Number of Surveyed Spiral-Wound Cells by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks		Total
	31-40°C	>40°C	
2.23-2.27	180,000	78,000	258,000
Total	180,000	78,000	258,000

Table C8-2. Number of Surveyed Spiral-Wound Cells by Replacement Experience, Configuration, Float Voltage, and Maximum Ambient Temperature

Age of Installation	Cells in Monoblocks		Total
	2.23-2.27 vpc		
	31-40°C	>40°C	
>4 yrs	---	39,000	39,000
Total Not Replaced	180,000	39,000	219,000
Total	180,000	78,000	258,000

Table C8-3. Percentage of Surveyed Spiral-Wound Cells by Replacement Experience, Configuration, Float Voltage, and Maximum Ambient Temperature

Age of Installation	Cells in Monoblocks		Total
	2.23-2.27 vpc		
	31-40°C	>40°C	
>4 yrs	---	50.0	15.0
Total Not Replaced	100.0	50.0	85.0
Total	100.0	100.0	100.0

Table C9-1. Total Number of UPS Cells Surveyed by Configuration, Float Voltage, Maximum Ambient Temperature

Float Voltage	Cells In Monoblocks				Cells in Groups				Total
	20-30°C	31-40°C	N/A	Subtotal	20-30°C	31-40°C	N/A	Subtotal	
2.23-2.27	180	230	2,160	2,570	4,249	3,420	180	7,849	10,419
Not Floated	---	---	---	---	---	---	1,134	1,134	1,134
Total	180	230	2,160	2,570	4,249	3,420	1,314	8,983	11,553

Table C9-2. Number of UPS Cells at Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks	Cells in Groups				Total
	31-40°C	20-30°C	31-40°C	N/A	Subtotal	
2.23-2.27	110	181	1,740	60	1,981	2,091
Not Floated	---	---	---	---	---	0
Total	110	181	1,740	60	1,981	2,091

Table C9-3. Percentage of UPS Cells at Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Monoblocks				Cells in Groups				Total
	20-30 °C	31-40°C	N/A	Subtotal	20-30 °C	31-40°C	N/A	Subtotal	
2.23-2.27	---	47.8	---	4.3	4.3	50.9	4.6	22.1	18.1
Not Floated	---	---	---	0.0	---	---	---	0.0	0.0
Total	0.0	47.8	0.0	4.3	4.3	50.9	4.6	22.1	18.1

Table C9-4. Number of Surveyed Cells Replaced in UPS Installations by Age of First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks				Cells in Groups				Total
	2.23-2.27 vpc			Subtotal	2.23-2.27 vpc			Not Floated	
	20-30°C	31-40°C	N/A		20-30°C	31-40°C	N/A	N/A	
<1	---	---	---	0	---	---	---	23	23
1-2	---	4	---	4	---	---	2	---	2
3-4	---	---	36	36	51	34	---	---	85
>4	6	---	---	6	30	---	---	---	30
Total	6	4	36	46	81	34	2	23	140

Table C9-5. Percentage of Surveyed UPS Cells Replaced by Age of First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Monoblocks				Cells in Groups				Total
	2.23-2.27 vpc			Subtotal	2.23-2.27 vpc			Not Floated	
	20-30°C	31-40°C	N/A		20-30°C	31-40°C	N/A	N/A	
<1	---	---	---	0.0	---	---	---	2.0	0.3
1-2	---	1.7	---	0.2	---	---	1.3	---	0.1
3-4	---	---	1.7	1.4	1.2	1.0	---	---	0.9
>4	3.3	---	---	0.2	0.7	---	---	---	0.3
Total	3.3	1.7	1.7	1.8	1.9	1.0	1.3	2.0	1.6

Table C10-1. Total Number of Surveyed PV Cells by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Groups			Total
	<20°C	20-30°C	31-40°C	
<2.23	---	6	---	6
2.23-2.27	---	24	---	24
>2.27	24	978	1,080	2,082
Total	24	1,008	1,080	2,112

Table C10-2. Number of PV Cells at Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Groups			Total
	<20°C	20-30°C	31-40°C	
<2.23	---	6	---	6
2.23-2.27	---	24	---	24
>2.27	24	198	---	222
Total	24	228	0	252

Table C10-3. Percentage of PV Cells at Surveyed Installations Experiencing No Cell Replacements by Configuration, Float Voltage, and Maximum Ambient Temperature

