LIES, DAMNED LIES AND STATISTICS:
THE STATISTICAL TREATMENT OF BATTERY FAILURES

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ABSTRACT

It sometimes seems that electrochemists operating in the world of electrical engineering are doomed to be perpetually misunderstood. So the idea of battery people using statistics may conjure up images of politicians using statistical arguments to make just about any point they want. Statistical analysis can, however, help to improve system reliability. As new technologies such as lithium ion start to be considered, their electronic subsystems must be qualified and statistical measures of failure rates are a legitimate tool for this process.

This paper provides a framework for the use of statistics as they relate to battery reliability, without resorting to complex equations. It examines series and parallel strings and shows how different battery chemistries provide varying results for statistical reliability. The paper also provides guidance for evaluating practical limits to the number of parallel battery strings by application and chemistry.

INTRODUCTION

As Mark Twain famously wrote, ‘There are lies, damned lies and statistics.’ Indeed, statistics are all too frequently used and abused by politicians in their claims. In the field of electronics, however, statistical analysis is an essential tool of reliability professionals, and as consumers we have all benefited from this benign application of statistics.

There is increasing interest among users of stationary batteries in the application of lithium-based technologies. The necessity of electronic controls for the safe operation of these systems has been discussed previously at Battcon[1], and these electronic subsystems naturally point us towards a statistical analysis of reliability. As will be discussed in this paper, simple statements regarding component quality or MTBF are inadequate for proper reliability assessment of batteries. More advanced concepts such as Failure Mode and Effects Analysis provide a much more realistic means of assessing and improving system reliability.

Rather than shrugging off the alphabet soup of MTBF, MTTF, MTTR, FMEA, RPN, and all the other statistical abbreviations, this paper seeks to describe basic concepts of reliability in layman’s terms and to show how they can be applied to present battery designs and applications.

MTBF AND LIFE

One of the most common statistical values quoted for electronic components is MTBF (Mean Time Between Failures), which some people confuse with life expectancy. In fact, MTBF has nothing to do with life, and the best way to explain this is to start with the familiar ‘bathtub’ curve of failure rates, illustrated in Figure 1. This curve shows the three life phases that are associated with electronic components (and indeed with many other things, including humans). The infant mortality phase is associated with defects, while the increasing failures at the end of life are due to wear-out. The phase in between is described as the ‘useful life’ of the item, and is characterized by a constant failure rate.

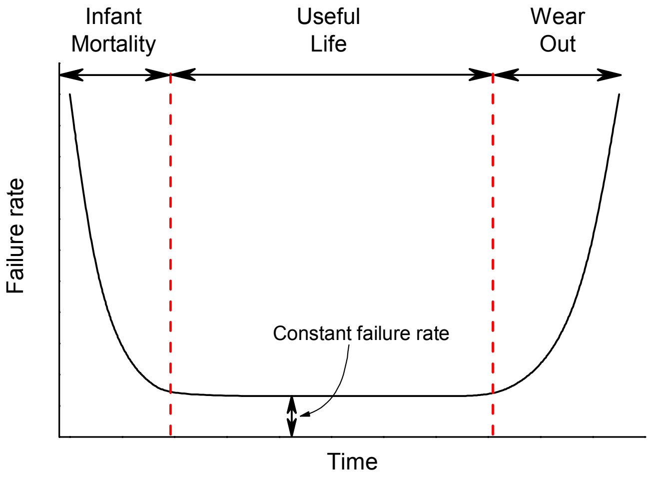


Figure 1 – Life phases for electronic components

This constant failure rate is measured in 'failures per unit time.' MTBF is simply the reciprocal of this constant failure rate and its units should therefore be expressed as 'time per failure.' Unfortunately the units are commonly abbreviated to just 'time,' and this leads to the confusion with life expectancy. As Kevin Daly puts it[2], "A 'thirty-something' American (well within his constant failure rate phase) has a failure (death) rate of about 1.1 deaths per 1000 person-years and, therefore, has an MTBF of 900 years (of course it's really 900 person-years per death). Even the best ones, however, wear out long before that."

MTBF is therefore a measure of reliability. An 'improved' item might show the same time for the onset of the wear-out phase (i.e. have the same life expectancy). However, a lower failure rate in the useful life phase (i.e. a better MTBF) would make it more reliable.

