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TECHNOLOGY BRIEF

CELScan® Chemical Electrical Layer Scanning

This Technology Brief reviews the basis and capabilities of CELScan® (Chemical Electrical Layer Scanning) technology for assessing the health of lead acid and other batteries.

ABSTRACT

Effective management of a battery installation requires timely information about the condition of each battery unit (cell or monoblock) within the installation. To satisfy this requirement, Global Energy Innovations (GEI®) has developed the hand-held EC-Series™ Analyzers, which measure electrochemical impedance characteristics of a battery over a range of AC frequencies. The measurements are processed by GEI's CELScan® (Chemical Electrical Layer Scanning) algorithms to provide information not only about which battery units are approaching failure but also about the nature of those failures.

INTRODUCTION

A large and growing installed base of lead acid batteries is providing mission-critical backup power to hospitals, banks, mobile telecommunication sites, receiving and transmission utility sites, and countless other industrial and commercial installations. Because the need for backup power can arise without warning, it is essential that the batteries remain in peak condition at all times.

The GEI® EC-Series™ (EC1000™ and EC2000™) Handheld ElectroChemical Battery Analyzers use CELScan® technology to assess the electrical and chemical states of every battery unit within an installation and to identify any units that are approaching failure. Hence, unlike conventional monitoring methods, which measure only the basic electrical properties of a battery, CELScan® technology provides predictive information about its state of health. With this information, units that are likely to suffer premature failure can be identified and replaced before they jeopardize system reliability. In the absence of such predictive information, it is common practice to replace all of the battery units ahead of schedule, regardless of their relative health.

Although CELScan® algorithms were originally developed for stationary battery applications, they have since found acceptance in a range of other applications, including traction and automotive batteries.

BATTERY HEALTH

The finite lifespan of a battery is a reflection of irreversible changes that take place in the physical and/or chemical structure of its components. A quantitative assessment of battery health (in terms of projected lifespan) requires information about both the nature and the extent of those changes. Unlike the State of Charge (SOC), which is determined simply by measuring the actual charge stored in the battery, the assessment of battery health depends on factors both intrinsic and extrinsic to the batteries that comprise an installation.

Factors intrinsic to the batteries include:

- The degree of cell matching
- The baseline (i.e., beginning-of-life or BOL) electrical characteristics
- The mode(s) of battery failure

Extrinsic factors include:

- The application
- Electrical interference
- Ambient temperature
- Interconnection topology

The influence of these factors on battery health is outlined in **Table 1**.

Factor	Effect
Cell Matching	For batteries connected in series, the same current must pass through all cells. Hence for a string on float at a pre-set voltage, a cell with above average internal resistance will be charged less completely than a cell with below average resistance, distorting the results of electrical tests. For the same reason, a low-resistance cell will be discharged more deeply, causing it to age more rapidly. Matching cells or monoblocks during string assembly (e.g., by means of an EC-Series™ Battery Analyzer) can greatly enhance lifespan.
Baseline Characteristics	Although qualitative information about the health of a battery can be obtained from its electrical characteristics, a quantitative assessment requires comparative "baseline" values representative of BOL characteristics. When necessary, the EC-Series™ Analyzers can estimate baseline values for a string of batteries from the spread of the electrical characteristics observed.
Failure Mode	The relationship between the electrical characteristics of a battery and its projected lifespan depends on the internal changes responsible for battery aging. E-Series™ Battery Analyzers are unique in their ability to distinguish between sulfation and dryout – two leading causes of premature failure.
Battery Application	The measure of battery health varies widely from one application to another. In standby service, the health is rated in terms of the calendar time remaining before the battery will cease to deliver at least 80% (or some other specified percentage) of the nameplate charge (Ah) capacity. For portable applications, health is normally rated in terms of remaining cycles. For automotive SLI (Starting, Lighting and Ignition) batteries, the end of life (EOL) is reached when the battery can no longer meet a specified CCA (Cold Cranking Amps) requirement. For electric vehicles, mileage range is critical so battery EOL corresponds to a specified minimum energy (Wh) storage capacity. For hybrid electric vehicles, the ability to deliver peak power is important, so a key factor determining battery health would be the

