Charging pure lead-tin batteries:

A guide for CYCLON® and Genesis® products

First Edition

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General

The superior charging characteristics of the pure lead-tin[1] product makes it the power source of choice in demanding applications that require features such as extremely rapid charging and other characteristics not found in conventional valve regulated lead acid (VRLA) batteries. Conventional sealed lead batteries are not suited for this type of charging, where charge currents can be of the order of $2C_{10}$ or higher[2].

Although constant current (CC) charging is one of the methods covered in this guide, two factors should be kept in mind. First and foremost is that Hawker Energy Products Inc. considers constant voltage (CV) to be the <u>PREFERRED</u> method of charging CYCLON® and Genesis® batteries. Second, single level CC charging must be avoided unless it is at extremely low levels ($0.001C_{10}$ to $0.002C_{10}$) such as in solar applications.

Basic concepts of charging

Charging pure lead-tin (PLT) cells, like charging other rechargeable batteries, is a matter of replacing the energy depleted during a discharge. Because no physical process is 100% efficient, to fully charge the battery it is necessary to return more than 100% of the energy removed during the discharge.

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Battery charging waveform quality considerations

The quality of the charging current waveform is an important factor that should be considered when designing a charging system. Poor waveform quality may have a significant impact on battery cycle life, even when the charging regime is otherwise an effective one.

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[1] The term "pure lead-tin" will imply CYCLON® and Genesis® product; in addition, although not strictly correct, the terms "cells" and "batteries" will be used interchangeably

[2] C_{10} is the rated capacity of the battery, expressed in amperes. Thus the $2C_{10}$ rate of charge or discharge for a 26Ah battery is $2 \times 26A$ or 52A.

Average (AVE) and root mean square (RMS) values

A good quality waveform should have an AVE value that is sufficient to meet the control limits required by the chosen charging algorithm. <mark>The AVE value of the waveform is an important consideration due to the fact that it is the AVE value of the waveform that is responsible for putting the ampere-hours into the battery</mark>.

The root mean square (RMS) value of a waveform is frequently used in electric power measurements. The RMS value of a waveform describes a measure of equivalent energy transport or dissipation into a standard resistive load.

This makes it conceptually possible to dissipate 100 watts of power in a 1Ω resistor using either a purely sinusoidal 10 amperes RMS or a pure 10 amperes of DC. However, that same sinusoidal 10A RMS waveform, when connected to a battery, will <mark>return zero ampere-hours, regardless of how long the charger is left connected to the battery</mark>. This is due to the fact that the AVE value of a sinusoidal waveform is zero.

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Ripple values

One measure often used to qualitatively describe the DC power supply output is the percentage of ripple contained in the output voltage waveform over a range of electrical load conditions.

It is recommended that the total variation of the DC supply, including load regulation effects, is <mark>less than ±2% (peak-to-peak) of the nominal charging voltage</mark>. This means that for a system being charged at 2.45 volts per cell (vpc), the absolute limits of voltage variation are from 2.401 to 2.499 vpc.

The PLT product from Hawker Energy Products Inc. incorporates the gas recombination principle which allows almost all of the oxygen generated at up to the $0.33C_{10}$ overcharge rate to be recombined to form water at the negative plate, virtually eliminating oxygen outgassing. Hydrogen gas generation is substantially reduced due to the use of pure lead–tin grid material, which has high hydrogen overvoltage. The corrosion of the positive current collecting grid has also been reduced by the use of pure lead–tin.

The amount of energy necessary for a complete recharge depends upon how deeply the cell has been discharged, the method of recharge, the recharge time and the temperature. Typically, be-

tween 105% and 110% of the discharged ampere–hours must be returned for a full recharge. Thus, for every ampere–hour discharged, one must put back between 1.05 and 1.10 ampere–hours to ensure a full recharge.

If watt-hours rather than ampere–hours are measured, the required overcharge factor will be higher. It is important to note that although the battery can deliver at or near its full capacity prior to receiving the required overcharge, in order to obtain long cycle life, the battery **MUST** receive the required overcharge, at least on a periodic basis.

