PERFORMANCE AND LIFETIME COMPARISONS OF THE ROUND CELL, RECTANGULAR FLOODED CELLS AND VALVE REGULATED LEAD ACID (VRLA) CELLS

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ABSTRACT

At INTELEC 2004[1], the authors presented a limited analysis of field tests of 14,468 Round Cells. Failure and cell leakage rates were calculated and presented. For comparison purposes, some analysis was conducted on rectangular flooded and VRLA cells. Only cell leakage data was analyzed for the rectangular cells and failure rates were the only parameter presented for VRLA cells.

This paper will extend the analysis initiated in the INTELEC paper to include failure rates and leakage data on 28,000+ rectangular and 14,000+ VRLA cells. These data, when compared to the Round Cell performance, reinforces the superiority of the Round Cell in the critical areas of performance, life and maintenance.

Using the field results of the three battery types discussed above, an economic analysis was performed. This analysis considered initial hardware costs, real estate costs, installation costs, maintenance costs and replacement costs in determining the total cost of ownership.

The economic analysis demonstrated that the Round Cell has a lower life cycle cost than the other products when considering a long-term view. The length of the payback depends on many factors and was shown to be between 1.3 and 14.9 years. A view of 15 years or greater favors the Round Cell in every case considered.

INTRODUCTION

At the 2004 International Telecommunications Energy Conference (INTELEC)[1], the authors presented a review, 30 years after its invention, of performance experience with the Round Cell, which had been developed by Bell Laboratories in the 1960’s and placed into commercial production in 1974. With more than 1.5 million Round Cells shipped since that time, the paper described its unique design features, the early expectations of improved performance and life and presented actual field test data on some 14,000 Round Cells, ranging in age up to 24 years.

The summarized results indicated of that entire group of more than 14,000 Round Cells, at most only 19 and more likely only **two** individual cell’s reserve capacity had actually fallen below the 80% figure considered failure by the industry. Of the more than 600 strings of Round Cells tested, there were **no** string capacity failures throughout the entire 24 year period

While post seal leakage is generally considered a serious maintenance and safety issue with conventional cells, there were zero leaks in the entire 14,000 Round Cell group.

Further, original accelerated test predictions of positive grid corrosion and growth (normally the life limiting process in stationary lead acid batteries) had proved to be quantitatively accurate, based on measurements from a limited number of actual cells removed from the field after up to 23 years’ service.

Also, in that publication[1], some limited data were presented on the behavior of competitive Rectangular Flooded and VRLA cell designs also intended primarily for back-up reserve use.

Round Cell design, early performance expectations, and detailed actual performance behavior is contained in the INTELEC reference and will not be repeated here.

In addition to the Round Cell data previously presented, the extensive performance files of TPI have provided detailed information of capacity behavior, post and jar-cover leakage of both conventional and extra-large rectangular flooded as well as VRLA cells and batteries of the types most used in Telecom standby applications. These data will be presented, performance trend lines established for the various categories and comparisons made to similar data for the Round Cell.

The above information will allow more accurate characterization of lifetimes of the various designs. However, a primary purpose for the introduction and display of these data is to extract the type and frequency of needed test, maintenance and replacement information. Such information will allow assessment of quantitative maintenance and replacement costs throughout life to be applied to the various cell types. This information will then be introduced into standard Net Present Value (NPV) and break-even cost analyses to be made in comparison with the Round Cell.

EXPERIMENTAL PROCEDURE

1. Field Testing Procedures

TPI provides independent dc power system testing to various customers in the telecommunications, utility and UPS industries. Over the last 12 years as part of these evaluations, TPI has capacity tested over 70,000 cells, which included over 14,000 Round Cells. The purpose of these tests varies from site to site and from customer to customer.

Many of the tests on new batteries were on-site acceptance tests. Many of the other tests were by the request of customers to verify the battery performance. Some of the requests were the result of abnormal observations by the customer such as irregular voltages, unusual appearance and/or deep discharge events. In some cases, the customer was planning to redeploy the cells and wanted to ensure that the capacity was adequate.

The population of tested cells was not random as the customers selected the strings based on their specific needs. However, considering that in many cases the customer was concerned about the performance based on an abnormal observation, the sample used in this report would most likely be biased towards lower performing cells than a truly random sample.

The procedure for testing the battery strings was essentially the same for all sites. The guidelines of IEEE 1188[4] or IEEE 450[5] were followed with one exception; the cells were not equalized prior to the test. The cells were tested in an ‘as found’ condition unless there was a high resistance connection or cable that might jeopardize the site. In those cases, the connection/cable was repaired and/or replaced.

Prior to testing the battery, while the battery was still on-line, float voltages, specific gravities, temperatures and connection resistances were measured and recorded on every cell. Individual cell plate polarizations were determined using reference electrodes in most, but not all, strings tested. Each cell was visually inspected which included a ‘hook and look’ inspection for all List 1 Round Cells. Also included was a simple flashlight inspection for “sparkling” lead sulfate crystals, indicative of a float anomaly. Additionally, dc float current, ac ripple current/voltage, positive/negative to ground and ambient temperature were measured for most strings.

For VRLA cells, neither the specific gravity nor plate polarization was measured. However, internal ohmic values were recorded for every VRLA cell.

The string was isolated from the system prior to test. An automated load bank was used to provide a constant current load to the battery. The automated load bank held the current within one ampere throughout the test. The coup-de-fouet was recorded for every string tested. Typically, individual cell voltages during the test were recorded every two minutes.

The test rate in the vast majority of tests was based on the three-hour manufacturer’s rate to 1.75 volts. The tests were continued until at least three hours unless one or more cells reached a critically low voltage. If the average cell voltage was not at or below 1.75 volts at the end of the test, the test was continued beyond three hours until the average cell voltage reached 1.75 volts.

The string capacity was calculated in accordance with IEEE 1188[4] and IEEE 450[5]. The capacity was corrected for temperature after the test. The battery was recharged and reconnected to the system when the battery voltage was within 0.5 volts of the system. The battery completed the recharge at the normal float voltage of the system.