MORE ALPHABET SOUP – FMEA AND RPN

MTBF statistics provide a good measure of reliability for individual components in a system, but give an incomplete picture of the reliability of the system as a whole. Questions remain regarding the severity of a particular failure mechanism and its impact on system functionality. The need for a better tool in reliability analysis has been met by the use of Failure Mode and Effects Analysis (FMEA). FMEA is 'designed to identify potential failure modes for a product or process, to assess the risk associated with those failure modes, to rank the issues in terms of importance and to identify and carry out corrective actions to address the most serious concerns.'[3] This tool is incorporated in documents from standards organizations throughout the world, including IEEE, IEC, SAE, ISO, BSI, DOD (MIL standards), etc. One such document directly related to the battery industry is IEEE Std 1625[4], covering batteries for portable computing.

FMEA is applied to product design by identifying potential in-service failures, and to the manufacturing process by identifying potential problems with procedures or components. An end user can also use the technique in designing a system and establishing maintenance standards. When potential failure modes and their causes have been identified, the next step is to assess the risk involved in each case and to prioritize corrective action. The tool for this is the Risk Priority Number (RPN), which involves three distinct assessments:

- The **Severity** of the failure mode in question
- The likelihood of its **Occurrence**
- The ease of **Detection** prior to actual failure

These parameters are assessed on a rating scale, usually from 1 to 5 or from 1 to 10, in which higher numbers denote greater seriousness or risk. The RPN is then calculated as

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}$$

Failure modes with high RPNs would be assigned a high priority for corrective action. An example of the use of RPNs can be seen in an analysis of open-circuit failures in valve-regulated lead-acid (VRLA), vented lead-acid (VLA) and nickel-cadmium (Ni-Cd) cells.

RPN AND OPEN-CIRCUIT CELL FAILURES

Severity

An open circuit failure in a single cell will obviously affect the entire string in which it is installed. In a single-string battery system there would be a catastrophic loss of function and the Severity parameter would be given a high number. In low-rate applications such as telecommunications this rating can be reduced by splitting the required capacity between two or more parallel strings. Although there is no true redundancy, since no additional capacity is installed, the result is that a single cell failing open results in functionality being reduced rather than completely lost.

For reasons of battery efficiency it is not practical to follow this same practice for applications involving high-rate, short-duration discharges, as explained in a previous Battcon paper by the author[5]. However, installing fully redundant strings reduces the Severity rating to a much lower level, since a single cell failure will have no impact on system functionality.

Occurrence

When assessing the probability of an open-circuit cell failure it is apparent that cell chemistry and design has a major impact. The steel internal structure of Ni-Cd cells renders them virtually immune to hardware failures. The only real possibility of open-circuit failure would be as a result of complete dryout through neglect or charger malfunction.

VLA cells are somewhat more likely to fail open, typically through post corrosion in the seal area or connection failure. Failure in open circuit through dryout could also occur, for the same reasons and with the same probability as for Ni-Cd cells.

VRLA cells have a similar risk of hardware failure as their vented counterparts, and are much more likely to experience dryout through such causes as valve failure, loss of compression and thermal runaway. Early VRLA designs were also particularly prone to negative strap corrosion and failure – a phenomenon that has been greatly reduced by the use of the cast-on strap manufacturing process.

From this assessment the lowest rating for Occurrence would be assigned to Ni-Cd, with a higher rating for VLA and higher still for VRLA. Older VRLA designs made without cast-on straps would have the highest rating of all.

Detection

There is a certain human component to the Detection rating, since the process of detection requires a person to be actively involved. Even when an automated monitoring system detects an imminent open-circuit condition, a human must take notice of a warning and react to it in some way. The following discussion assumes that the humans involved will react diligently as a result of feedback from the procedures they are following. The adequacy, or lack thereof, of those procedures is the subject of this discussion.

The detection and avoidance of dryout in vented cells is a relatively easy task that can be accomplished by one or more of the following: visual inspection and water addition as necessary; programmed water additions (e.g. every *x* years); or the use of an automated level detection system and water additions as necessary. Since abnormally high voltages will lead to faster water consumption, the use of a high-voltage alarm in the charger will allow the frequency of inspection and/or water additions to be optimized for the specific application. Such a program will result in a low risk of non-detection and a correspondingly low Detection rating for this particular aspect of open-circuit failure.