Charging can be accomplished by various methods. The objective is to drive current through the cell in the direction opposite to that of the discharge. ***Constant voltage*** (CV) charging is the conventional (and preferred) method for charging the PLT cell. However, ***constant current*** (CC), taper current and variations thereof can also be used for charging these cells.

Constant voltage (CV) charging

Constant voltage (CV) charging is the preferred method of charging CYCLON® and Genesis® sealed–lead products. In this scheme the battery is allowed to pull as much current as it needs during any point in the charge cycle.

Table I in a later section on fast charging shows recharge time as a function of charge voltage and inrush current at $25°$C. The minimum inrush current for single level CV charging **in a cyclic application**[3] is of the order of $1C_{10}$, and one must allow about sixteen (16) hours for a full charge under repetitive and deep (60% to 100%) depth of discharge (DOD) cycling conditions. If the CV charger used in a deep discharge application has an inrush current less than $1C_{10}$, either the charge time allowed must be increased or special charge algorithms should be evaluated.

The inrush current magnitude is less critical in a standby application as the time on charge is sufficiently long to enable a full charge. However, even in standby applications we recommend an inrush current of $0.2C_{10}$ and preferably not less than $0.1C_{10}$.

Generally speaking, when the initial current is less than $1C_{10}$, the time on charge must be lengthened. One rule of thumb is to increase charge time by the hourly rate at which the charger is

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[3] If the **AVERAGE** time on charge between two successive discharges is 30 days and the **MINIMUM** time between two successive discharges is no less than 14 days then the application may be considered to be in the nature of a backup application; otherwise the application is cyclic and charging appropriate to cyclic applications must be used.

limited. In other words, if the charger is limited to the $0.10C_{10}$ rate, then 10 hours should be added, giving a total charge time of 26 hours. Using the same rule, if the charger is limited to the $0.20C_{10}$ rate, then 5 hours should be added and recharge would require about 21 hours instead of 16 hours.

There is one other important point to be kept in mind when designing chargers for CYCLON® and Genesis® batteries in cyclic applications. While some flexibility in inrush current is acceptable, particularly with DODs less than 50% or so, the same is not true for the charge voltage. *It must be in the 2.45 to 2.50 vpc range at 25°C or 77°F. In a cyclic environment the cells must see this voltage at its terminals*

Note that no practical limits are imposed on the maximum current by the charging characteristics of either the CYCLON® or Genesis® product during a CV charge. For cyclic applications, it is imperative that the charge voltage be in the 2.45 to 2.50 volts per cell (vpc) range. Lowering the voltage to anything under 2.45 vpc in such an application will lead to a rapid loss in capacity, <u>regardless of the magnitude of the inrush current</u>.

Fast charging or cyclic charging

A **fast charge** is broadly defined as a method of charge that will return the full capacity of a cell in four to six hours from a fully discharged state. However, many applications require a return to a high (80% and above) state of charge in one hour or less. Prior to the development of PLT products, commercially available lead acid batteries required far longer charging times merely to be brought up to a high state of charge.

Unlike conventional parallel flat plate lead-acid cells, CYCLON® and Genesis® cells use a starved electrolyte system where the electrolyte is contained within a highly retentive separator, creating the starved environment necessary for homogeneous gas phase transfer.

The gassing issue is minimized with the CYCLON® or Genesis® system, as the extremely high purity of lead significantly reduces the oxygen and hydrogen gas generation during overcharge and almost all oxygen gas generated is able to recombine within the sealed cell.