The test results and all of the readings were documented in the final report for each site.

2. Economic Analysis Procedures

Based upon the limited data presented, the INTELEC 2004 paper[1] found that the Round Cell battery appeared superior to conventional flooded or VRLA cells. The additional data presented in this paper confirms that superiority. The long-term capacity, life and cell integrity is markedly better than the other lead-acid cells. However, this high quality comes with a price tag. The Round Cell is widely considered as a superior cell, but it is also accepted that the Round Cell is a more expensive product.

As with any product, one would expect to pay more for higher quality. This is the case for many items such as televisions, appliances and furniture. An initial high price may be justified by an expected increase in life, an anticipated reduction in maintenance and lower or less frequent repair costs.

The question is whether the increase in quality is worth the cost. In order to determine this quantitatively, an economic cost analysis was conducted. Since economic factors are an important aspect in the battery selection process, this study may be helpful to users who are not driven by initial battery costs alone.

The economic study considered initial cell costs, battery stand costs, installation, initial acceptance tests, on-going maintenance activities, battery replacement costs, disposal costs, de-installation costs and real estate costs.

For comparison purposes, the costs were normalized on a conventional 4000 Ampere-Hour (AH), 48 Volt string. In addition, costs were based on a seismic zone 4 installation with an acid containment system.

The Round Cell costs were compared to a 4000 AH rectangular cell, a 1680 AH rectangular cell and a 2000 AH VRLA AGM cell. Conventional rectangular cells typically require a 1.25 ageing factor to account for an expected capacity loss as the cell ages. The 4000 AH rectangular cell must be sized for an effective capacity of 3200 AH. Therefore, for the cost analysis, two 1600 AH List 1S Round Cell strings were considered equivalent to the single 4000 AH string. The expectation of the Round Cell is that there is no capacity loss as part of the ageing process and therefore an ageing factor of 1.0 is using for sizing.

The 1.25 ageing factor is also required for the 1680 AH rectangular cell as well as the 2000 AH VRLA cells. Using the aforementioned logic, two 2000 AH VRLA strings and 2.4 1680 AH rectangular flooded strings were considered equivalent to the single 4000 AH string for this analysis.

The results of the economic study were calculated and presented using two methods. The first method (‘Cumulative Costs’) utilized a simple year-by-year calculation of the cost. The cumulative costs are graphed over time from zero to 40 years.

The second method utilized a Net Present Value (NPV) calculation. NPV converts all future expenditures into today’s dollars utilizing an Internal Rate of Return (IRR) expressed in percent. The NPV calculation was performed for every year from zero to 40 years.

When determining the costs associated with the various types of cells, every effort was made to utilize an objective source. The key costs for this analysis were the product costs and the replacement costs based on the projected lifetime of the cells. Whereas the product costs of the Round Cell can be accurately determined, the costs of the other products can vary depending on the manufacturer. Adding to the variability, different customers pay different amounts depending on their size and negotiations.

To remove as much variability as possible, typical customer pricing and list prices were used. The rack, containment and seismic modifications costs were similarly obtained.

The expected lifetime of the cells were obtained from the new TPI database information which is presented in this paper and from those data published in the INTELEC 2004[1] paper. The Round Cell data demonstrated that the capacity was consistent through 25 years of testing and the plate growth measurement and calculations indicated that it will have a lifetime of at least 40 years.

For the 4000 AH rectangular cell, only limited long term test data are available. However, rectangular flooded battery data indicates that the lifetime of these cells in typically between 15 and 20 years. However, post seal and jar/cover seal leaks have been, and continue to be, an issue as shown in the field results section. Although these leaks have little effect on plate capacity, they do lead to maintenance and connection problems. The leaks frequently cause end users to replace the cells even before the capacity becomes a problem. Based on these factors, the effective lifetime of the 4000 AH cells was determined to be 17 years.

The 1680 AH rectangular flooded cell lifetime was determined in a similar manner. There is significantly more data available for the 1680 AH cells as this cell type was distributed as the KS 15544 List 508 cell under the Western Electric name for at least 40 years. This cell has a good performance record but also suffers from post and jar/cover seal leaks. The lifetime for these cells was estimated to be 19 years.

The VRLA cell lifetime was based on the recent VRLA data presented herein and at INTELEC 2004[1]. Numerous papers[2,3,7] have documented the low reliability of VRLA designs. Based on the data presented in the results section, the lifetime of VRLA cells was determined to be seven years.

Installation costs were obtained from discussions with battery installers and installation groups. One advantage of the Round Cell is the ease of installation of the Round Cell rack. The time to install a Round Cell rack is substantially less than a conventional battery rack. However, much of the advantage is eliminated when compared to the 4000 AH cell since two Round Cell racks need to be installed for every 4000 AH string.

Acceptance costs were based on performing an on-site acceptance test for each installed string. These costs are based on the author's experience.

Maintenance costs are based on a review of the maintenance requirements of each type of cell for various manufacturers and the maintenance requirements of IEEE 1188[4] and IEEE 450[5]. The Round Cell maintenance requirements have been recently relaxed but have not been published at the time of the writing of this paper. However, the author's experience with the various products was also utilized in determining these maintenance costs. Since the Round Cell uses much less water and requires much less scheduled maintenance, the Round Cell maintenance was assumed to only be required once every other year. The maintenance requirements of the other flooded batteries were projected to be yearly. Due to the reliability issues of the VRLA cells, the maintenance requirements of the VRLA cells were projected to be the highest.

All of the costs are summarized in the Results section.

FIELD TEST RESULTS

1. Capacity Behavior

Overall String Capacity test results for Round (608 strings, 14,400 cells), Rectangular Flooded (1141 Strings, 28,000 cells) and VRLA cells (558 strings, 14,000 cells) are shown in Figures 1, 2, and 3.