Factor	Effect
	internal resistance, with EOL being reached when that resistance exceeds some preset value.
Electrical Interference	Electrical noise from active loads and/or charging circuits can interfere with the battery response to a test signal and lead to unreliable readings. The electrical interference is often intermittent, so E-Series™ Battery Analyzers validate the integrity of the response signal before attempting to interpret it.
Temperature	Variations in local temperature within the battery enclosure (e.g., cabinet, room, or engine compartment) can produce inconsistencies in the response of individual batteries to a test signal. E-Series™ Battery Analyzers are capable of compensating for temperature variations.
String Topology	The response of a battery to a test signal can vary with its connectivity within the string. For example, testing a battery that is connected in parallel with one or more similar batteries will yield a response that is characteristic of the parallel combination. When the same battery is tested in a series string, the response will depend not only on the battery but also on the parallel network comprising all the other batteries plus the power supply and load. Consequently, even if an individual battery is fully characterized before it becomes part of a network, the original characteristics cannot necessarily be used as a baseline to quantify changes that take place in service.

Table 1. Factors that influence the determination of battery health.

FAILURE MODES

A battery begins to age as soon as it is activated and the aging continues until it is taken out of service. The health of a standby battery is normally rated in terms of what percentage of its nameplate capacity can be delivered at a specified C-rate (The C rate corresponds to the fraction of the nominal capacity that would be discharged in 1 hour. For example, discharging a 30Ah battery at the C/3 rate would require a current of 30/3 = 10A.). A standby battery that can deliver ≥100% of its nameplate capacity at the specified C-rate is considered to be at the beginning of life (BOL) while one that can deliver ≤80% of that capacity is normally considered to be at the end of life (EOL).

The maximum lifespan for a well-constructed lead acid battery is generally limited by gradual corrosion of the positive electrode grid, a process in which the positive current collector (a lead alloy) is converted into lead dioxide. At first, the process can actually increase the cell capacity because the corrosion product is chemically identical with the active material on the positive plate. Over time, however this benefit is outweighed by detrimental side effects such as grid growth. Because lead dioxide takes up more space than the original lead, the conversion leads to a physical expansion of the plate. Extra space is normally designed into the cell to accommodate this expansion, however, the growth can eventually result in short-circuits as it pushes together the positive and negative bus-bars at the top of the cell.

A second failure mode common to all lead acid batteries, is a process known as sulfation, where the normal discharge process of lead sulfate formation becomes irreversible. In normal operation, the lead sulfate forms as small crystals that readily re-dissolve during the charging process, allowing the active materials to revert to their original form. If, however, the usage profile is not carefully controlled, the lead sulfate crystals can gradually grow in size, becoming progressively more difficult to convert back to active material. In the early stages, while recharge is still possible (albeit somewhat slow), the condition is known as “soft sulfation”. Eventually, however, the crystals grow so large and dense that recharge becomes impractical and the battery must be replaced. At this point, the condition is known as “hard sulfation”. The output readings generated on the EC1000™ and EC2000™ via the CELScan® algorithms are equally sensitive to both “soft” and “hard” sulfation, allowing detection of sulfation before it becomes irreversible.

An important failure mode observed in valve regulated lead acid (VRLA) batteries, is "dryout" - the progressive loss of water from the electrolyte. When properly managed, VRLA batteries retain adequate water throughout their design lives. However, when subjected to prolonged overcharging, overheating, or when a valve malfunctions, water loss from VRLA cells can appreciably lower the separator conductivity. Dryout of an AGM (Absorbed Glass Mat) separator causes it to shrink away from the electrodes, ultimately producing a large increase in internal resistance and a sudden loss in capacity. Similarly, water loss from a gel separator can lead to disintegration of the separator and a corresponding drop in capacity. The early stages of dryout can go undetected by load tests because the effect on capacity is small until very late in the process.

Exacerbating the problem of dryout is a feedback effect whereby each increment of water loss increases both ohmic heating and (during charge) the oxygen recycle current. The increased heat generation further accelerates water loss, ultimately leading to a catastrophic failure process known as thermal runaway. Hence, early detection of this failure mode will not only extend battery life, it may also avert a major accident.

CELScan® TECHNOLOGY

As implied by the name, Chemical Electrical Layer Scanning (CELScan®) technology provides the capability of monitoring changes in both electrical and chemical characteristics of lead acid batteries. This capability permits the identification of incipient sulfation and/or dryout processes even when single-point measurements (e.g., conductance or resistance) register no appreciable deviation from nominal values.