The high plate surface area of the thin plates used in CYCLON® and Genesis® cells reduces the current density to a level far lower than normally seen in conventional lead-acid cells, thereby enhancing the fast charge capabilities of PLT cells.
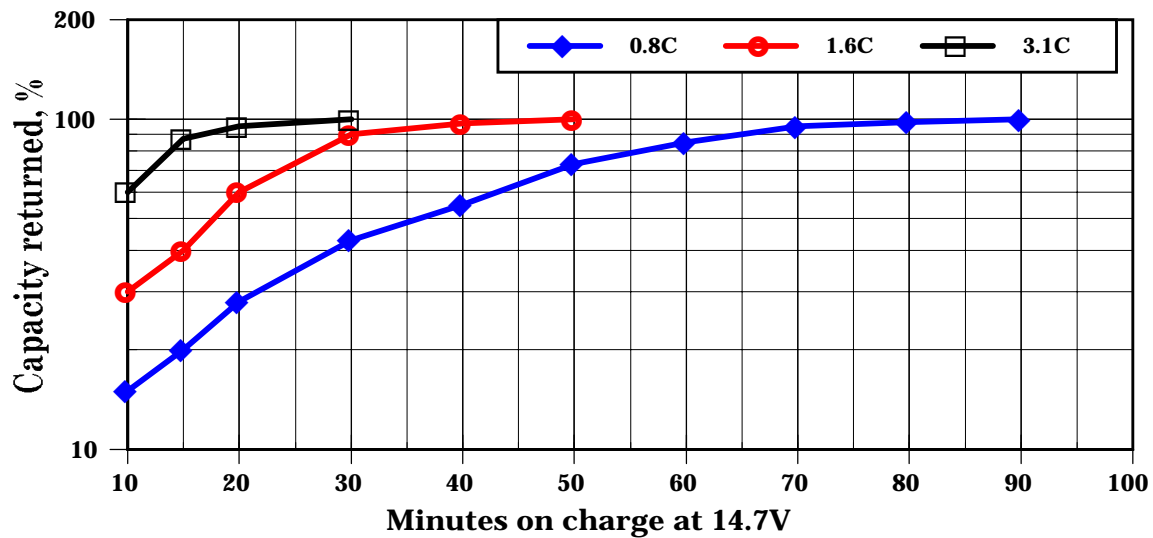
The pure lead-tin technology of CYCLON® and Genesis® batteries lends itself extremely well to rapid charging. Figure 1 shows, at three levels of inrush current, the exceptional fast charge characteristics of these batteries when charged at a constant 2.45 volts per cell (vpc) or 14.7V for a 12V module,.

Table I illustrates the capacity that is returned to a 12V Genesis® battery as a function of the magnitude of the inrush current. It shows that with a $0.8C_{10}$ inrush current, a 100% discharged battery can have 80% of its capacity returned in 57 minutes; doubling the inrush to $1.6C_{10}$ cuts the time taken to reach the same threshold capacity to only 28 minutes.

Table I and Figure I clearly show that if quick charging capability of a VRLA cell is a major requirement, then the PLT technology from Hawker Energy Products Inc. must be given serious consideration.

Table I: PLT fast charge characteristics at 2.45 VPC & 25°C

Capacity returned	Inrush current magnitude		
	$0.8C_{10}$	$1.6C_{10}$	$3.1C_{10}$
60%	44 min.	20 min.	10 min.
80%	57 min.	28 min.	14 min.
100%	90 min.	50 min.	30 min.

Figure I: Fast charging PLT batteries from 100% DOD

A word of clarification is in order regarding the interpretation of the graph depicted in Figure I. The data given in this figure give an indication of the excellent charge acceptance of the PLT battery, making it very amenable to opportunistic charging where quick bursts of high power charging is applied to the battery. As Figure I shows, both CYCLON® and Genesis® batteries rapidly reach high states of charge, proving their ability to operate effectively in applications that employ opportunistic charging.

It is extremely important to keep in mind that in purely cyclic applications the battery must be charged for time periods substantially longer than those shown in Figure I. This will ensure that the battery is given adequate overcharges that are necessary for it to deliver its design cycle life.

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IUI algorithm for medium power charging

The previous section had an important underlying assumption. A quick look at the graph on rapid charging (or at the numbers in Table I) reveals that the lowest inrush current is $0.8C_{10.}$ In other words, the availability of a high power charger is implied.

While having high power chargers may not be an issue in some applications, the lack of adequate charging power in many more situations is likely to be a limiting factor in the successful application of the pure lead-tin chemistry.