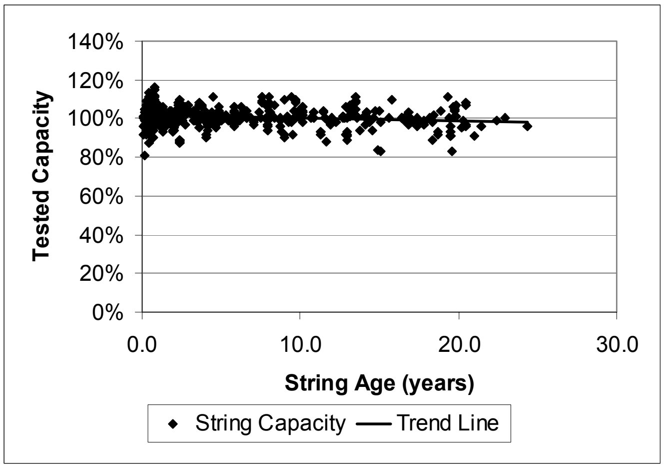

Figure 1 Round Cell Capacity vs Age

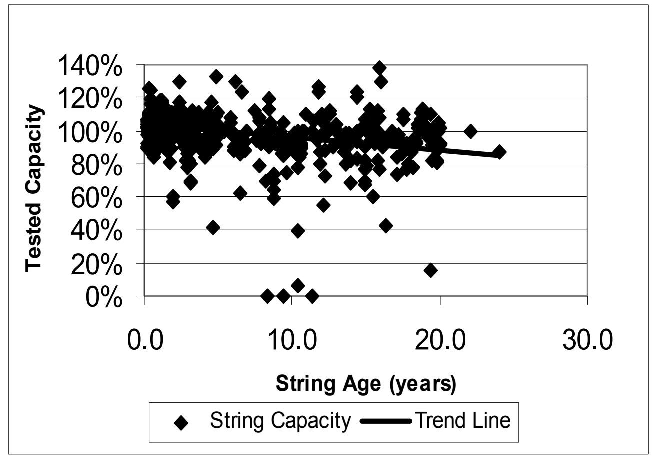

Figure 2 Rectangular Flooded Cell Capacity vs. Age

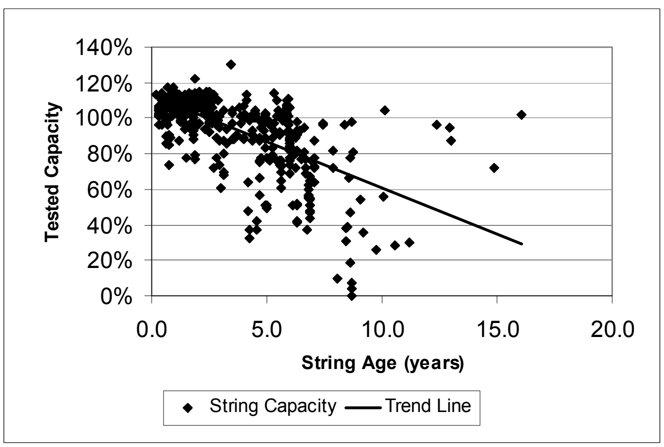

Figure 3 VRLA String Capacity vs. Age

A great deal of the data from the TPI database contained new cells. This influenced the trend lines in a positive manor. Additionally, failures during the first five years of life are typically caused by manufacturing issues. Therefore, it seemed advantageous to look at the data after this period to determine the typical life of these cells. Figures 4, 5 and 6 reflect capacity data for the three types of cells studied in this paper with those cells less than five years old removed. Also, the rectangular flooded data was further filtered to display only select sizes. Finally, the VRLA data was further modified by removing the GEL (non-AGM) cells which had skewed the data somewhat.