Incipient hardware failures in lead-acid cells are often difficult to detect by voltage measurements, specific gravity readings (in vented cells) or visual inspection. If a maintenance program uses only these techniques then the Detection rating will be quite high, especially for VRLA cells in which no internal visual inspection is possible. This rating may, however, be reduced quite simply by the implementation of internal ohmic measurements (ac impedance, ac conductance or dc resistance).

There is also a commercial element here. For the largest possible reduction in the Detection rating the frequency of internal ohmic measurements must be such that all potential open-circuit failures are detected before they affect the system. More frequent measurements are, of course, more costly. An automated monitoring system with ohmic measurement feature would provide the lowest possible Detection rating, but would have a high up-front cost.

RPN Calculation

Having established the battery choice, system design and maintenance variables, and their associated ratings for Severity, Occurrence and Detection specific to open-circuit failures, a series of RPNs can be calculated. Even though the Severity value for open-circuit failure is high, if it is combined with low values for Occurrence and Detection, as is the case for Ni-Cd, for example, then the corresponding RPN will be low. The RPNs can be considered relative to the criticality of the system and the costs involved. When looking at open-circuit failures in a critical installation, for example, a VRLA battery would have to be implemented in a multi-string configuration, possibly with redundancy, and in conjunction with routine ohmic measurements, to equal the low RPN of a single-string Ni-Cd system with more basic surveillance.

This procedure is repeated for other failure modes, taking appropriate measures as necessary to reduce any high RPN values that are found. In this way the FMEA process can be a valuable tool in making system design and maintenance choices for improved reliability.

STATISTICS 101 – SERIES AND PARALLEL BATTERY STRINGS

The capacity and voltage of stationary battery systems are built up by connecting cells together in series and often also in parallel. In addition to following basic electrical rules (series connections increase the voltage while keeping the capacity constant; parallel connections increase the capacity while keeping the voltage constant), these arrangements also follow fundamental statistical rules, which are outlined in this section.

Reliability

The calculations below make use of the reliability parameter, R. The statistical definition of reliability is the probability that a randomly selected sample will still be operational after a specific time has elapsed. This definition is fundamentally different from MTBF, which deals with failure rate during the specific period of 'useful life' (see Figure 1). The reliability number should really carry the suffix 'over x years,' and the reliability will of course decrease as x increases. Of equal certainty, there will be differences in the reliability number between battery technologies, and between products within a particular technology.

In the interest of analyzing differences attributable to battery architecture (series/parallel arrangements of cells), a constant reliability number has been assumed for most of the cases, and the time element has been ignored.

Series Systems

From a statistical point of view, a series system is any system in which the failure of any one of the components causes the failure of the system. The simplest series systems are those in which the components do not influence each other. An example of a simple series system is rolling a pair of dice in an attempt to come up with double sixes. The second die is clearly not influenced by the results of the first, and the system 'fails' whenever one (or both) does not produce a six.

Series-connected battery systems are not always statistical series systems. Take the example of a long string of cells in which the predominant failure mode is in short circuit. If a shorted cell will continue to pass the string discharge current then its failure does not cause the failure of the whole system. A long string will tolerate a certain number of such failures before it can no longer perform its function and as such it behaves statistically as a k-out-of-n parallel system (see below).

For cells that fail in open circuit a series string will obviously behave as a statistical series system – when the first cell fails open, the system also fails. The cells are statistically identical and, for the most part, do not influence each other. For this type of system the reliability is given as

$$R_{\text{system}} = R_{\text{cell}}^{n}$$

where n is the number of series-connected cells. For a cell type with reliability of 0.995, connected in a string of 24 cells, the battery reliability is therefore 0.995^{24}, or 0.887.

Simple Parallel Systems

Simple parallel systems are those in which only one out of n units needs to be operational for the system to function. Fully redundant battery strings, in which each string is sized for the full load requirements, meet this criterion. The system reliability is calculated as

$$R_{\text{system}} = 1 - [(1 - R_1) \times (1 - R_2) \times \ldots \times (1 - R_n)]$$

where n is the number of strings in parallel. Thus if the reliability of a single string is 0.887, adding a redundant string in parallel will increase the system reliability to 0.987 and adding a third string will improve it to 0.9986.