To counter this situation, Hawker Energy Products Inc. has developed an IUI (CC/CV/CC) adaptive algorithm that requires only moderate charger power levels. **This does not mean that the IUI algorithm cannot be used with high power chargers**. If a high power charger incorporates the IUI profile, the adaptive nature of the algorithm allows it to adjust the total charge time automatically downward to accommodate the increased power levels.

Although the adaptive algorithm calls for only moderate charging power levels, the magnitude of the inrush current should still be as high as possible. In fact, our tests have shown that for the IUI profile to be effective the inrush current **must not be less than $0.40C_{10}$**. The charge algorithm profiled below can adequately charge deeply discharged CYCLON® and Genesis® batteries when the inrush current is only 50% of the lowest inrush shown in Table I.

In-house testing of Genesis® batteries using a special IUI (CC/CV/CC) algorithm has yielded good cycle life, while reducing the charge time from sixteen (16) hours to only six (6) to eight (8) hours for batteries that have been 80% to 100% discharged.

In a cyclic application, undercharging is typically more likely than overcharging, and therefore the battery is likely to fail prematurely. This fact makes proper charging of a cyclic battery a critical issue. Batteries in cyclic applications can fail due to undercharge in less than thirty cycles. This is a disappointing result, considering that one can expect about 500 cycles to 80% depth of discharge (DOD) from a properly charged Genesis® battery. The importance of adequate charging in a cyclic environment cannot be overemphasized.

It should be noted that in all the steps outlined below, it is preferable to have a temperature compensated charger. The temperature compensation coefficient may be obtained from Figure IV in the section on temperature compensation. Because the coefficient is negative the charge voltage must be reduced for ambient temperatures in excess of 25°C and increased for temperatures lower than 25°C.

Figure II illustrates the IUI charge voltage profile. Region A is a constant current mode, and continues until the battery terminal voltage reaches between 2.45 and 2.50 volts per cell (vpc). In this figure 2.45 vpc is used. The time to reach this peak, T_1, is noted and becomes the reference point for triggering subsequent trip points during the charge cycle.

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Region B commences as soon as the voltage peaks at 2.45 vpc, at which point the charger switches to a constant voltage (CV) mode at 2.45 vpc, and continues in this mode until time $(T_1 + 1.5T_1)$, or $2.5T_1$ hours. As an example, if time T_1 is 1 hour, then the corresponding time for Region B is 1½ hours, giving a total time of 2½ hours until the end of Region B is reached.

At the end of $2.5T_1$ hours, the charger switches to a CC mode (Region C in Figure II), with the current limited to $0.05C_{10}$. In addition to the limitation on the charge current, two other constraints should be designed into the charger. First, the battery voltage must not be allowed to exceed 2.60 vpc; second, the length of time that the battery sees this CC charge is $0.5T_1$ or 1 hour, whichever is less. **In other words, $(T_3 - T_2) = 0.5T_1 \leq 1$**.
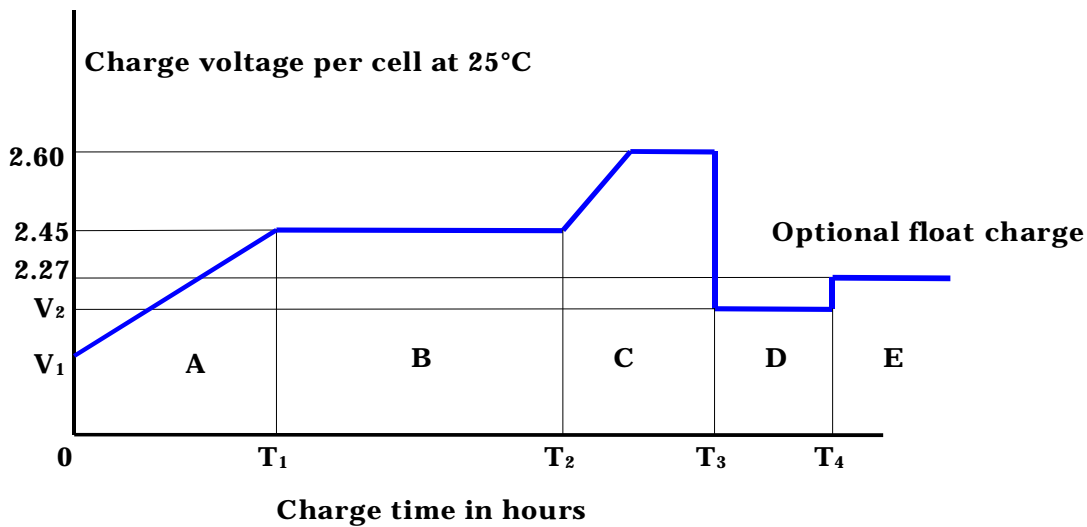
In practice, the battery voltage in Region C will rapidly rise to the 2.60 vpc ceiling; however, **charging must continue in the CV mode at 2.60V per cell**. At the end of time T_3 hours from the commencement of charging, the charger may be shut off.