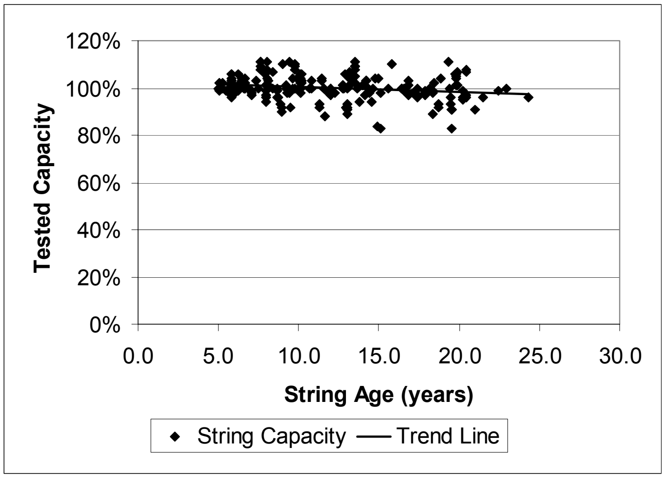

Figure 4 Round Cell 5+ years

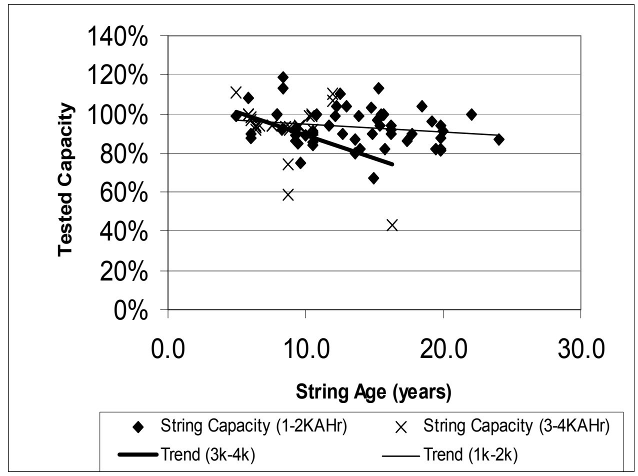

Figure 5 Rectangular Flooded Cells 5+ Years

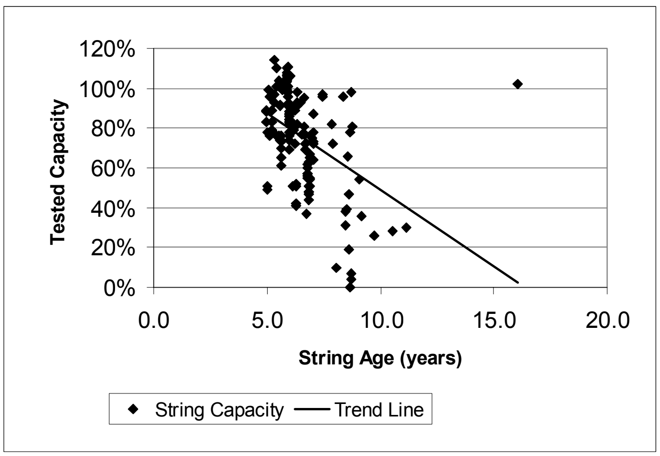

Figure 6 VRLA Cells 5+ Years

The string failure rates (all data) are shown in Figure 7, 8 and 9.

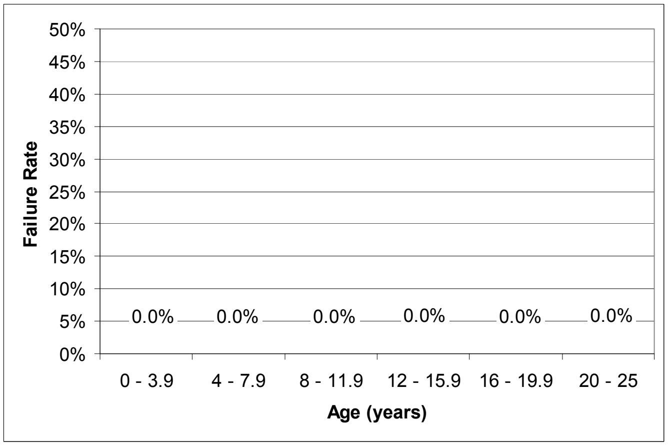

Figure 7 Round Cell String Failure Rate

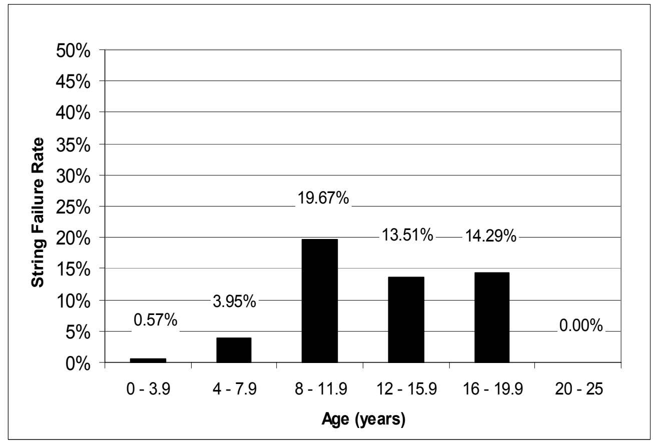

Figure 8 Rectangular Flooded String Failure Rate

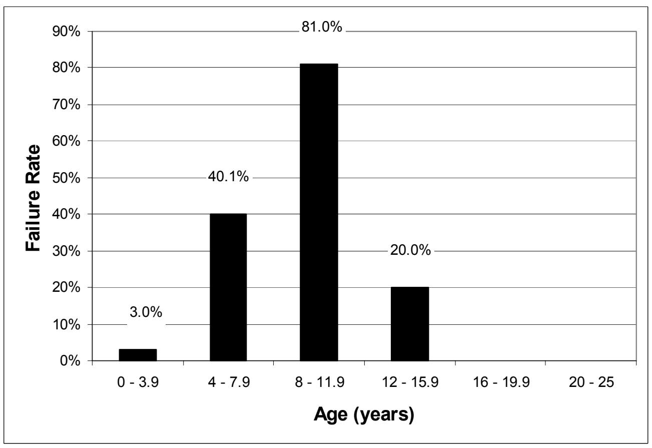

Figure 9 VRLA String Failure Rate

The individual cell failure rates (all data included) are shown for the Round Cell and the rectangular flooded cells in Figures 10 and 11. The data for the individual VRLA cell failures were not readily available.

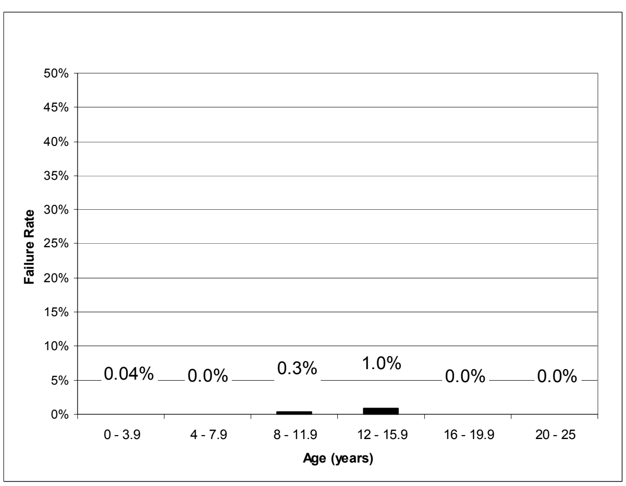

Figure 10 Round Cell Failure Rate

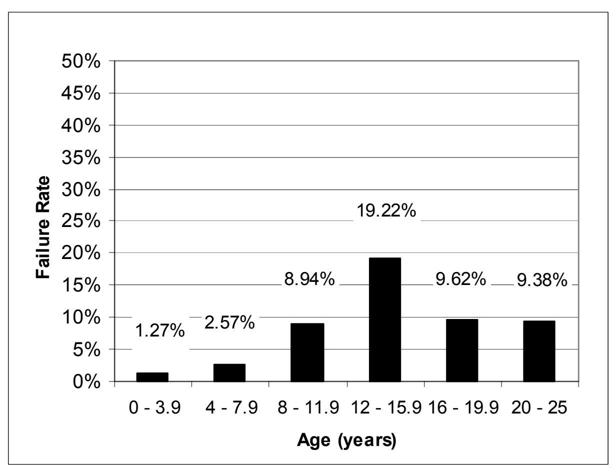

Figure 11 Rectangular Flooded Cell Failure Rate

The flooded rectangular data were further resolved to quantify the 1000 – 2000 Ahr size. These data are shown in Figures 12, 13, 14, 15, 16 and 17. Cells less than one year old were removed from this data.