Float Voltage	Cells in Groups			Total
	<20°C	20-30°C	31-40°C	
<2.23	---	100.0	---	100.0
2.23-2.27	---	100.0	---	100.0
>2.27	100.0	20.2	---	10.7
Total	100.0	22.6	0.0	11.9

Table C10-4. Number of Surveyed PV Cells Replaced by Age at First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Groups					Total
	<2.23 vpc	2.23-2.27 vpc	>2.27 vpc			
	20-30°C	20-30°C	<20°C	20-30°C	31-40°C	
<1	---	---	---	3	---	3
1-2	---	---	---	1	3	4
Total	0	0	0	4	3	7

Table C10-5. Percentage of Surveyed PV Cells Replaced by Age at First Cell Replacement, Configuration, Float Voltage, and Maximum Ambient Temperature

Age at First Cell Replacement (years)	Cells in Groups					Total
	<2.23 vpc	2.23-2.27 vpc	>2.27 vpc			
	20-30°C	20-30°C	<20°C	20-30°C	31-40°C	
<1	---	---	---	0.3	---	0.1
1-2	---	---	---	0.1	0.3	0.2
Total	0.0	0.0	0.0	0.4	0.3	0.3

Appendix D. Calculation of Survey Sample Significance

At workshops and conferences, the authors faced questions regarding the significance of the survey sample relative to the total number of VRLA cells operating in the U.S. There is no sanctioned source for the physical quantity of batteries in operation in stationary applications, in terms of cells, amp-hours (Ah) or kilowatt hours (kWh). As a result, the authors first had to estimate the total number of cells operating in the U.S., and then compare that total to the 742,857 cells identified in the survey.

Battery Council International (BCI) provides data on the dollar value of annual battery sales to its members. BCI generously shared its data on annual sales from 1993 to 2000. The sales were summed to obtain an estimate of the total dollar value of VRLA cells in operation in the U.S.

BCI collects data on battery sales for communications, UPS, switchgear, and other applications. Communications sales could not be disaggregated into spiral-wound and LTE48V battery sales, which is how the analysis of the survey is structured. Likewise, BCI disaggregates large utility use by switchgear and UPS, whereas the survey handles them jointly. As a result, there are three categories for analysis: communications, UPS/switchgear, and PV/other.

The cell count is calculated from the dollar value of 1993-2000 sales (\$ sales) as follows:

$$(\$ \text{ sales})/[(\$/\text{kWh}) * (\text{voltage}) * (\text{Ah}/\text{cell})] = \# \text{ cells}$$

Where dollar per kWh is a factor provided by BCI and Sandia

- \$200 for UPS and switchgear applications
- \$150 for communications and other applications

Voltage of typical installations

- 48 V for communications and PV/other
- 125 V for UPS and switchgear

Ah/cell estimates were derived for typical installations from the survey

- 3.36 for UPS/switchgear
- 5.02 for communications
- 10 for PV/other

Ah/cell estimates are not on a per-cell basis, as cells are connected in different series and parallel strings to maximize voltage or amps, depending on site requirements. Assuming that the installations participating in the survey are typical of those throughout the U.S., the average Ah per cell was calculated for each group of survey respondents. This average Ah/cell for surveyed installations is far less than the Ah value of individual cells.

The three resulting equations are:

$$\text{Communications: } [1,499/(150*48*5.02)] = 41.5 \text{ million cells}$$

UPS/switchgear: $[646/(200*125*3.36)] = 7.7$ million cells

PV/other: $[231/(150*48*10)] = 3.2$ million cells

The results and relative significance of the survey sample are presented in Table D1.

Table D1. Survey and Estimated US Total VRLA Cells

Application	Million Cells		Survey % of Total
	US Total	Survey	
Communications	41.48	0.729	1.8%
UPS/switchgear	7.68	0.012	0.2%
PV/other	3.21	0.002	0.1%
Total	52.38	0.743	1.4%

Appendix E. Cell Health

Back-up power for stationary applications is needed when outages occur to provide a continuous supply of power. Each end-user wants to know that his/her backup power system will be able to perform when called upon. Failure to perform such duties may result in loss of profits for the company or worse.

VRLA batteries historically have been known as “maintenance-free batteries,” as they were originally marketed in this fashion to appeal to those end-users who had power sources in remote locations that required back-up power. Because of the remoteness of the locations, it was expensive to maintain flooded lead-acid batteries. These end-users saw the advantage of installing VRLA cells at those locations in order to reduce maintenance labor costs.