CELScan® is a system of classification and pattern recognition algorithms that interpret changes in the impedance spectrum of a battery in terms of specific failure modes. In the case of lead-acid batteries, these failure modes include sulfation and dryout. Algorithms are under development for monitoring other failure modes such as grid corrosion but those types of failure normally appear relatively late in a battery's design life.

CELScan® technology is built into the Global Energy Innovations’ EC1000™ and EC2000™ Analyzers – microprocessor-based instruments that use impedance spectroscopy to characterize batteries and other low-impedance devices. This capability is a radical advance over prior technology.

In order to gain a qualitative idea of how electronic measurements can provide chemical information, let us examine the following charts. **Figure 1** shows a typical complex-plane impedance or “Nyquist plot” for a lead acid battery. Similar plots are observed for Lithium-ion, NiMH and other battery chemistries. Nyquist plots, which display the variation of real vs. imaginary components of impedance, are generated by passing a series of alternating current sine wave frequencies through the battery and measuring the alternating voltage response. As shown in Figure 1, the frequencies may range from kilohertz (kHz) down to microhertz (µHz).

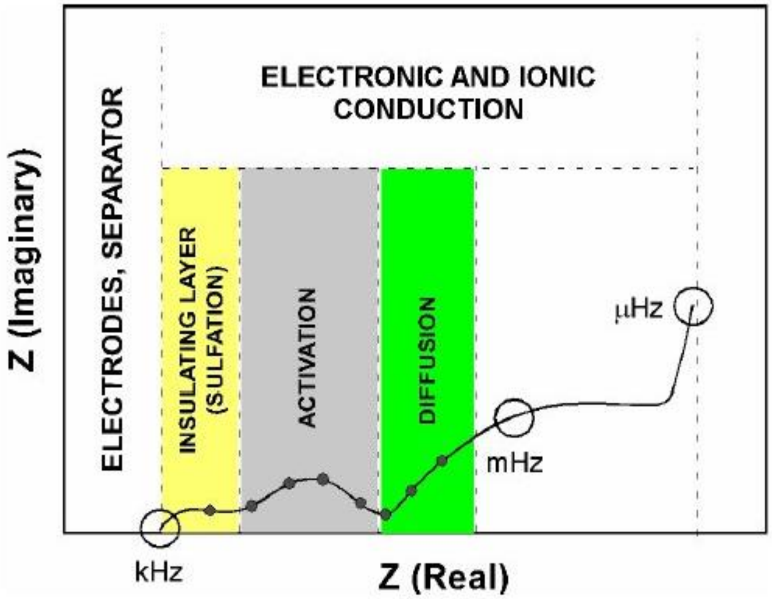

Figure 1. Typical Nyquist plot for a lead acid battery.

Each point in the complex plane corresponds to a single frequency. From the shape of the Nyquist plot, experienced scientists can deduce a great deal of information about the condition of the battery. At the highest frequencies, the impedance is controlled by electron movements in metallic components and resistive films. As the frequency is lowered, a sequence of other processes becomes important including (from high to low frequency), ionic migration, the electrostatic charging of electric double layers, and charge transfer reactions at electrode surfaces. At frequencies in the millihertz (mHz) range and below, diffusion processes in liquid and solid phases tend to dominate. Obtaining data in this low frequency range is impractical outside the laboratory because it would require many minutes per data point. (1mHz corresponds to 1 cycle every thousand seconds). Fortunately, the most useful diagnostic information tends to occupy the middle range of frequencies. However, it should be clear from the intricate shape of the Nyquist plot that reliance on a single frequency point cannot possibly provide adequate information about all the processes that affect the health of a battery.

CELScan® uses a frequency scanning technique for acquiring the relevant impedance data points and response waveforms for a given battery chemistry required for an accurate and repeatable assessment of battery health.

CELL AGING

As cells and batteries age, they go through various zones. **Figure 2** divides the life of a battery into three distinct zones. The initial zone shows little change in the capacity or single-point (ohmic) electrical characteristics. It is important to test the battery at this stage, not only to catch possible infant mortality failures, but also to look for premature signs of aging that might signify improper battery management.

