WANTED: REAL WORLD BATTERY LIFE PREDICTION

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ABSTRACT

For years lead-acid battery manufacturers have been telling us that their "life" estimates are only that -- estimates. Actual service life can –and will – be different. The rule of thumb has been that a battery's life will be cut in half for every so-many degrees that it is operated above nominal 25°C [e.g., every 8.3°C for VRLA, every 10°C for vented] [editorial note - A search of the literature finds values all over the board for this number; differences in specific gravities of the batteries are partly to blame, as is the point where temperature is measured] . The problem is that people who can control the battery environment will normally not choose to run continuously above the optimum temperature. Those who cannot control their environment will never see continuous operation at a constant temperature – no matter what it is! It will be hot one day and cold another. So what is a user supposed to do with that information? Which is worse - a single excursion of 30 days at 30°C or twelve excursions once per month of only 24 hours each at 40°C?

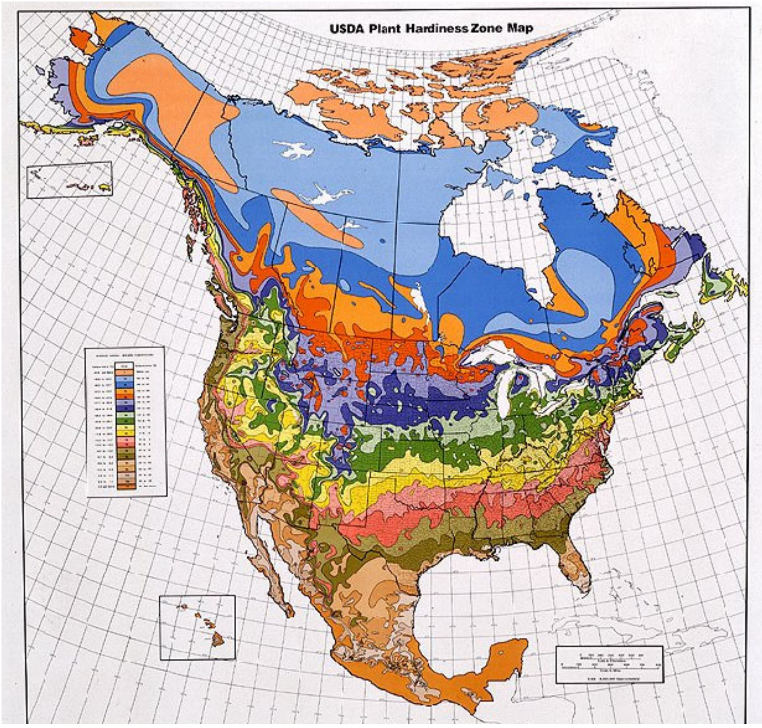
This paper attempts to explain how battery life is affected when the ambient temperature is characterized by frequent peaks of both hot and cold. It then proposes a format for battery manufacturers to inform their customers what life to reasonably expect from any particular battery model when it is operated in the conditions in which the customer will actually place it.

INTRODUCTION

Users of stationary lead-acid batteries have been frustrated for years about how long they can expect their battery to last. We see terms like "design life," "warranted life," and "expected service life." The latter is usually the one we care about. But pinning down a realistic service life is hard to do. Battery manufacturers, if they address it all, usually publish something about life expectancy at a certain temperature. Of course there are many other variables, such as the number & depth of discharges, time spent on high-voltage charge, plate design, oxygen recombination efficiency, etc., but these are usually shaken off. Heat is the real killer. So the manufacturer tells you something like, "VRLA battery life is reduced by 50% for every 15° F increase in temperature above nominal 77° F." In other words, dear user, if you maintain your battery at 92° F instead of 77° F, your "ten year battery" will only last five years. But who do you know that will keep their batteries at 92° F day in and day out on purpose? It just doesn't happen. And don't forget the fine print. Is the manufacturer talking about "ambient temperature" (i.e., the temperature of the air in the vicinity of the battery), or "battery temperature" (the temperature of electrolyte inside the battery)? The former is pretty easy to get and the latter is extremely difficult to get. What we need is a standard method of predicting performance in terms that the average user can understand.