Such simple parallel arrangements are fairly common in UPS applications. More electrically paralleled systems, however, including most of those in telecom applications, are actually statistical k-out-of-n parallel configurations.

***k*-out-of-*n* Parallel Configurations**

Taking a simple telecom application and assuming a constant 8-hour load, it is standard practice to divide the required capacity between two or more parallel strings. In this case there is no redundancy, but string failures cause the system output to be reduced, rather than failing completely. If the reduced output is tolerated then the system behaves statistically as a k-out-of-n system, where k is the minimum acceptable number of functioning strings and n is the total number of strings.

Since the number k represents any combination of k units out of the total of n, the reliability calculation involves summing a series of binomial distributions for the different operating scenarios. In the interest of keeping this paper easily understandable the necessary formulas are not included here, but they can be readily studied in any statistical text covering series and parallel systems.

Table 1 – Reliability for a *k*-out-of-6 system for different *k* values

Parallel strings (*n*)	Min. strings req'd (*k*)	Battery reliability
6	1	0.999998
6	2	0.99990
6	3	0.9980
6	4	0.9777
6	5	0.8585
6	6	0.4859

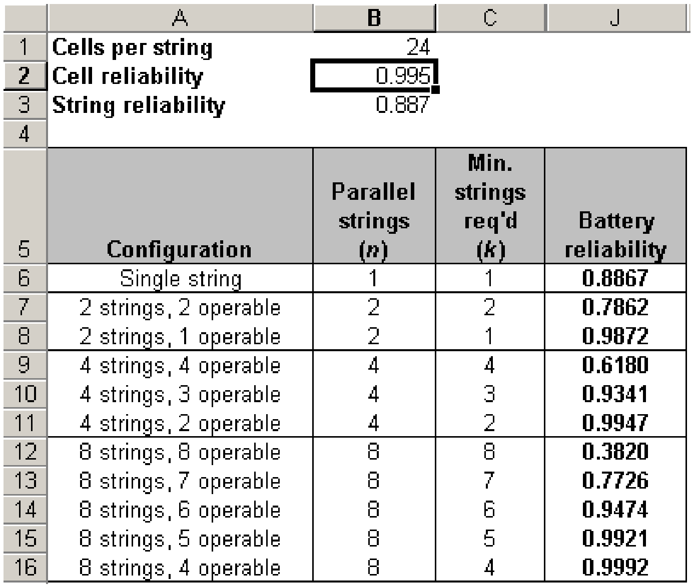
Table 1 shows reliability calculations for a system with 6 parallel components, each with a reliability of 0.887. It is important to note that when k is 6, i.e. all components must be operational for the system to work, the reliability is the same as that of a statistical series system: $0.887^6 = 0.486$. At the other end of the spectrum, when k equals 1 the system becomes a simple parallel system.

RELIABILITY OF BATTERY SYSTEMS

In this section of the paper we will examine reliability calculations for typical battery systems, based on cell failure in open circuit or short circuit. Both telecom and UPS systems will be evaluated. For a valid comparison of system architectures it will be assumed that all cell reliabilities are equal.

Telecom Systems

As observed earlier, batteries in which series-connected cells fail open are also considered as statistical series systems. In telecom systems these products are typically installed with the required capacity distributed between parallel strings in a *k*-out-of-*n* system. Figure 2 shows a spreadsheet in which the reliability calculations have been performed for a variety of such telecom system architectures.