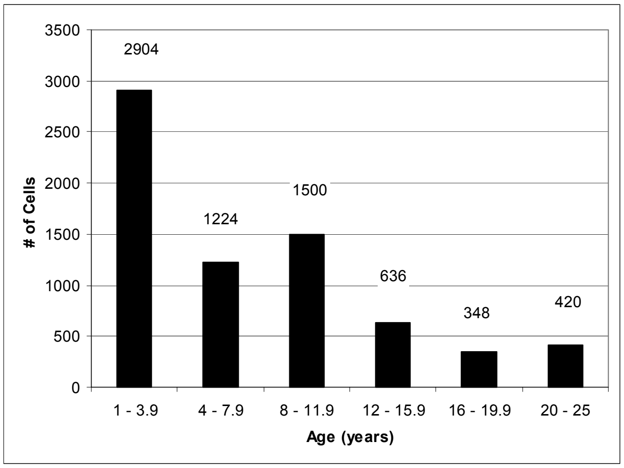

Figure 12 Total Number of Cells (1K-2KAH)

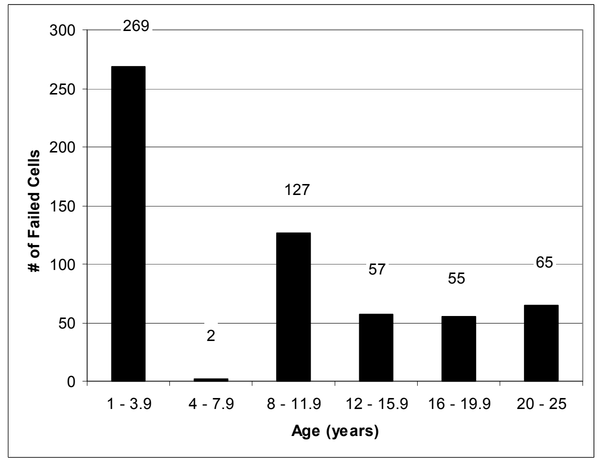

Figure 13 Number of failed cells (1K-2KAH)

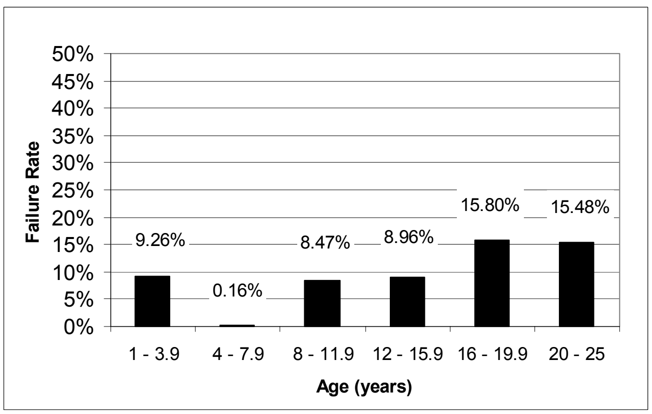

Figure 14 Cell Failure Rate (1K-2KAH)

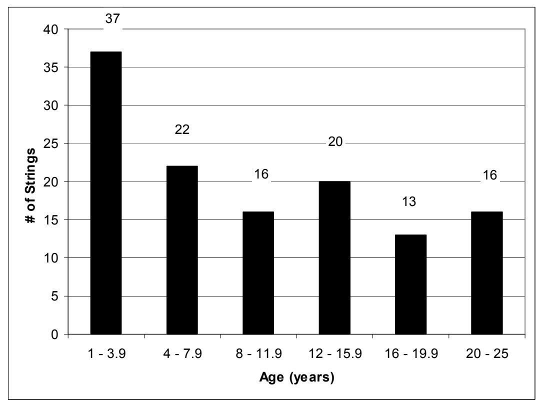

Figure 15 # of strings (1K-2KAH)

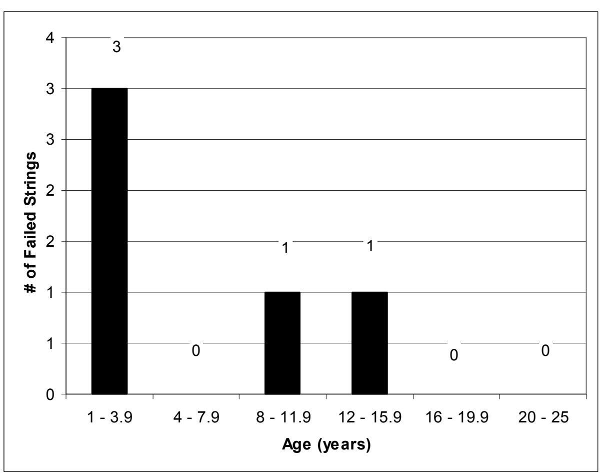

Figure 16 # of failed strings (1K-2KAH)

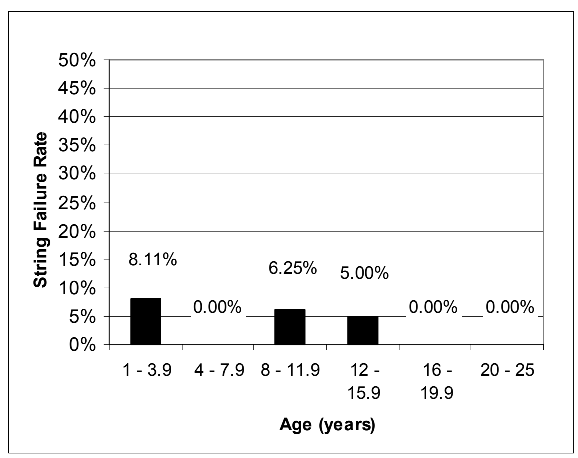

Figure 17 String Failure Rate (1K-2KAH)

An attempt was made to isolate and review the 3-4kAH rectangular flooded data. Unfortunately, the data were limited in this size cell and those data that were available were mostly new cells. The breakdown of cells in this range is shown in Figure 18.