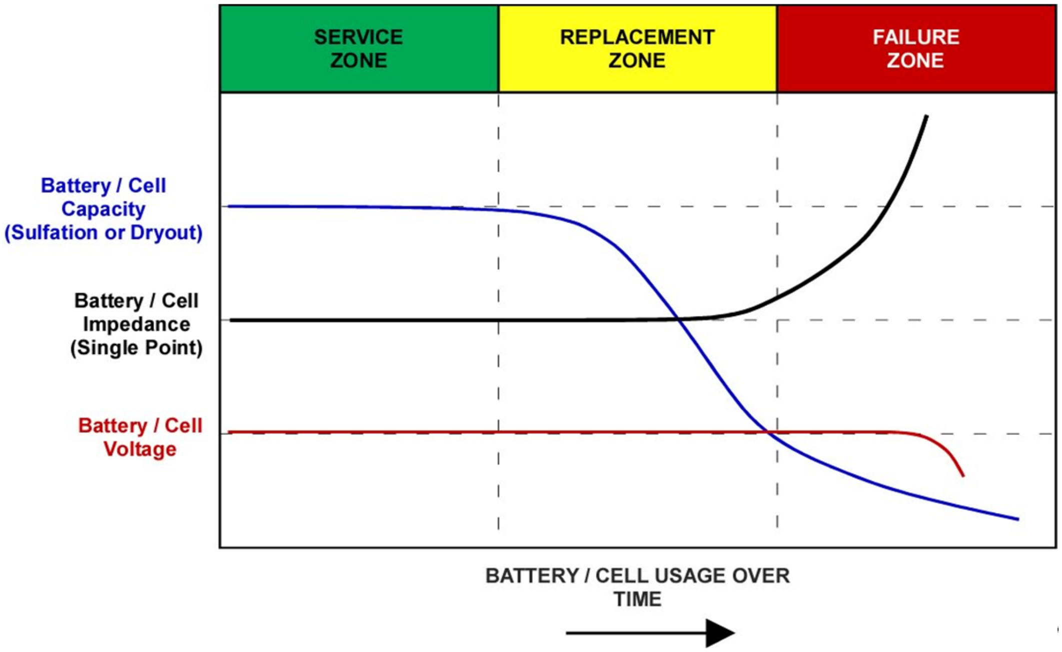

Figure 2. Aging zones of the lead acid battery.

In the middle zone, chemical changes become more important and discharge tests reveal an accelerating roll off in capacity. Unlike single-point electrical characteristics, the EC1000™ and EC2000™ using CELScan® algorithms give early warning of potential problems in this zone and allows the operator to apply corrective measures. In the final zone, cell capacity declines erratically and failure can be too sudden to be predicted by routine electrical measurements.

Different battery chemistries such as Lithium-ion, NiMH and others have different zones of degradation that can also be closely monitored using CELScan®, multi-frequency algorithms.

To demonstrate how much the impedance pattern of a battery can change over time, **Figure 3** compares the Nyquist plot of a battery before and after an accelerated aging treatment of 450 cycles. Just as the human eye can readily discern the changes, CELScan® algorithms apply digital pattern recognition to diagnose and quantify the failure processes.

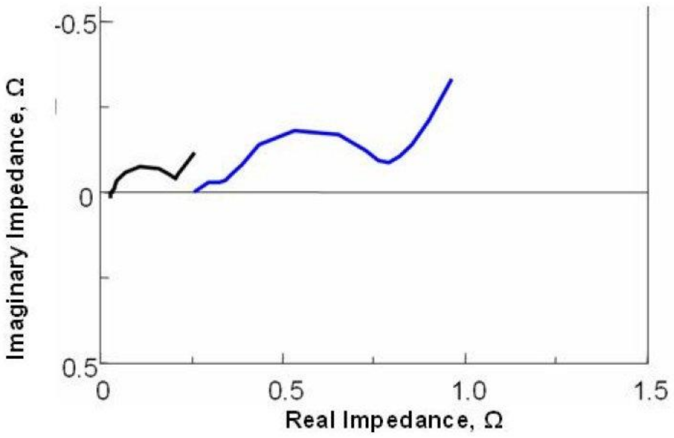

Figure 3. Nyquist plots for a lead acid battery before (black) and after (blue) 450 accelerated aging cycles.

A number of excellent publications are available that show complex plane impedance responses to various battery types and conditions. Some of these publications are listed in **Table 2** below.