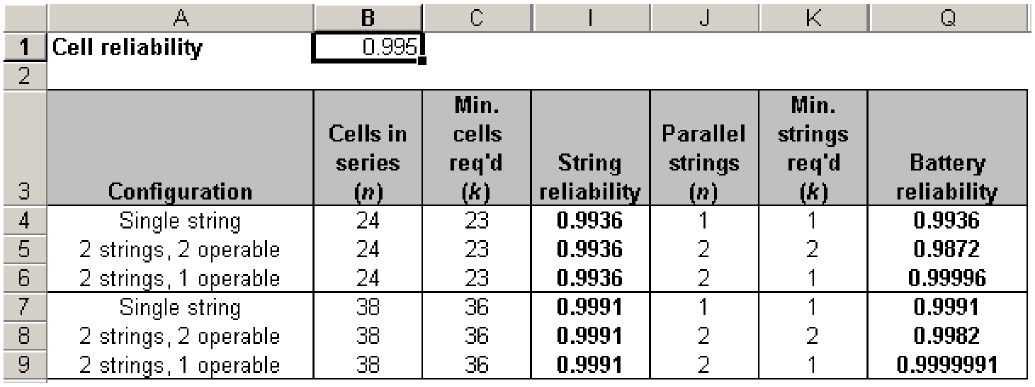


	A	B	C	J
1	**Cells per string**	24		
2	**Cell reliability**	0.995		
3	**String reliability**	0.887		
4				
5	**Configuration**	**Parallel strings (*n*)**	**Min. strings req'd (*k*)**	**Battery reliability**
6	Single string	1	1	**0.8867**
7	2 strings, 2 operable	2	2	**0.7862**
8	2 strings, 1 operable	2	1	**0.9872**
9	4 strings, 4 operable	4	4	**0.6180**
10	4 strings, 3 operable	4	3	**0.9341**
11	4 strings, 2 operable	4	2	**0.9947**
12	8 strings, 8 operable	8	8	**0.3820**
13	8 strings, 7 operable	8	7	**0.7726**
14	8 strings, 6 operable	8	6	**0.9474**
15	8 strings, 5 operable	8	5	**0.9921**
16	8 strings, 4 operable	8	4	**0.9992**

Figure 2 – Reliability of telecom systems for cells failing in open circuit

As can be seen from Figure 2, a large number of parallel strings must be installed, and the operator must be willing to tolerate the possibility of a number of them failing, with the corresponding reduction in run time, to achieve reasonably high reliability at the system level.

The situation is very different for cells failing in short circuit, assuming that they are able to carry the string current after failure. In the case of a 24-cell lead-acid battery, normally charging at, say, 2.25 V/cell or 54 V overall, one shorted cell would leave the remaining 23 cells charging at 2.35 V/cell – an acceptable level for a few weeks or months until the next inspection. Such a battery would be statistically a 23-out-of-24 parallel system. Since Ni-Cd cells have a lower voltage and 38 cells are normally used in telecom systems, they can easily tolerate short-circuit failure of 2 cells, changing the charging voltage from 1.42 to 1.50 V/cell. The statistical calculations for these two cases are shown in Figure 3, again assuming that the required capacity is distributed between strings in a *k*-out-of-*n* configuration.



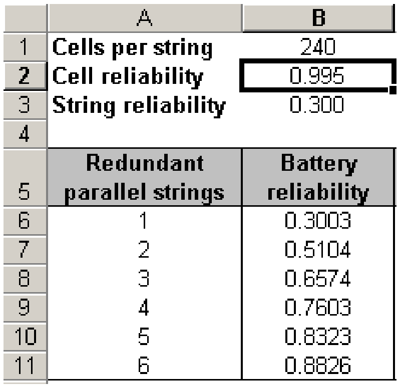
	A	B	C	I	J	K	Q
1	**Cell reliability**	0.995					
2							
3	**Configuration**	**Cells in series (*n*)**	**Min. cells req'd (*k*)**	**String reliability**	**Parallel strings (*n*)**	**Min. strings req'd (*k*)**	**Battery reliability**
4	Single string	24	23	**0.9936**	1	1	**0.9936**
5	2 strings, 2 operable	24	23	**0.9936**	2	2	**0.9872**
6	2 strings, 1 operable	24	23	**0.9936**	2	1	**0.99996**
7	Single string	38	36	**0.9991**	1	1	**0.9991**
8	2 strings, 2 operable	38	36	**0.9991**	2	2	**0.9982**
9	2 strings, 1 operable	38	36	**0.9991**	2	1	**0.9999991**

Figure 3 – Reliability of telecom systems for cells failing in short circuit

It is easy to see the major difference between cells failing in open circuit (statistical series systems) and those failing short (*k*-out-of-*n*). With much higher reliability at the string level, fewer parallel strings are required to achieve extremely high system reliability.

UPS Systems

With the dc bus voltage in many UPS systems now at 480 V, the number of cells per string is an order of magnitude higher than in telecom batteries. This has serious implications for technologies suffering from open-circuit failure, as seen in Figure 4. Figure 4A shows the spreadsheet calculation for the same 0.995 cell reliability used in the other cases.