BACKGROUND

Uncertainty about the reliability of a battery to deliver energy when it is most needed is the number one reason why users migrate to other sources of back-up power such as fuel cells, flywheels, and gen sets. Recognizing this problem several years ago for batteries in outdoor enclosures, Bellcore (now Telcordia) drew some arbitrary lines across the map of North America at various latitudes and designated four zones. [1] Batteries in the band reaching across the Canadian border should be at or near their design life. As one moves south a larger percentage is chopped off the battery's life, so that a "10-year" battery lasts 9 years in Zone 1 and drops off to only 3 years in Zone 4. While this method was simple to use, it was inadequate. Even poor students of geography understands that some sections of the country get more sunlight than others, and higher altitudes tend to be cooler than lower altitudes, as shown in Figure 1.



USDA plant hardiness zones [2]
Figure 1

Figure 1 shows that the same climate can extend across all of the Bellcore zones. Plus there are both daily and seasonal variations. For example, Dayton, Ohio and Denver, Colorado are both at about the same latitude, but Denver sees more extremes. The yearly average high and low temperatures for Denver range from 36°F to 64°F, with extremes from –40°F to +104°F. Dayton averages a more moderate 50°F to 61°F, with extremes from -22°F to +102°F. Dallas, Texas and San Diego, California are at the same latitude, but Dallas temperatures run 20°F hotter in the summer months and 10°F -to-15°F cooler in the winter months. The vagaries of weather can be surprising. Fairbanks, Alaska has seen temperatures from a high of +96°F to a low of -64°F. The record high temperature for North Dakota (121°F) is higher than for any of the southern states including Texas, Louisiana, Mississippi, Alabama, Georgia, or Florida [3]

Stationary batteries installed in UPS systems for data centers or central offices and mobile switching centers for telecommunications generally have a pretty pampered life, with temperatures fairly constant (and reasonably low) throughout the year. By contrast, there are some 200,000 wireless cell sites scattered around the country, many of which have little or no conditioning of the battery's environment. Godby and Ashton[4] reported temperatures inside SLC cabinets in Arizona as high as 161°F during the day. In some parts of the country, night-time temperatures may drop significantly, while in other places temperatures never drop below the manufacturer's recommended temperature for weeks or even months at a time. Godby and Ashton's data showed cabinet temperatures dropping to a chilly 113°F in those Arizona July evenings!

Because batteries have a high thermal mass, their internal temperatures tend to lag slowly behind changes in their ambient air temperature. If daily air temperature excursions are fairly extreme, the battery strings will tend to stabilize around the temperature midpoint. Jaworski [5] [6] noted that a battery will not be able to follow very rapid temperature changes but should have no trouble following slow trends. One expects to see seasonal variations but not daily ups and downs. Jaworski also presented data showing that batteries that experience high peak internal temperatures are likely to suffer lower life than batteries that experience more prolonged temperatures at lower levels above nominal 77°F.

Unfortunately for lead-acid batteries, time spent at cold temperatures does not make up for time spent at high temperatures. This is less so for flooded batteries, which allow liquid to be replenished during maintenance. Valve regulated batteries are not designed to add liquid. When a VRLA battery gets hot enough, recombination breaks down, the valve opens, and hydrogen escapes. The hydrogen can never be recovered, so it can never recombine into water molecules that the battery needs. The result is dry-out and death of the battery.

The IEEE has attempted to give guidelines on the effect of high temperature on battery life. IEEE 1187 [7]. Annex C shows the usual temperature-vs-life chart with a fairly linear effect of 50% reductions in life for every 8.3°C (15° F) increase in <u>electrolyte</u> temperature. IEEE 450 has a similar section. [8] It then goes on to extrapolate from that a formula for "months at elevated temperature" versus months at "normal (25°C) temperatures." It says, "the number of intervals used… depends on the observed temperature fluctuation; more intervals should be used if the temperature variation is significant." [note: variations of more that 3°C are considered "significant."] It then gives a fairly scary looking formula that really boils down to this: calculate from Table 1 what percentage of life you will lose at each temperature, then calculate the number of months (or other time intervals) you will spend at each temperature level, add them together, and compare the total to what your battery's life is supposed to be at normal (25°C) temperature.

Suppose you have a battery rated for 10 years (120 months) at 25°C (77°F), but you operate your battery at 33° C (92° F) for one month. The table says to reduce the life of the battery to approx 52% of its rating (which is what your battery life would be if you operated for 120 months at that temperature). However, since you operate the battery at 33°C for only one month, it would be the equivalent of (1 / 0.52) = 1.92 months at nominal 25°C, so it would take almost one month off the life of the battery. If you operate at several different temperature levels, you would sum all of the deratings and apply them against the nominal battery life.