The “maintenance-free” misperception still exists today, as many of the participating end-users mentioned that their cells “certainly weren’t maintenance-free.” It is imperative that the “maintenance-free” concept be clarified. VRLA end-users most likely used flooded lead-acid batteries in the past. Flooded batteries require the addition of purified water at regular intervals. VRLA cells don’t require this periodic action as they have an internal oxygen recombination cycle that reduces the amount of water vented into the atmosphere. As D. Berndt’s book¹³, Maintenance Free Batteries, mentions:

“maintenance-free” should not mislead the user to abandon all kinds of supervision. To ensure its proper function, the maintenance-free battery has to be observed and checked regularly, unless it is monitored automatically.

The state of charge (the ratio of total capacity that can be drawn from a battery at a given time, to that battery’s rated capacity) and the state of health, which describes its aging, cannot be measured directly. The influence of the aging processes on available capacity is complex and depends not only on battery design but also on operating conditions (refer to D. Berndt’s book).

To ensure reliable service, some VRLA end-users incorporate a monitoring regime or provide continual battery supervision that observes battery operating parameters and the environment. When this is done consistently, the likelihood of predicting cell failure in time to avoid loss of service is increased.

The best way to determine the health of the VRLA battery is to perform a discharge test. However, these tests are not ideal as they:

- cause accelerated aging of the battery,
- are time consuming,
- require taking the battery off-line, rendering it unavailable should a duty cycle be required,
- are expensive.

¹³ D. Berndt, *Maintenance-Free Batteries*, Taunton, UK: Research Studies Press Ltd., 1993.

E.1 Monitoring Parameters

Many end-users are monitoring battery health in terms of temperature, voltage, current, charge, and internal ohmic measurements (see Table E-1).

Table E-1. Some Common Battery Monitoring Parameters

Monitored Parameter	Technical Value
Battery Temperature	Can signal thermal stress problem
String Voltage	May indicate rectifier problem
Cell Voltage	May identify weak cells
Float Current	Indicates high resistance battery/current path
Battery Conductance	Passively identifies weak cells/batteries

Adapted from Cox, D. C. and R. Perez-Kite, "Battery State of Health Monitoring, Combining Conductance Technology with Other Measured Parameters for Real-Time Battery Performance Analysis," Proceedings of 22nd Inteltec, 2000, Section 19-2.

Temperature plays a huge role in the success or failure of VRLA cells. Prolonged exposure to high temperature is a key contributor to a failure mechanism known as thermal runaway. Thermal runaway is the condition characterized by the rate of heat generation within the battery exceeding the capability of the battery (and its operating environment) to dissipate the heat, leading to catastrophic heat build-up in the battery. Partly for this reason, the recommended operating temperature of all VRLA cells is 25°C (or 77°F). Also, water loss from the battery increases with higher temperature, and water loss will lead to permanent loss of performance. Temperature can be measured at many different locations:

- ambient room temperature
- cell temperature at the post terminal
- internal temperature of a cell

Internal cell temperature provides the best information, but it is expensive to measure because temperature probes must be installed inside cells during construction, and maintenance personnel must take those readings. Most survey respondents monitored ambient temperature only.

VRLA batteries often are closely packed in module racks or designed as monoblocks, making the measurement of individual cell voltages difficult. In addition, the spread of individual cell voltages in VRLA batteries during float service usually exceeds that of conventional flooded batteries, especially when the battery is new, making float voltage measurements less meaningful (refer to D. Berndt's book). Meaningful voltages can only be measured at the cell level. If voltage is determined at the module or string level, it may indicate whether there is a problem with the charging rectifier; it cannot predict the battery's capacity.

Current can be measured in each parallel string to determine whether internal resistance or wiring resistance has increased.

Internal ohmic measurements include internal resistance, impedance, and conductance. They can be used to detect faults that impact a battery's capacity^{14,15} (see Figure E-1). Cell impedance will gradually increase during the life of a cell due to loss of electrolyte or corrosion of the conducting components.¹⁶ Conductance indicates a battery's ability to deliver current. As conductance increases, generally, so does the expected performance of a cell.

Figure E-1. Making Internal Ohmic Measurements

Source: Energetics, Inc.

E.2 Monitoring Regimes

Although most manufacturers include operating instructions that specify the type of monitoring regime recommended to ensure optimal performance of their batteries, not all regimes are ideal for every installation. End-users must take into consideration the amount of money they are willing to spend monitoring their installations and then decide for themselves which parameters or parameter combinations are most effective in identifying their battery's state of health.