1	J.M. Hawkins, L.O. Barling, “Some aspects of battery impedance characteristics”, Telstra Research Laboratories, Victoria Australia, INTELEC 95.
2	F. Huet, “A review of impedance measurements for determination of the state-of-charge or state-of-health of secondary batteries”, CNRS, Physique des Liquides et Électrochimie, Université Pierre et Marie Curie, France, Journal of Power Sources, 70 (1998) 59-69.
3	A.J. Salkind, P. Singh, A. Cannone, E. Atwater, X. Wand, D. Reisner, “Impedance modeling of intermediate size lead-acid batteries”, Journal of Power Sources, 116 (2003) 174-184.
4	A.K. Shukla, V.G. Kumar, N. Munichandraiah, T.S. Srinath, “A method to monitor valve-regulated lead acid cells”, Journal of Power Sources, 74 (1998) 234-239.

Table 2. A selection of publications on the complex plane impedance characteristics of various battery types over a range of operating conditions.

Bode plots such as those presented in **Figure 4** show how the magnitude and phase angle of impedance vary with AC frequency for different battery types.

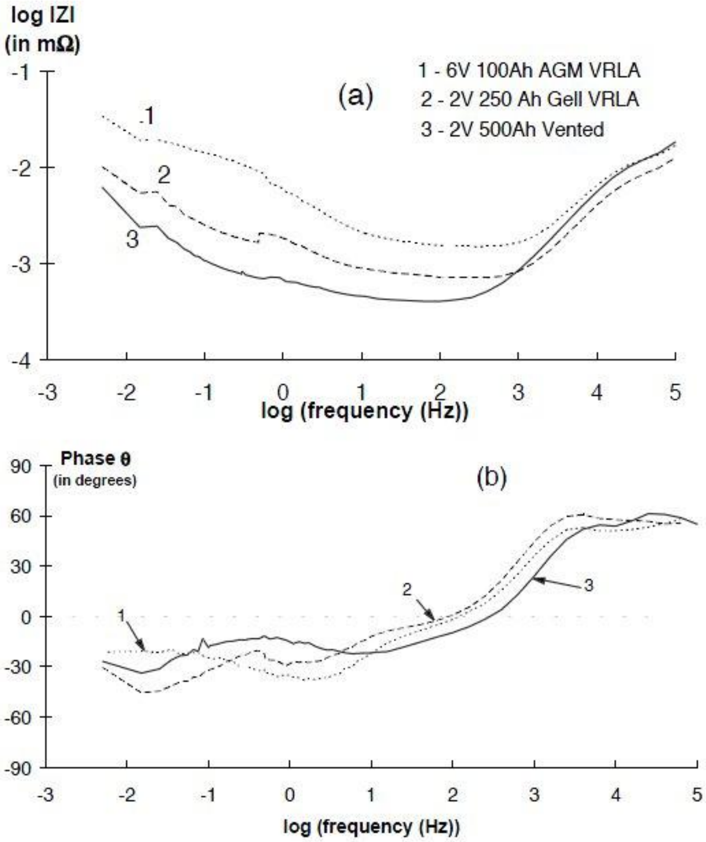

Figure 4. Bode impedance plots of (a) magnitude and (b) phase angle vs. frequency for three different types of lead-acid battery.

The results in **Figures 3** and **4** were obtained on fully charged batteries at open circuit. More details can be found in Publication 1 listed in **Table 2**.

CELScan® CASE STUDIES

The following test results are offered to illustrate the reliability with which CELScan® algorithms as implemented on the E-Series™ analyzers can assess capacity losses due to dryout and sulfation in lead acid batteries.

In a series of laboratory tests, accelerated aging tests were performed on sets of GNB Absolyte IIP 104 Ah VRLA cells and Enersys Powersafe 3CC-3, 50 Ah, VLA-type batteries. The baseline C/3 capacity of each battery was established at the beginning of life (BOL). Sulfation was artificially induced by lowering the float voltage and raising the temperature. Dryout was induced in a set of VRLA cells with a flow of nitrogen. After aging, each battery was fully charged so that capacity losses measured by C/3 load testing could be compared with results predicted by CELScan®.

Figures 5 and **6** show the comparisons for sulfated batteries and **Figure 7** shows the comparison for dried-out batteries. In all three cases, the agreement (expressed as a percentage of nameplate capacity) was within ~4%.