IEEE 450 gives the following example.

$$\text{Life} = \frac{\text{Nominal life expectancy of battery in months}}{\left\{ \left[\frac{1}{\%\,\text{Life}} * \text{Mos @ } T_1\right] + \left[\frac{1}{\%\,\text{Life}} * \text{Mos @ } T_2\right] + \ldots + \left[\frac{1}{\%\,\text{Life}} * \text{Mos @ } T_n\right] \right\}}$$

Where: Life = Predicted battery life after derating for temperature
% Life = Value from the chart for a given temperature
Mos @ T_n = Number of months (or other time periods) at a given temperature

Formula 1

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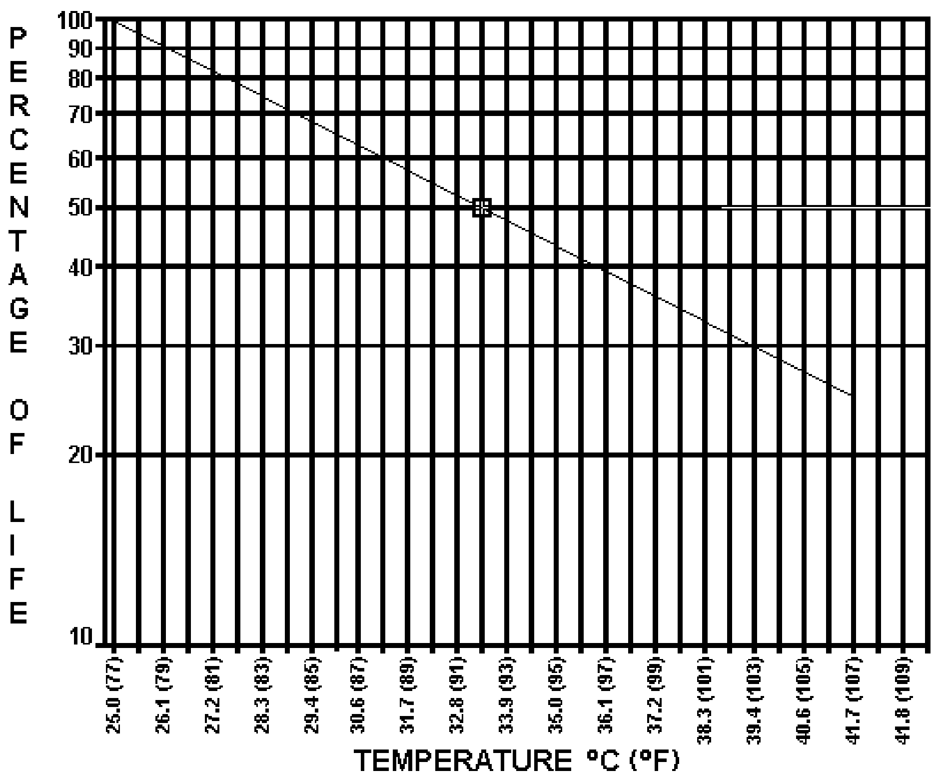
Table 1
Thermal Degradation Curve For lead Calcium Batteries
Battery Life vs. Average Battery Temperature [8]



EXAMPLE: The electrolyte temperature at installation "Y" averages 91° F for four months of the year, 86° F for four months of the year, and 77° F for four months of the year. The nominal life (per the battery manufacturer) is 20 years (240 months)

$$\text{Life} = \frac{240}{\left\{ \left[\frac{1}{0.52} * 4\right] + \left[\frac{1}{0.65} * 4\right] + \ldots + \left[\frac{1}{1.0} * 4\right] \right\}}$$

$$\text{Life} = \frac{240}{7.69 + 6.14 + 4} = \frac{240}{17.84} = 13.45 \text{ years}$$

The installation "Y" battery ages:	7.69 months at its 4 months at 32.8° C (91° F)					
	6.14	"	" "	4	"	" 30.0° C (86° F)
	4.0	"	" "	4	"	" 25.0° C (77° F)

Therefore, the battery ages an equivalent of 17.4 months per calendar year. If the battery sees these temperature blocks every year, the battery life will drop from 20 years to 13.45 years.