VRLA manufacturers typically recommend different monitoring regimes for their cells. Some of the variations include:

- Monitor pilot cells' charge conditions monthly and check individual cell voltages, battery terminal voltage, and ambient temperature on an annual basis. These checks should also be done whenever a battery is given an equalization charge.
- Clean the cell covers and inspect the battery cables periodically.

¹⁴ M. Hlavac, D. Feder, "VRLA Battery Monitoring Using Conductance Technology," Proceedings of 17th Intelec, The Hague, The Netherlands, October 1995; pages 285 to 291

¹⁵ M. Troy, D. Feder, M. Hlavac, D. Cox, J. Dunn, W. Popp, "Midpoint Conductance Technology Used in Telecommunication Stationary Battery Applications," Melbourne, Australia, October, 1997, Section 29-4.

¹⁶ D. Berndt, *Maintenance-Free Batteries*, Taunton, UK: Research Studies Press Ltd., 1993.

- Measure both the voltage of each cell or monoblock and ambient temperature quarterly and conduct annual discharge tests.
- Perform an annual check of intercell connections and a visual inspection of post seal and cover jar.

Although most manufacturers have some sort of regime specified, others refer their end-users to the recommendations made in the current IEEE 1188 standard. The monitoring recommendations made by the IEEE tend to be more costly as they require more time by a technician than most of our surveyed end users were willing to support. The standards include:

A monthly general inspection to check and record:

- Overall float voltage measured at the battery terminals
- Charge output current and voltage
- Ambient temperature and the condition of ventilation and monitoring equipment
- Individual cell/unit condition visual check to include:
 - Cell/unit integrity for evidence of corrosion at terminals, connections, racks or cabinet
 - General appearance and cleanliness of the battery, the battery rack or cabinet and battery area, including accessibility
 - Check cover integrity and look for cracks in cell/unit or leakage of electrolyte
 - Excessive jar/cover distortion
- DC float current (per string)

A semi-annual inspection should include the previously noted monthly items, and check and record the following:

- Voltage of each cell/unit
- Cell/unit internal ohmic values
- Temperature of the negative terminal of each cell/unit of battery

The yearly inspection and the initial installation should include both the monthly and semi-annual items, and check and record the following:

- Cell-to-cell and terminal connection resistances of entire battery
- AC ripple current and voltage imposed on the battery

While IEEE 1188 suggests quarterly maintenance be performed on VRLA cells, discussions with many end-users indicate that quarterly maintenance of VRLA cells is not cost-effective.

All surveyed participants were asked to identify the battery-monitoring regime they implemented, including frequency (daily, weekly, monthly, semi-annual, annual, and by exception), the level at which each measurement was taken (cell, module, string), and parameters measured.

It is important to note that most respondents were reluctant to firmly state the frequency of repeated visits to each installation. More often, they responded with their company's suggested maintenance regime.

E.3 LTE48V Parameter Monitoring

The LTE48V installations monitored various combinations of voltage, ambient temperature, current, charge, and internal ohmic measurements (see Table E-2). Of these, the end-users identified seven different sets of parameter combinations. Over 50% were monitoring three parameters in their regime. None of the cells were monitored for all of the parameters. The most common regime was voltage, temperature, and current, impacting 67% of the monoblock cells. The second most common combination was monitoring ohmic measurements: 86% of the grouped cells and 31% of the monoblock cells followed this regime.

Table E-2. Parameters Monitored in Surveyed LTE48V Battery Cells

Parameter	Monitoring Combinations							Total Cells
Voltage	X	X	X	X	X			249,762
Temp.	X	X	X			X		253,734
Current	X					X		236,244
Charge						X		5,160
Ohmic		X		X			X	229,161
Cells in Groups	180	6,672	4,176	333	708	5,160	108,000	125,229
Cells in Monoblocks	230,904	6,120	522	36	111	---	108,000	345,693
Total Cells	231,084	12,792	4,698	369	819	5,160	216,000	470,922

As mentioned previously, not only must companies monitor their cells, they must do it consistently to assess battery health accurately. Of the surveyed LTE48V battery cells, 82% were monitored on an annual basis; the remaining cells were monitored semi-annually. For the grouped cells, 78% were monitored annually, and the remaining 22% were checked every six months. Ninety-one percent of all monoblock cells were monitored annually, and most of the rest were monitored monthly. These infrequent monitoring regimes are due to the cost of monitoring small, remote installations.