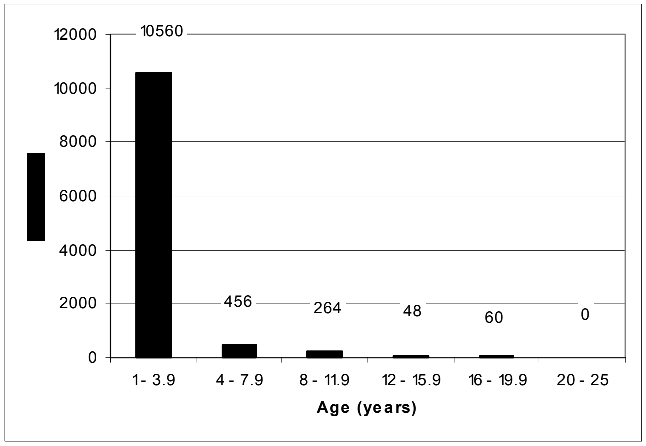

Figure 18 Total Number of Cells (3K-4KAH)

2. Leakage Results

Post seal leakage data for the various types of cells are shown in figures 19, 20, 21 and 22.

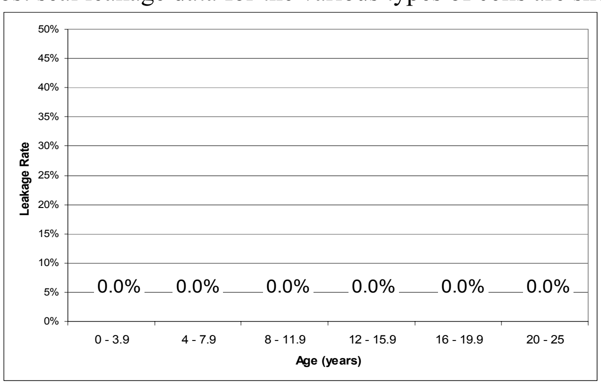

Figure 19 Round Cells Post Seal & Jar/Cover Leakage Rate by Age

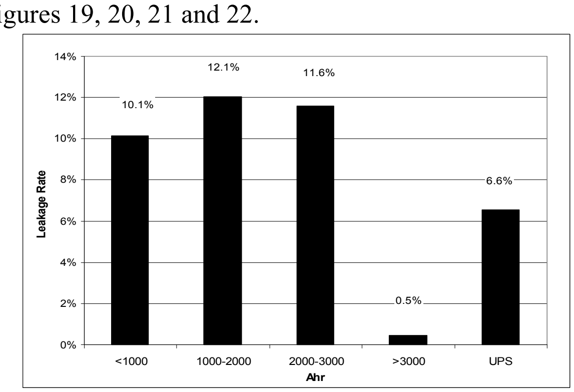

Figure 20 All Rectangular Flooded Leakage Rate by Cell Size

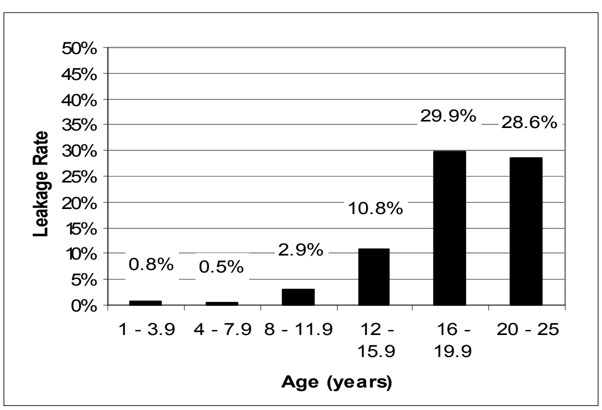

Figure 21 1K-2KAhr Rectangular Flooded Leakage Rate by Age

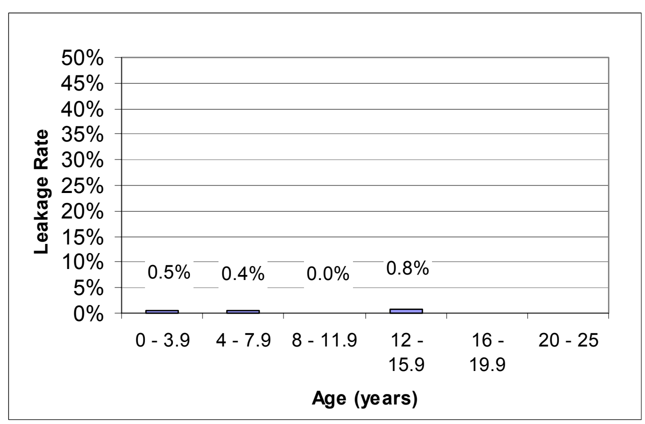

Figure 22 VRLA Leakage Rate by Age

3. Economic Analysis Results

In order to perform the economic analysis, certain costs had to be determined. This includes the values shown in Table 1. The labor rate and the real estate costs were obtained with conversations with users and installation and maintenance vendors. The inflation rate was determined based on a 10 year average increase of the Consumer Price Index (CPI) as reported by the Bureau of Labor Statistics[6]. The NPV Internal Rate of Return (IRR) was set slightly higher than the inflation rate.