In some instances, the charger designer may desire a float voltage setting in order to provide an extended (over the weekend, for example) slow charge. If this is the case, there should be a one (1) hour rest after the CC mode before the charger switches into the float mode. This rest period is depicted as Region D in the charge profile. We recommend that, if implemented, the temperature compensated float charge (Region E) be set at 2.27 vpc at $25°$C.

While this is clearly a more complex charger design, having a charger that accommodates Region E is important in applications where the battery is frequently undercharged, such as in hybrid electric vehicles (HEV). In this case Region E serves to provide a slow, long overcharge that neutralizes the negative effects of any prior undercharge.

The various time relationships shown in Figure II are summarized below:

T_1 = time for terminal voltage to reach 2.45 vpc (Region A)

$T_2 = (T_1 + 1.5T_1) = 2.5T_1$ (Region B)   **$(T_3 - T_2) = 0.5T_1 \leq 1$ hour (Region C)**

$(T_4 - T_3) = 1$ hour (Region D)   **V_1 = cell OCV at start of charge cycle**

V_2 = cell voltage as it nears full charge

Charge voltage per cell at 25°C

2.60

2.45
2.27
V_2

V_1

Optional float charge

A   B   C   D   E

0   T_1 T_2 T_3 T_4

Charge time in hours

Figure II: Voltage profile under IUI charge (not to scale)

Using the minimum current limits of $0.4C_{10}$, where C_{10} is defined as the rated capacity of the battery expressed in amperes, and a charge voltage of 2.45 vpc, **the MINIMUM charger power necessary to maximize cyclic performance of CYCLON® or Genesis® product is 1 watt per cell per ampere-hour of capacity.** Thus a 12V, 26Ah Genesis® battery, comprising six cells will need a charger with a minimum output power rating of (6×26) watts or 156 watts per 12V module.

It is important to note here that the minimum power number of 1W/cell/Ah is the charger output rating <u>AFTER</u> accounting for overall efficiency of the charger and power losses in cables connecting the battery to the charger

It is always good practice to avoid seriously overcharging the batteries in the event of a charger malfunction. This could happen, for example, if the charger failed to shut off after the charge portion defined by region B was completed (see Fig. II) and continued to drive energy into the batteries at 2.60V per cell.

As a safety feature, we recommend designing in an ampere–hour counter that is capable of turning off the charger as soon as a cumulative threshold ampere–hour value is exceeded. If the charger fails, it could continue feeding energy into the batteries. It is suggested that when **200% of**

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its rated capacity (52Ah for a battery rated at 26Ah) have been replaced, the charger should be shut off. In addition, charging <u>must</u> discontinue if the battery case temperature reaches 55°C (131°F).

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Additional comments on IUI charging

The IUI algorithm described above is necessary when the inrush current (or current limit) is between $0.4C_{10}$ and $1C_{10}$ amperes. If the current limit is greater than $1C_{10}$, the one-hour charge defined by Region C in Figure II can be eliminated. Generally speaking, if high inrush currents are available, the IUI algorithm may not be necessary. Region C may also be avoided if the battery will primarily be cycled to depths of discharge that are no more than 50%.