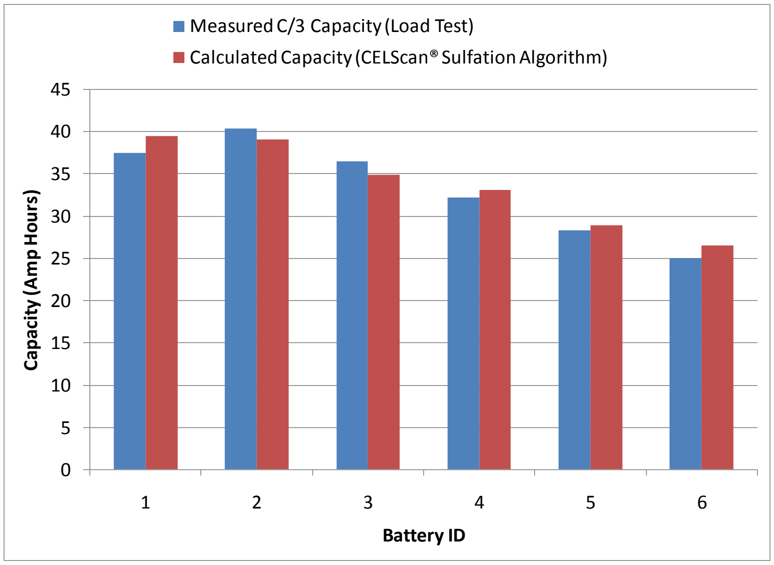

Figure 5. Sulfation-induced capacity loss for 50 Ah VLA-type cells.

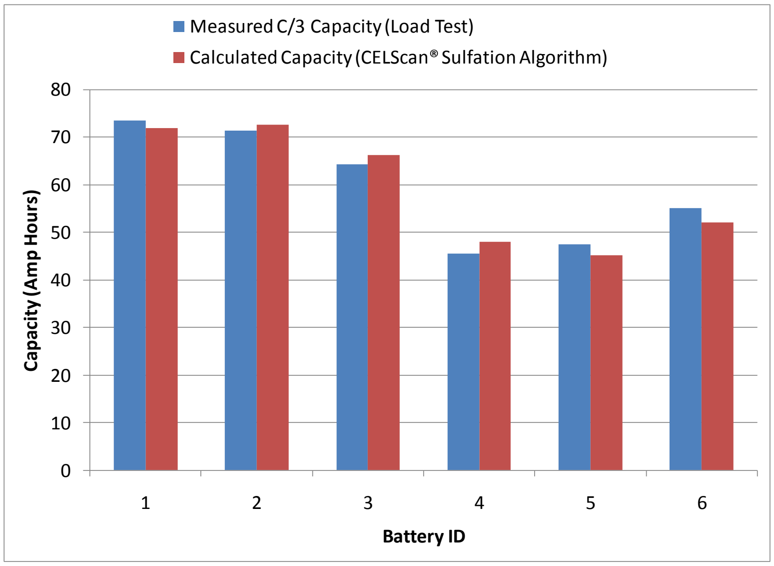

Figure 6. Sulfation-induced capacity loss for 104 Ah VRLA-type cells.

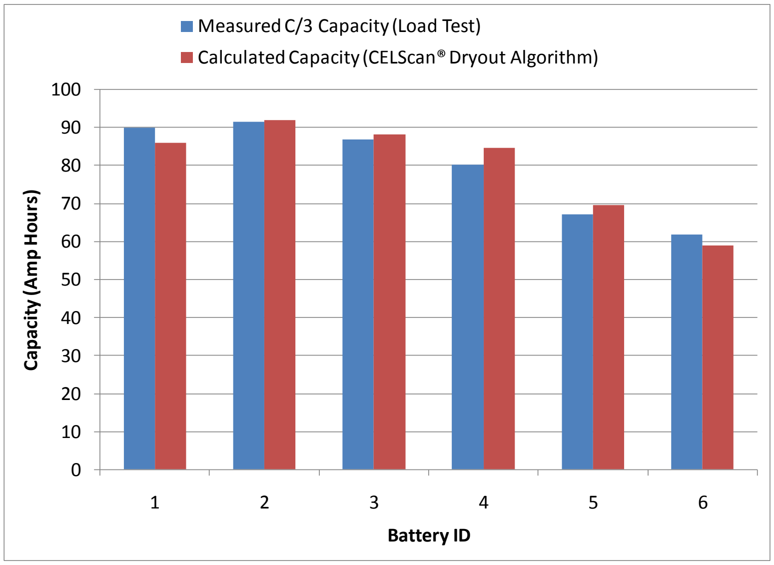

Figure 7. Dryout-induced capacity loss for 104 Ah VRLA-type cells.