Table 1 General Costs

Item	Cost
Labor rate	$70/hr.
Real Estate Costs	$45/sq.ft.
Inflation	3%
NPV IRR	5%

Table 2 Economic Analysis Pricing

	Round Cell	4000 AH	1680 AH	2000 AH VRLA
Life (years)	40	17	20	7
Cell Cost	$900 ($1,226)	$1,300 ($2,250)	$590 ($890)	$662 ($1000)
*Rack Cost (48V)	$3,180 ($4,100)	$2,216 ($4,000)	$1,425 ($3,000)	$0 ($0)
*Installation Hours	32	83	30	24
*Uninstall Hours		40	25	20
*Disposal Cost	$2,500	$2,500	$1,250	$1,250
Foot Print (sq ft)	18.75	30	28.58	10.58
Acceptance Test	$2,000	$3,000	$2,000	$2,000
Maintenance/yr (hrs)		17	10	20
Maintenance every other year (hours)	6			
Leak Cleaning (hours) -starting year		6 10	6 10	
Cell Replacement Cost -starting year		$3000 12	$1500 12	$1000 5
Acid Containment -Materials -Labor (hours)	$1,960 ($2,800)	$3,257 ($4,655) 16	$2,646 ($3,470) 10	
Seismic Zone 4 Rack -Materials -Labor (hours)	$2000 ($2600) 8	$2600 ($5300) 8	$675 ($1600) 4	$1200 ($1750) 1
Total Install Cost	$67,080 ($87,448)	$49,763 ($78,445)	$57,566 (82,824)	$41,676 ($59,000)
*Per String	**Numbers in parenthesis are list prices**			

Due to the reported post/jar leaks of the flooded cells, an additional cost was added to the 4000 AH and 1680 AH costs. It was determined that there will be additional maintenance after a certain point to perform cleaning activities associated with these leaks. These costs are reflected in Table 2.

Finally, it is likely that there will be some cell failures prior to a complete string failure. This is reflected in the data presented herein. At a point in the life of a battery string, there will be some cell replacements required. Although some of these failures may be covered under warranty, there is a cost associated with the replacement and disposal activities which is reflected in the cost analysis as shown in Table 2.

The economic analysis was completed using a typical customer pricing and also using the list price. The graphical results are shown in Figures 23, 24, 25 and 26. From this data, a break even point was calculated for each method and pricing. This is shown in Table 3.

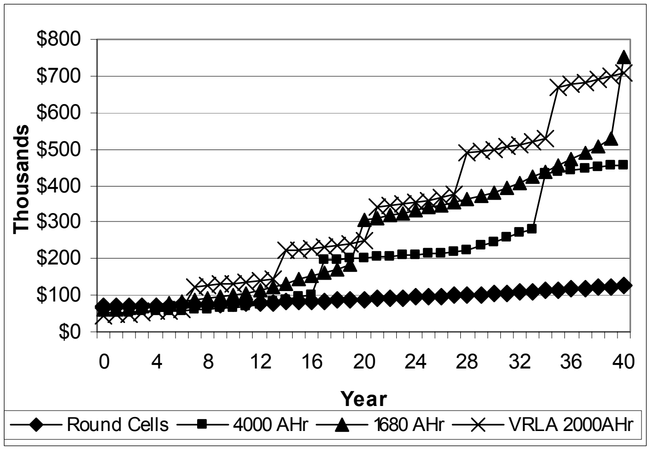

Figure 23 Cumulative Costs - Typical Customer Pricing

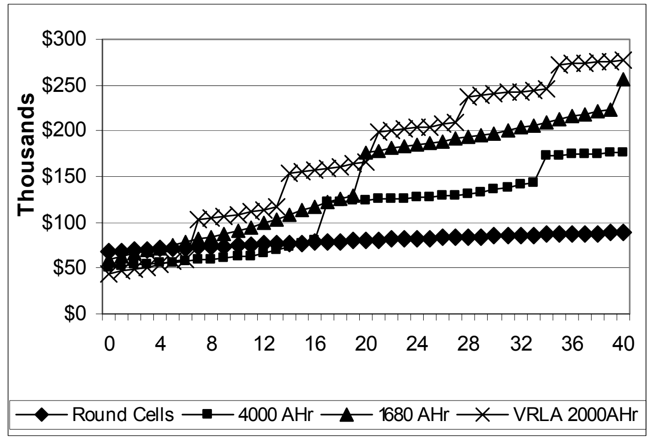

Figure 24 NPV Analysis - Typical Customer Pricing

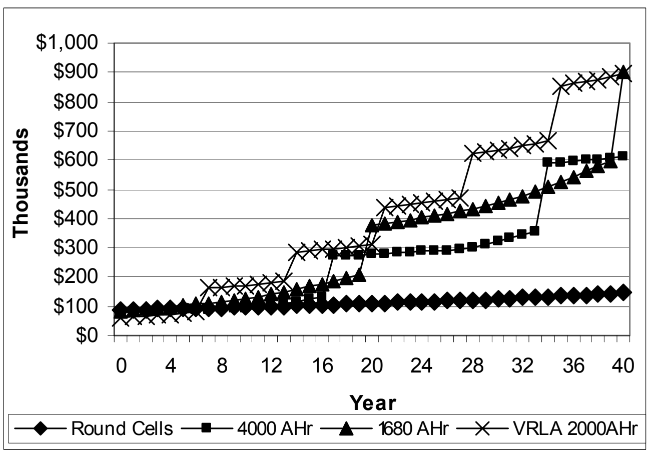

Figure 25 Cumulative Costs - List Price

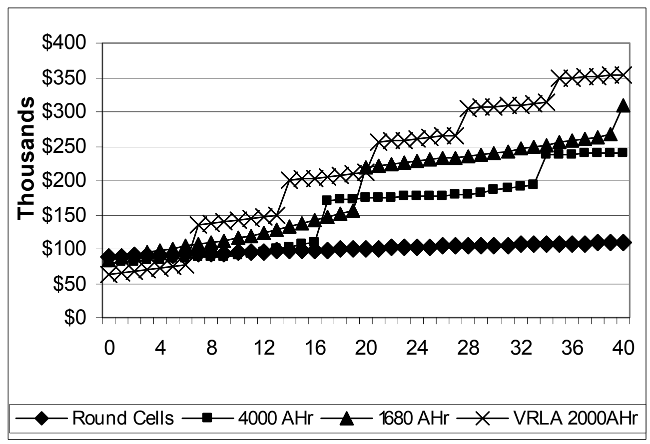

Figure 26 NPV Analysis - List Price

Table 3 Break Even Point as Compared to the Round Cell (years)