Fast charge algorithm development is continuing at several locations. Modifications to the one described above are certainly feasible; however it is always prudent for the battery system designer to verify the effectiveness of a charge regime when applied to a specific application.

Finally, it should be noted that although all of the testing, in-house as well as in the field was done on the Genesis® battery, the IUI algorithm should be equally effective when applied to the CYCLON® family of cells.

Float charging

When pure lead-tin products are to be used in a purely float application, the recommended charge voltage setting is 2.25 to 2.35 volts per cell (vpc) at 25°C, depending on the specific cell type. We also recommend that this charge voltage be temperature compensated as discussed in the next section. <u>We do not recommend the use of CC charging in float or standby power applications.</u>

In some cases batteries may start out as sources of backup power but become more and more cyclic as time passes. An UPS installed in an area that has poor power availability provides a good example. Because of frequent power outages at these locations, the batteries may be required to deliver backup power more often than usual. They are therefore cycled far more than what is typical for a float application.

In this type of situation two factors are critical to the proper selection of batteries. First, they must be capable of being rapidly charged because of frequent power outages. In other words the cells must have high charge acceptance. Second, since float charge voltages are lower than cyclic voltages the batteries must be capable of being reasonably cycled even though charge voltages stay at float voltage levels. Table II and Figure III below demonstrate the capabilities of PLT cells in this regard.

Table II: Genesis® float charge characteristic at 2.27 VPC at 25°C

Inrush current	Hr. to 80% SOC	Hr. to 90% SOC	Hr. to 100% SOC
$0.1C_{10}$	8	11	22
$0.2C_{10}$	4	5	12
$0.4C_{10}$	2½	3	7½
$1.0C_{10}$	1½	2	6
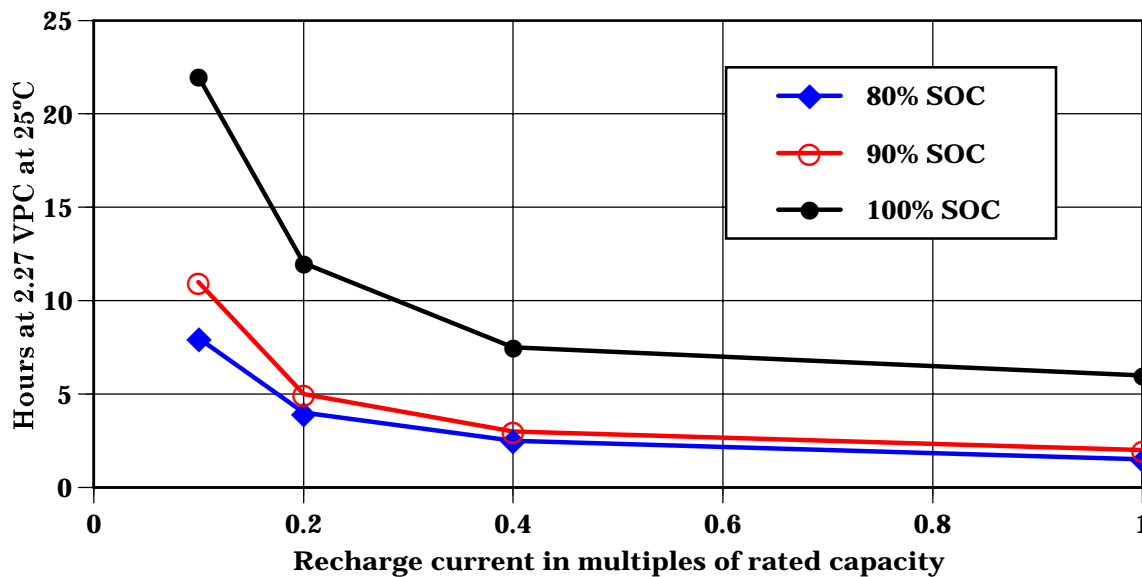
Figure III: Cycling of PLT cells at 2.27 VPC at 25°C

The data presented in Figure III and Table II illustrate the suitability of pure lead-tin batteries for standby applications that may be cycled occasionally. Even with an inrush current as low as $0.2C_{10}$ and a charge voltage of only 2.27 volts per cell, the batteries can be brought up to 100%

state of charge (SOC) from a fully discharged condition in only 12 hours. **Note that repeated cycling at 2.27 volts per cell is not recommended.**

Temperature compensation

High temperature reduces the life of a VRLA cell. At an elevated temperature, the voltage necessary to return full capacity to a cell in a given time is reduced because of the increased reaction rates within the battery. Low temperature, on the other had, reduces capacity.