	A	B
1	**Cells per string**	240
2	**Cell reliability**	0.995
3	**String reliability**	0.300
4		
5	**Redundant parallel strings**	**Battery reliability**
6	1	0.3003
7	2	0.5104
8	3	0.6574
9	4	0.7603
10	5	0.8323
11	6	0.8826

Figure 4A – Spreadsheet calculation

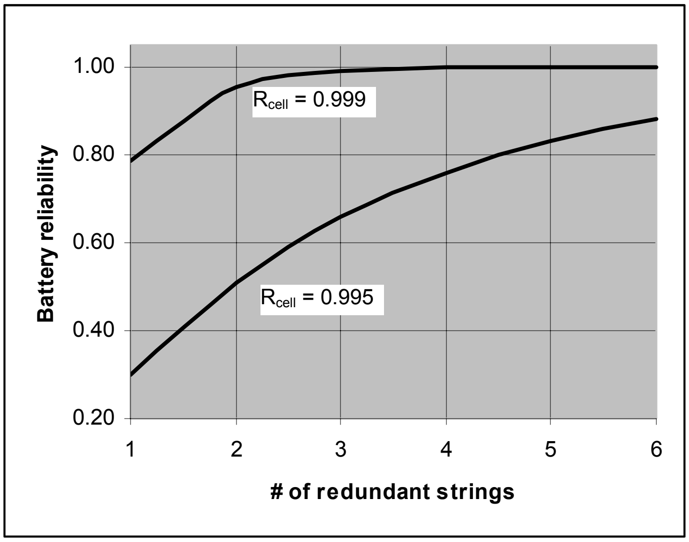
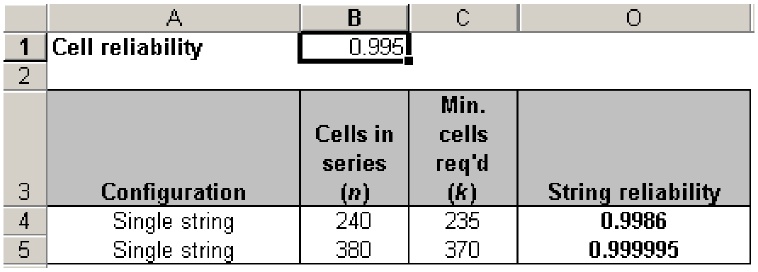


Figure 4B – Different cell reliability levels

Figure 4 – Reliability of 480 V UPS systems for cells failing in open circuit

This calculation raises severe doubts about the reliability of any high-voltage system in which cells are likely to fail open. Even with six fully redundant strings—and at six times the cost, a very unlikely configuration—the overall system reliability still falls short of an acceptable level. Figure 4B shows these numbers in graphical form, along with reliability data for cells with extremely high reliability of 0.999. Even though such a reliability number is probably unachievable in practice, it would still require two or three fully redundant strings to achieve good reliability at the system level. It should be borne in mind that normal utility power is considered to have reliability of around 0.999, so it would be reasonable to require a UPS system to provide more 'nines' than this.

This rather unpalatable situation is completely reversed when considering cells that fail in short circuit. Taking the same numbers as in telecom systems, increased by an order of magnitude, we have statistical 230-out-of-240 parallel systems for lead-acid and 360-out-of-380 for Ni-Cd. Considering that the system run time would be severely reduced with the minimum cell count, particularly if some cells went into reversal, Figure 5 shows calculations for more conservative 235-out-of-240 and 370-out-of-380 systems, respectively.



	A	B	C	O
1	**Cell reliability**	0.995		
2				
3	**Configuration**	**Cells in series (*n*)**	**Min. cells req'd (*k*)**	**String reliability**
4	Single string	240	235	**0.9986**
5	Single string	380	370	**0.999995**

Figure 5 – Reliability of 480 V UPS systems for cells failing in short circuit

These calculations again demonstrate the dramatic differences in reliability for these different failure modes. In fact, for technologies that tend to fail open, such as VRLA, it is highly questionable whether a high-voltage UPS system could ever be made sufficiently reliable. At a minimum, a high-reliability system would require VRLA cells of exceptionally high reliability, deployed in multiple redundant strings, and, probably, a full monitoring system with single-cell ohmic measurement capabilities.