Which is worse: one long moderate temperature or several short high temperatures?

The author posed the following hypothetical problem to several battery experts:

Assume you have two operating conditions. Which one takes the most life from the battery?

Condition 1: A VRLA battery operates continuously at 30° C for one month (720 hours)
For the rest of the year the battery operates at 25° C

Condition 2: The same VRLA battery model operates at 40° C for one day (24 hours) out of every month
For the rest of the year the battery operates at 25° C

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METHOD A - Curtis Ashton says one could do a fairly quick calculation directly from the Arrhenius formula (which is the basis for the curve in Table 1)

$$\text{In}\left[\frac{\text{Life 2}}{\text{Life 1}}\right] - \frac{\Delta H}{R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

Where:

ΔH =	activation energy; for lead-acid batteries equal to approx 17,000
T1 and T2 =	temperatures in absolute Kelvin
Life 1 =	assumed life at T1 (77° F)
R =	constant equal to 1.987

Arrhenius Equation
Formula 2

If you assume no heat-up or cool-down time, you can extrapolate as follows. Suppose your nominal battery life is eight years at 25° C.

For the hours when the battery in condition 1 operates at 30° C, you accelerate life by a factor of 1.6. In other words, in the 720 hours of that month you operate at 30° C, you have actually used up 1156 hours of battery life.

For the hours when the battery in condition 2 operates at 40° C, you accelerate by 3.95. In other words, every 24 hours at 40° C equates to 95 hours of battery life used.

Running the calculations on an eight-year battery that should die on December 31 of the 8th year…

Condition 1	battery dies on August 23 of the eighth year (loss of 4.25 months total)
Condition 2	battery dies on April 15 of the eighth year (loss of 8.5 months)

The basic flaw of this approach is that the battery does not jump rapidly from one temperature to another. If the ambient temperature jumps quickly, the battery will lag, so that the cumulative effect of several short temperature extremes with cool-off periods in between could be less than suggested above. The thermal mass of the battery (hence the heat-up and cool-down rate) depends upon the size of the battery.

METHOD B - Frank Vacarro suggested a more scientific approach along the lines of the IEEE model, making certain assumptions that the primary failure mode is positive plate corrosion and growth. The minimum energy required for the onset of this corrosion is approximately 17 kcal/mole. This is equivalent to life halving for each 9^0C rise in temperature, or (Life T^0C /Life25^0C) = $2^{(T-25)/9}$

For Condition 1,

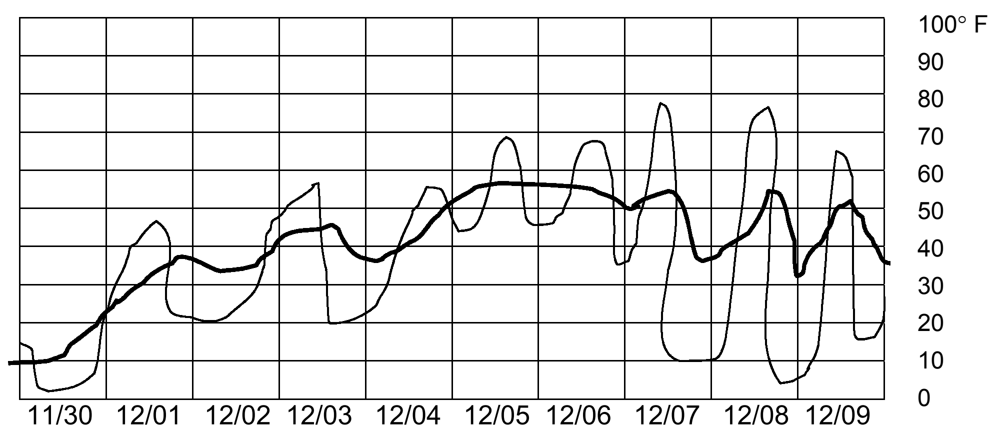
T^0C = 30^0C for 30 days/year.
Aging Factor = $2^{(30-25)/9}$ = 1.47 for 30 days/year.
or 30 days at 30^0C = 44 days at 25^0C
1.04 years of life are expended every year, i.e., (335+44)/365

For Condition 2,

T^0C = 40^0C for 12 days/year.
Aging Factor = $2^{(40-25)/9}$ = 3.18
or 12 days at 40^0C = 38 days at 25^0C
1.07 years of life are expended every year, i.e., (353+38)/365

Conclusion: The battery ages slightly faster in Condition 2 than in condition 1, but this could be offset depending upon the battery's size and mass.