To maximize life, a negative charge temperature coefficient of approximately 3mV to 5mV per cell per °C variation from 25°C is used at temperatures significantly different from 25°C. **Note that since this coefficient is negative, as the ambient temperature increases the charge voltage must be reduced, and vice versa**.

While many chargers use a single value for the full operating range, in reality the temperature correction coefficient is a non-linear relationship, as shown in Figure IV, which plots charge voltages for float and cyclic applications at various temperatures.
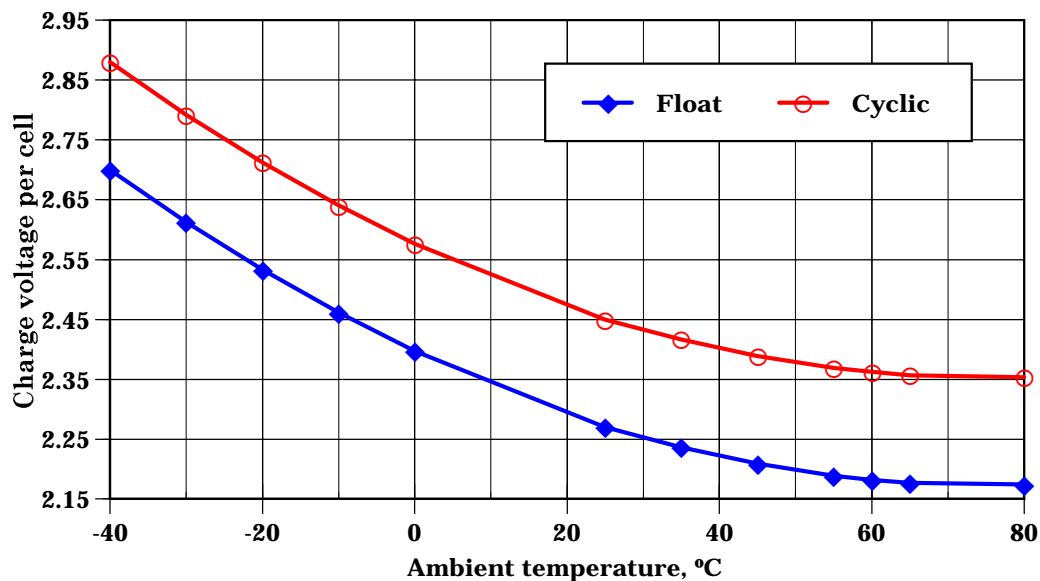
Figure IV: Temperature compensation of charge voltage

The temperature compensated charge voltages can also be computed by solving the following equations, depending on the nature of the application, i.e., float or cyclic:

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$$VPC_{float} = 2.397 - 0.00598(T) + 0.00004(T^2)$$

$$VPC_{cyclic} = 2.397 - 0.00598(T) + 0.00004(T^2) + 0.180$$

where VPC_{float} is the compensated **float charge** voltage per cell at an ambient temperature of T°C and VPC_{cyclic} is the compensated **cyclic charge** voltage per cell at T°C. For example, the compensated float voltage for an ambient temperature of 32°C is 2.247 vpc and the compensated float voltage for an ambient temperature of 0°C is 2.397 vpc. The corresponding parameters for a cyclic application are obtained by simply adding 180mV per cell to the compensated float voltage numbers.

It is important to note here that even if the charge voltage were perfectly compensated for high temperatures, the float life expectancy of the cell would still be reduced. This is due to the fact that while the charge currents are lowered because of lower charge voltages, the high temperature continues to exert a negative influence on the life of the battery. Thus, temperature compensation of the charge voltage only partially offsets the impact of high temperature on the float life of the cell.