E.4 Spiral-Wound Parameter Monitoring

The spiral-wound cells were monitored for voltage, ambient temperature, current, or internal ohmic measurements. Nearly 70% of all the surveyed cells monitored internal ohmic measurements exclusively (see Table E-3). These cells were monitored on an annual basis.

Table E-3. Parameters Monitored in Surveyed Spiral-Wound Cells

Parameter	Monitoring Combinations		Total Cells
Voltage	X		78,000
Temp.	X		78,000
Current	X		78,000
Ohmic		X	180,000
Total Cells	78,000	180,000	258,000

E.5 UPS Parameter Monitoring

The surveyed UPS installations reported six different parameter combinations (see Table E-4) of voltage, ambient temperature, current, and internal ohmic measurements. Of those, 74% of the cells were monitored for three different parameters. All surveyed UPS cells had voltage measurements taken. None of the end-users monitored all the parameters. Unlike the LTE48V cells, none of the UPS cells monitored internal ohmic measurements exclusively.

Table E-4. Parameters Monitored in Surveyed UPS Cells

Parameter	Monitoring Combinations						Total Cells
Voltage	X	X	X	X	X	X	11,553
Temp.	X	X	X				2,579
Current	X			X			8,274
Ohmic		X		X	X		7,849
Cells in Groups	1,494	245	720	4,500	884	1,140	8,983
Cells in Monoblocks	120	---	---	2,160	60	230	2,570
Total Cells	1,614	245	720	6,660	944	1,370	11,553

The most common monitoring regime for grouped cells was voltage, ambient temperature, and internal ohmic measurements, impacting 50% of all cells. Voltage, temperature, and current were monitored for 17% of all cells, the second most common regime. The monoblock cells were typically monitored for voltage, current, and internal ohmic measurements.

When compared to the LTE48V cells, the UPS cells were monitored more frequently. Monthly monitoring was performed on 43% of all surveyed UPS cells, impacting 54% of the grouped cell configurations. Figure E-2 shows typical monitoring equipment used at one UPS installation.

The monoblock cells typically were monitored less frequently as 84% had cell health assessments performed every six months (see Table E-5). Of all the surveyed UPS cells, 10% were operated by end-users who were not able to determine how often they were monitored.

Figure E-2. Monitoring Equipment at UPS Installations

Source: Energetics, Inc.

Table E-5. Total Surveyed UPS Cells by Configuration and Monitoring Frequency

Monitoring Frequency	Cells In Groups	Cells in Monoblocks	Total
Monthly	4,860	120	4,980
Quarterly	1,680	60	1,740
Semi-annual	---	2,160	2,160
Annual	365	---	365
Other	1,134	---	1,134
Unknown	944	230	1,174
Total	8,983	2,570	11,553

E.6 PV Parameter Monitoring

All PV installations monitored some combination of voltage, ambient temperature, current, and internal ohmic measurements (see Table E-6). The vast majority monitored voltage, temperature, and current. Additionally, these installations tended to be monitored on a monthly basis; and in fact, very few of the respondents could not determine how often the health of their cells was assessed.

Table E-6. Parameters Monitored in Surveyed PV Cells

Parameter	Monitoring Combinations		Total Cells
Voltage	X	X	2,112
Temp.	X	X	2,112
Current	X		2,064
Ohmic		X	48
Total Cells	2,064	48	2,112

Appendix F. Glossary

Absorptive Glass Mat (AGM) - A blotter-type separator used between the plates in an AGM battery. The AGM separator absorbs most or all of the free liquid electrolyte, thus immobilizing the electrolyte.

Age at First Cell Replacement – The age (in years) of the cells in an installation when the first cell is replaced. Calculated by subtracting the year the cells were installed from the year the first cell was replaced.

Ambient Temperature – The temperature in °C of the room or container in which the battery is located.

Ampere-Hour (Ah) - The product of multiplying the ampere flow by the time over which it flows. For example, five amperes flowing consistently for eight hours produce 40 Ah.

Battery - Two or more cells connected in series. The nominal open circuit voltage is two volts per cell. For example, a 12-volt battery would have six, two-volt cells connected in series.

Battery Rack - A stand on which individual batteries are installed. Racks are typically rated for their seismic capabilities and act to support the batteries.

Cell – An assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components.

Cell Configuration – The way the cells are assembled, as grouped cells or monoblocks.

Conductance (Mho)-A measure of a material's ability to conduct current. It is the reciprocal of resistance.

Critical Load - The equipment to which a battery supplies power during a grid failure.

Current - The flow of electrons through a conductor typically measured in amperes.