Results of field tests performed by an automotive company on 90-Ah VRLA batteries that were recovered from operating vehicles are shown in **Figure 8**.

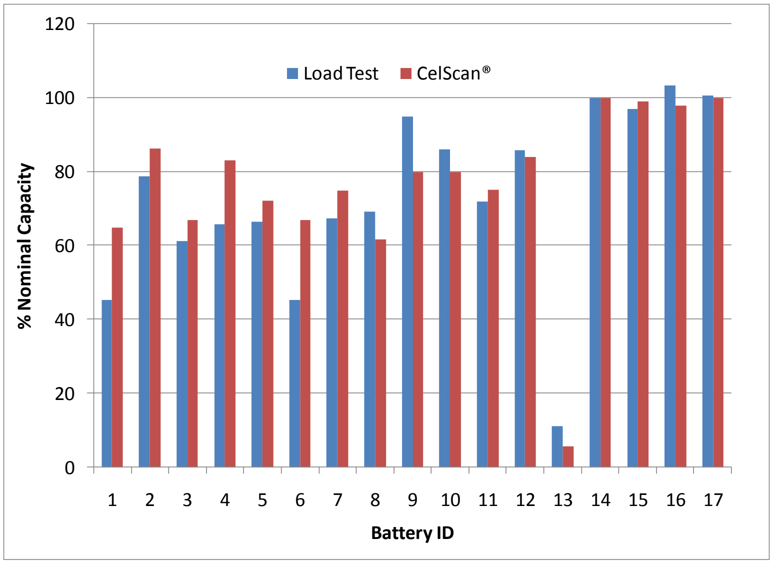

Figure 8. Percentage capacity loss for used automotive batteries.

On average, the correlation in **Figure 8** between CELScan® and load test results was within ~10% of the nameplate capacity. This agreement is remarkable, considering that the CELScan® algorithms (originally developed for standby-power type batteries) had not been adjusted for automotive batteries.

Even closer correlations between CELScan® and load-test results were observed in two other third-party studies. **Table 3** gives results obtained at a global telecommunication company on a string of 2000Ah cells and **Table 4** gives results obtained at a global power utility company on a string of 220Ah cells. For the cells in **Table 3**, the agreement was within 4% and in **Table 4** it was within 7%.

Cell No.	%Capacity from CELScan®	%Capacity from Load Test	Difference, %
1	100%	100%	0.0%
2	100%	100%	0.0%
3	91.3%	94.8%	3.5%
4	87.2%	91.2%	4.0%
5	100%	100%	0.0%
6	100%	100%	0.0%
7	100%	100%	0.0%
8	100%	100%	0.0%
9	100%	100%	0.0%
10	100%	100%	0.0%
11	98%	100%	2.0%
12	100%	100%	0.0%
13	100%	100%	0.0%
14	93.1%	92.3%	-0.8%
15	100%	100%	0.0%
16	97.9%	100%	2.1%
17	99%	100%	1.0%
18	100%	100%	0.0%
19	98.9%	100%	1.1%
20	100%	100%	0.0%
21	100%	100%	0.0%
22	99%	100%	1.0%
23	100%	100%	0.0%
24	100%	100%	0.0%

Table 3. Comparative test results on a string of Yuasa YL 2000-2 cells.

Cell No.	%Capacity from CELScan®	% Capacity from Load Test	Difference, %
1	Untested		
2	91%	92.0%	1.0%
3	96%	93.3%	-2.7%
4	82%	89.0%	7.0%

5	93%	91.0%	-2.0%
6	95%	91.6%	-3.4%

Table 4. Comparative test results on a string of Fulmen EHP 02200 cells.

CONCLUSION

CELScan® algorithms, which exploit the principles of electrochemical impedance spectroscopy, are proving invaluable in the timely diagnosis of lead acid battery health. Detecting incipient failures in lead acid batteries allows the user to take corrective action before serious consequences arise. By placing this predictive capability in the hands of the battery user, the Global Energy Innovations EC-Series™ Analyzers can dramatically reduce the cost and risk of battery ownership.

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