While the above methods are both a notch better than the previously mentioned Bellcore Zones, the limitations are immediately obvious.



US daily temperature variations, ten days [9]

Figure 2

Figure 2 shows an arbitrary ten-day spread of temperature excursions, with some fairly extreme variations in a short amount of time. The heavy line shows a 24-hour smoothed average that would be more like that experienced within a battery. You can see that even the smoothed out line shows some significant variations. Although this is wintertime data, you can see that trying to apply this type of erratic data to the IEEE model would be very tedious. Instead of three or four time periods, one might have to use dozens or even hundreds! Looking backward at the data and working with a computer might allow one to estimate the impact on an existing battery plant, but how to use the data as a predictor of future conditions is not clear.

Jaworski [5] proposed a method in which one would analyze statistical distribution of historical battery temperatures. This assumes that one has recorded accurate electrolyte data from previous installations in the area or one has extracted from ambient data that is available from the local weather bureau. Jaworski proposed the formula

$$L_{Average} = \int_{T_{max}}^{T_{max}} P(T)\, A_{25}\, (T)dT$$

Where: P(T) = the density function of the battery temperature distribution

Formula 3

One can vary the mean and variance to change the independent variables from battery to ambient temperature.

Without going into details of how this formula and all of its derivatives work, the reader can see that the process quickly gets more complicated than the average user can (or will be willing to) undertake. Although the technology probably exists to gather enough data points and to massage them through a microprocessor to arrive at fairly accurate predictions, the benefit of such precision may not justify the cost of collecting the data. Therefore we must make some trade-offs and content ourselves with close approximation.

PROPOSAL

The industry needs something that a user can quickly understand and implement. The battery manufacturer could conceivably use the technique that has been proposed by Jaworski (or they could use some other method) and tabulate the data in a user-friendly format. For every battery model that a manufacturer sells, the author would like to see a table similar to the one shown in Table 3.

Table 2

Proposed format

Approximate percent reduction in VRLA battery life for nominal 10-year (87,600 hour) design life

Hours oper'n at temperature above nominal	**Temperature (°F/°C)** (measured at the negative terminal of the battery)									
	77 25.0	**79 26.1**	**81 27.2**	**83 28.3**	**85 29.4**	**87 30.6**	**89 31.7**	**91 32.8**	**93 33.9**	**95 35.0**
<100	0	0	0	0	0	0	0	0.001	0.001	0.001
100-500	0	0	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003
500-1000	0	0	0.002	0.003	0.004	0.004	0.005	0.005	0.006	0.007
1k – 5k	0	0	0.010	0.015	0.018	0.021	0.024	0.027	0.030	0.033
5k – 10k	0	0	0.021	0.030	0.037	0.042	0.049	0.054	0.061	0.066
10k - 20k	0	0.001	0.041	0.059	0.073	0.083	0.097	0.108	0.121	0.132
20k – 30k	0	0.004	0.062	0.089	0.110	0.125	0.146	0.163	0.182	0.199
30k – 40k	0	0.013	0.082	0.119	0.146	0.167	0.194	0.217	0.242	0.265
40k – 50k	0	0.029	0.103	0.[illegible]	[illegible]	[illegible]	0.243	0.271	0.303	0.331
50k – 60k	0	0.050	0.123	0.[illegible]	[illegible]	[illegible]	0.291	0.325	0.363	0.397
60k – 70k	0	0.073	0.144	0.[illegible]	[illegible]	[illegible]	0.340	0.380	0.424	0.463
70k – 80k	0	0.091	0.164	0.237	0.292	0.333	0.388	0.434	0.484	0.530
>80,000 hrs	0	0.100	0.180	0.260	0.320	0.365	0.425	0.475	0.530	0.580

Warning !!
Example only; data in this table is not valid

From this table, the user would add the cumulative hours in each temperature bracket, irrespective of the number of excursions, and calculate the cumulative reduction of battery life at each level (shown as a percentage reduction on the table). Adding together all the percentages would yield a total percentage to be taken off the nominal life.