	4000 AH	1680 AH	2000 AH VRLA
Cumulative Costs - Typical Customer Pricing	12.8	2.9	6.2
NPV – Typical Customer Pricing	14.9	3.3	6.3
Cumulative Costs – List Price	11.3	1.3	6.2
NPV – List Price	12.2	1.4	6.3

DISCUSSION OF RESULTS

1. Capacity and Leakage Results

The comparison plots lead to the obvious conclusion (as has been shown in other publications[2,3,7]), that the capacity failures of the VRLA design place it in an entirely different life and reliability population than either the round or rectangular flooded designs. Figure 3 shows that the VRLA battery string capacity regression line reaches 80% in 6-7 years, while Figure 6 shows 40% string capacity failures in years 4-8, increasing to 80% string failures in the following 4 years. The wide capacity scatter shown in Figure 3 provides convincing evidence that the VRLA designs cannot be considered as reliable backup for more than 2-4 years. (This is further emphasized by comparison of Figures 4, 5 & 6).

By contrast, the rectangular flooded designs show relatively reliable capacity behavior for more than 15 years for the 1000-2000 AH designs. Fig. 2 shows a relatively flat capacity regression trend line, which has not reached 80% by 20 years. However, Fig. 14 shows significant capacity failures by year 12, increasing to more than 15% by year 16. Further, Figure 21 shows that beyond year 16, post seal leakage plagues almost 30% of this size rectangular flooded cell product. Although the data are limited, the larger 3000-4000AH designs appear to have a shorter reliable lifetime as shown in Figure 5.

By contrast, the Round Cell appears to be in both a qualitatively and quantitatively higher universe, showing zero string capacity failures for at least 24 years (Figure 7) and only 19 cell failures out of the more than 14,000 round cells in the entire test population (Figure 10). As discussed in the INTELEC 2004 paper[1], 17 of the 19 cell failures were attributed to known issues that were not related to the design or life of the Round Cell, leaving only two actual failures. Figure 19 documents the zero post seal and jar/cover seal leakage characteristics of the more than 14,000 Round Cells tested (>28,000 post seals (+) & (-)).

As was noted in the earlier paper[1], any of the alternative designs display, literally (and mathematically), infinitely more failures in either capacity or leakage when compared to the zero string capacity and zero post seal failures of the Round Cell. Consideration of at least a 40 year life for the round cell appears reasonable, based on the data presented and by comparison to the other designs.

While the data appear to show reasonable leakage behavior for the VRLA designs, it does not include the statistically limited, but financially overwhelming and equipment destructive, periodic catastrophic thermal runaway incidents which have resulted from those VRLA designs which have shown significant post seal and jar/cover seal leaks, often early in the life of the product[7]. Moreover, VRLA capacity behavior would rule against its usage in any other than short-term applications. The well behaved capacity behavior of the flooded rectangular product is stained by the post seal leakage results which cause significant inspection, cleaning and potential safety and maintenance efforts and costs, especially later in cell life.

2. Cost Analysis Results

The economic analysis clearly demonstrates that there is a significant cost difference between a short and a long-term view of battery purchasing. The Round Cell has the highest initial cost of any of battery types described in this paper. However, the number of years it takes for the Round Cell costs to equal the costs of the other battery types range from 1.3 to 14.9 years as shown in Table 3. After this point, the Round Cell becomes less expensive. As shown in Figures 23, 24, 25 and 26, the cost savings of the Round Cell can be nearly $800,000 at 40 years.

As shown in the economic analysis graphs, there is relative little difference between all of the cell types for about the first six years. However, over time, the cost savings in the Round Cell are obvious and dramatic.

The question posed earlier in the paper was whether the quality of the Round Cell was worth the cost. The answer depends on the projected lifetime of the installation and the type of cell to be installed. If the length of time considered is 15 years or greater, the Round Cell is always the least expensive choice. If one just considers the initial purchase price and/or a lifetime of a few years, then the Round Cell may be the most expensive choice.

There are also intangible benefits to consider such as piece of mind and reliability. The data on Round Cells clearly show that they have the highest reliability and the least problems (leaks, etc.). These items cannot be completely quantified in the economic analysis. However, due to these intangibles, an argument can be made that the Round Cell is a better choice for a short-term view even when the economic benefits are not evident.

The values for the economic analysis were determined in an objective manor with a direct correlation with the data presented in the paper where possible. Some of the values have a degree of subjectivity. This subjectivity may allow some to dispute the values selected. However, a change in one or two values has a minor impact on the final numbers. The four variations (Figures 23-26) of the analysis do provide a reasonable range of results.

CONCLUSIONS

This paper, along with the INTELEC 2004 paper[1], clearly demonstrates that all batteries are not created equal. The data show that the Round Cell is clearly a superior cell to other battery types compared.

The data also show that the Round Cell has the highest initial costs. An economic analysis was performed to determine if the superior quality could be cost justified over time. The economic analysis demonstrated that the Round Cell has a lower life cycle cost than the other products when considering a long-term view. The length of the payback depends on many factors and was shown to be between 1.3 and 14.9 years. A view of 15 years or greater favors the Round Cell in every case considered.

The majority of the data presented herein was obtained from environmentally controlled telecommunications installations. This analysis may not apply to other applications. However, given this constraint, the Round Cell is clearly the recommended choice when life-cycle costs are considered.

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