Cells that fail short have far higher reliability at the string level. The requirement here is that a failed cell must be able to support the full string discharge current, and must have an extremely low probability of ever failing open. Ni-Cd cells fit this description, with such high reliability at string level that redundant strings are not required for high reliability at the system level.

PARALLEL STRINGS – TOO MUCH OF A GOOD THING?

Applying the principles outlined in this paper, it might be assumed that it is generally better to install multiple parallel strings, and that more parallel strings are better than fewer. This is not always the case, as shown in Figure 4. This shows relative reliability and maintenance costs, related to the number of parallel strings. Cases are shown for a high-maintenance battery and a low-maintenance one, assuming that both have the same relative reliability.

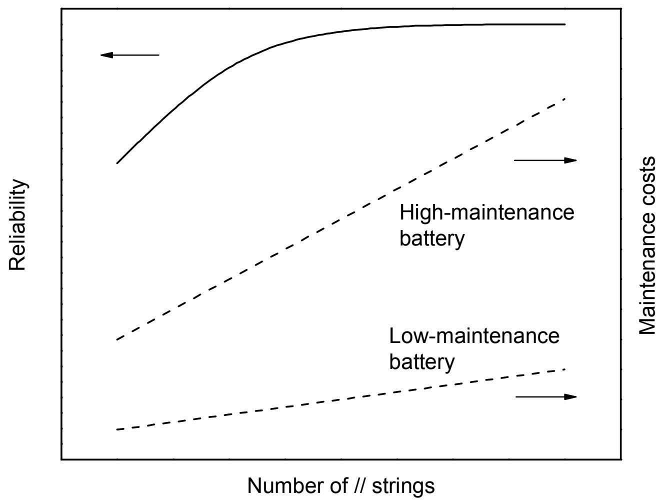


Figure 4 – Reliability and maintenance costs for parallel string configurations

For a battery technology with high inherent reliability there is less benefit to be realized by adding strings, and if the maintenance costs are high then chasing an extra 'nine' can carry a hefty price tag. On the other hand, a battery type with lower reliability and low maintenance costs can benefit substantially from parallel strings. From these principles a picture can be formed about the relative merits of parallel strings by battery technology and application.

- **Vented lead-acid** – with high reliability and high maintenance costs, parallel strings should be limited to those systems requiring fully redundant batteries for the highest possible reliability, or where needed because of capacity limitations.
- **VRLA** – with lower reliability and the possibility of failing open, parallel strings should be used as much as possible, particularly if a 'fit and forget' mentality is followed. Strings can be in a *k*-out-of-*n* system for energy applications such as telecom. High voltage strings, such as in UPS, should be avoided where possible. If used, they should be always be in fully redundant parallel configurations with as many strings as practical.
- **Ni-Cd** – with high reliability and very little chance of failing open there is little to be gained by implementing parallel strings, although the lower maintenance costs (compared to vented lead-acid) would not unduly handicap multiple-string systems
- **Lithium ion** – it should be ensured that the cells chosen are designed for float service with a normal failure mode of capacity fading, since technologies designed for consumer applications are much more likely to fail open. Having said this, the zero maintenance aspect of this technology effectively removes any constraints on parallel strings, (although the charge control electronics must be replicated for each parallel string and this cost must also be considered.) This outlook favors bulk production of a few cell types to achieve the lowest possible production costs, and a high degree of modularity in the final installation.

SUMMARY

Statistical analysis can be a valuable tool in improving the quality and reliability of the products we buy. For example, the calculations in this paper relative to series and parallel strings should help system designers make intelligent choices regarding the choice of technology and system architecture for their systems. At a minimum, the author hopes that users will think twice before deploying high-voltage VRLA batteries in critical UPS systems.

The FMEA methodology is already used extensively with electronic systems and can also be applied to electrochemical models. Such tools will become even more important as the industry moves into the electrochemical and electronic 'black box' approach of lithium-based systems, in which the closest some technicians will come to a battery is to see a status screen on a computer. As anyone with a passing interest in politics (or Mark Twain) will know, however, statistics can also have a darker side. It will always be possible to manipulate data and have the statistics favor a particular view, or product. As always, the rule of the day is *caveat emptor* – let the buyer beware.

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