For example, suppose you expect over the next ten years to expose your battery to the temperatures shown below.

20 days/yr = 480	hrs/yr x 10 years	= 4,800	hrs @ 93°F =	.030
40 “ “ “ 960	“ “ “ “ “	= 9,600	“ “ 91°F =	.054
75 “ “ “ 1800	“ “ “ “ “	= 18,000	“ “ 87°F =	.083
80 “ “ “ 1920	“ “ “ “ “	= 19,200	“ “ 79°F =	.001
				.168 x 100 = 16.8% reduction in life

0.168 x 87,600 = 14,717 hours / 24 = 613 days / 365 = 1.68 years of lost life
10 – 1.68 = 8.32 years expected life

The intention of table 2 is simply to propose how a battery manufacturer might present the information. The data is fictitious. It would be up to the battery manufacturers to determine what the appropriate intervals should be and to state their parameters and assumptions. These would include:

- Is the normal failure mode of this battery positive grid corrosion or negative limitation?
- Is the balance between grid corrosion and negative gassing the same at 25°C as it is at 30°C?… or 40°C?… or?
- What is assumed to be the charger voltage?
- Is temperature compensated charging assumed to be in use?
- Does this particular battery have excess electrolyte?
- What is the assumed number & depth of discharges over the life of the battery?

Ideally the battery manufacturers would agree on a standardized format that they all would use, with a common set of assumptions.

Perhaps the greatest failing of the proposed life prediction table is that it only addresses the cumulative hours at any given temperature; it fails to distinguish between one long operation at a given temperature compared to many short excursions separated by periods of cool operation. And of course it does not factor in such things as the number, depth and separation of discharges. Nevertheless, it could serve as a quick tool that would provide a much higher accuracy than is generally available today. For an owner who has gathered reasonably good data about temperatures to which the battery has been exposed, it would help identify when it is time to replace a battery. For a user who has pretty good information about the environment in which a battery will be used, it would provide a guideline for what life to reasonably expect for such an application.

CONCLUSION

Little information is available to help a user predict the actual service life of a battery when it is not kept at a stable temperature. Several approaches have been put forth to more accurately predict the reduction of life resulting from periodic exposure to high temperatures, but they are unwieldy and unlikely to gain wide user acceptance. This paper proposes one method of summarizing the calculations, and it makes a plea to battery manufacturers to provide user-friendly information. The battery manufacturers probably do not have the information needed to populate the proposed table. The manufacturers would have to do testing to provide reliable data. The battery manufacturers would also have to agree on a consensus standard on the best way to report such data. As creation of such standards take at least six years, work needs to be started as soon as possible.

ACKNOWLEDGEMENTS

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REFERENCES

[1] O'Sullivan, Thomas, "Generic Requirements and Objectives for Fiber in the Loop Systems," TA-NWT-000909, Bellcore, December 1993

[2] http://www.usna.usda.gov/Hardzone/, USDA Plant Hardiness Zone Map

[3] http://www.worldclimate.com, derived from NCDC TD 9641 Clim 81 1961-1990 Normals, 30 years between 1961 and 1990.

[4] Godby, J & Ahston, C, *Temperature of Equipment/Battery Cabinets in Non-Controlled Environment Locations in Phoenix, AZ,"* IEEE 0-7803-2034-4/94, 1994

[5] Jaworski, Robert K*, "Effects of Nonlinearity of Arrhenius Equation on Predictions of Time to Failure for Batteries Exposed to Fluctuating Temperatures,"* Proceedings of the Nineteenth Annual Intelec Telecommunications Energy Conference, San Francisco, CA, 1998

[6] Jaworski, Robert K, *"Statistical Parameters for Predicting Time to Failure of Telecommunications Batteries,"* Proceedings of the Twentieth Annual Intelec Telecommunications Energy Conference, Copenhagen, Denmark, 1999

[7] IEEE Std 1187-2002, *"IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications"*

[8] IEEE P450-R10, "*IEEE Recommended Practice for Maintenance, Testing and Replacement of Vented Lead-Acid Batteries for Stationary Applications,--Annex H, Effects of elevated electrolyte temperature on vented lead-acid batteries,"* April 2001.

[9] www.ems.psu.edu/wx/usstats/uswxstats.html, "*Hourly US Weather Statistics"*