Cycle - The discharge of a battery followed by recharging.

Discharge Test - A constant current or constant power load applied to a battery under standard temperature conditions to determine its actual ampere-hour or watt-hour capacity at the particular discharge rate.

Dry Out – Sometimes resulting from overcharging, dry-out refers to the loss of electrolyte due to gassing and inadequate recombination or leaks.

Early Replacement – installations experiencing first cell replacement within the first four years of operation.

Electrolyte - Any acidic, basic, or salt solution capable of conducting ionic current. In a lead-acid battery, the electrolyte is a solution of sulfuric acid (H_2SO_4) in water (H_2O).

Float Service - An application in which a battery is connected continuously to a charger and is seldom required to deliver any significant ampere-hours to the load. Typically, Float Service batteries are used for standby power in emergency lighting, cable TV, telecommunications, UPS systems, and automotive engine starting.

Float Voltage – The manufacturer-specified voltage for charging cells in float service.

Float Warranty – The number of years the manufacturer warrants the battery to operate under normal float service conditions.

Flooded Cell - A lead-acid battery with a liquid electrolyte, or a vented cell where the gasses produced through overcharging are vented directly to the atmosphere.

Gelled Electrolyte - A liquid electrolyte with fumed silica added as an immobilization technique. The result is a spill-proof battery capable of supporting an oxygen recombination reaction.

Grouped Cells – One or more cells connected in series or parallel.

Internal Ohmic Measurements - The measurement of the internal impedance, conductance, or resistance of battery cells/units.

Impedance - The resistive and reactive characteristics of a material that opposes the flow of current through the material. An AC signal is used to measure impedance.

Internal Resistance - Expressed in ohms, the total DC resistance to the flow of current through the internal components (grids, active materials, separators, electrolyte, straps, inter-cell welds and terminals) of the battery.

Lead-Acid Battery - A rechargeable electrochemical device used to store and deliver electrical energy. The active materials are lead dioxide, sulfuric acid and metallic lead. The individual cell has a nominal voltage of approximately two volts DC.

Load - The amount of current supplied by a battery to the device being powered.

Monitoring Frequency – The number of times per year that a given parameter is monitored: ≤ 4 /year includes quarterly, semi-annual, annual, and by exception; > 4 /year includes monthly and daily (very rare).

Monoblock - A unit consisting of two or more series-connected cells in a single container. For example, a 12-volt battery (e.g., a vehicle starting battery) is a monoblock consisting of 6 series-connected, 2-volt cells. If one cell fails, the entire monoblock must be replaced.

N/A – Table columns with the designation “N/A” refer to the number of units of the specified type for which detailed data (e.g., operating temperature) was not available.

Oxygen Recombination Cycle - In a VRLA battery, the process whereby the oxygen evolved at the positive plate diffuses through the separator to react with the negative plate and suppresses water loss. This is the characteristic that distinguishes the VRLA battery from vented lead-acid batteries.

Parallel Connection - Individual cells or batteries of the same voltage interconnected with all the positive (+) terminals connected together and all the negative (-) terminals connected together. The capacities of the individual units are cumulative.

Photovoltaic (PV) – An installation that generates electrical energy from sunlight. Batteries used in these installations are typically cycled as the energy source is intermittent.

Scheduled Replacement – Cells replaced after a given time in service, regardless of the health of the cells.

Series Connection - Individual cells or batteries of the same capacity interconnected with the negative (-) terminal to the positive (+) terminal of the next battery in the sequence. The voltages of cells or batteries are additive.

Spiral-Wound – Cell configuration with spiral-wound positive and negative plates in a cylindrical metal container.

Stationary Battery - A battery used in a fixed position and usually mounted in a rack, cabinet or stand, as opposed to a battery used in a mobile application.

Stratification - The tendency of the heavier sulfuric acid in the electrolyte solution to settle to the bottom of the container.

Thermal Runaway - A condition where a battery generates more heat than can be dissipated and eventually leads to catastrophic failure. This is often the result of over charging in a hot environment.

Uninterruptible Power Supply (UPS) - Emergency electricity source typically containing batteries that supply energy during power outages.

Valve-Regulated Lead-Acid Battery (VRLA) - A lead-acid battery, with an immobilized electrolyte and a one-way, self-resealing valve vent that permits an oxygen recombination cycle to operate in order to minimize gassing and water consumption.

Volt (V) - A unit of electromotive force sufficient to carry one ampere of current through one ohm resistance.

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