Intermittent charging

When PLT batteries are used in a standby or float application the battery user can incorporate a charging scheme that switches on and off when appropriate threshold conditions are met. This type of charging is acceptable due to the very low rate of self-discharge typical of both CYCLON® and Genesis® products.

By optimizing the amount of overcharge put into the battery, its life expectancy should increase. However, since this is a relatively new method of charging VRLA batteries there is not as yet sufficient data (field and laboratory) to quantify the increase in life expectancy, if any, that can be attributed to the potentially beneficial effects of intermittent charging.

The concept of intermittent charging is simple. The battery is charged until threshold criteria are met, when the charger is shut off. The battery begins to experience standing losses until a specified terminal voltage or a fixed time interval since charger shutoff is reached. The charger turns on and the cycle is then repeated. The charger also turns on if the battery is discharged through an external load.

Choosing the right threshold parameters and their values are critical to the success of an intermittent charging scheme. If the chosen parameters are too far apart the battery may be allowed to self-discharge to unacceptably low states of charge; if the threshold parameters make the charger kick in too soon the result can be close to a continuous float condition and the potential benefits of an intermittent charge are lost.

One possible scheme could be where the cells are charged using a constant voltage of 2.45 vpc, with an inrush current of the order of $1C_{10}$ or more for 16 hours. At this point the charger shuts off automatically and remains in that condition for two to three weeks when it starts charging the battery again. Should the battery be discharged before the rest period is over the charger will override the timer and turn on following the discharge.

It is important to keep in mind that intermittent charging is an acceptable method of charging PLT batteries ***ONLY IN A FLOAT OR STANDBY APPLICATION.*** The possibility of consistently undercharging the batteries makes intermittent charging unsuitable for cyclic applications.

Constant current (CC) charging

Constant current (CC) charging, accomplished by the application of a nonvarying current source can be another viable method of charging PLT cells. CC charging charges all cells or batteries equally because it is independent of the charging voltage of each cell in the battery.

As we have stressed on several previous occasions, CV charging is to be preferred over CC charging. During a CV charge the battery itself is allowed to regulate the current draw to a level that is needed to charge or maintain a high state of charge. In contrast, when CC charging is used the charger rather than the battery regulates the current flow. There is, therefore, a significantly higher risk of seriously overcharging the cells in a CC mode.

Figure V is a family of curves depicting cell voltage as a function of percent of capacity of previous discharge returned at different CC charging rates. The plots were generated at an ambient temperature of 25°C. Table III summarizes the key points conveyed by these curves; in addition it provides similar terminal voltage data for ambient temperatures of 0°C and 45°C.

As shown by these curves, the voltage of the cell rises sharply as a fully charged state is approached. This increase in voltage is caused by the plates going into overcharge when the majority of the active material on the plates has been converted from lead sulfate to spongy lead on the negative

plate and lead dioxide on the positive plate. The peak occurs at the point in the charge cycle when 100% of previously discharged capacity is returned.

The voltage increase will occur at lower states of charge when the cell is being charged at higher rates. This is because at the higher CC charge rates, the charging efficiency is reduced. The voltage curves in Figure V are somewhat different from those of a conventional lead-acid cell due to the effect of the recombination of gases on overcharge within the pure lead-tin (PLT) system.

Table III: PLT constant current charging characteristic

Parameter	Temp.	$0.2C_{10}$	$0.1C_{10}$	$0.07C_{10}$	$0.05C_{10}$
Peak voltage, volts per cell	$0°C$	2.91	2.87	2.84	2.82
	$25°C$	2.83	2.79	2.76	2.73
	$45°C$	2.78	2.71	2.67	2.64
Hours to reach peak voltage	$0°C$	4.71	9.61	15.00	20.00
	$25°C$	5.88	10.95	17.87	22.28
	$45°C$	5.80	11.05	16.62	22.10

Voltage Profiles at 25C
Constant Current Charging
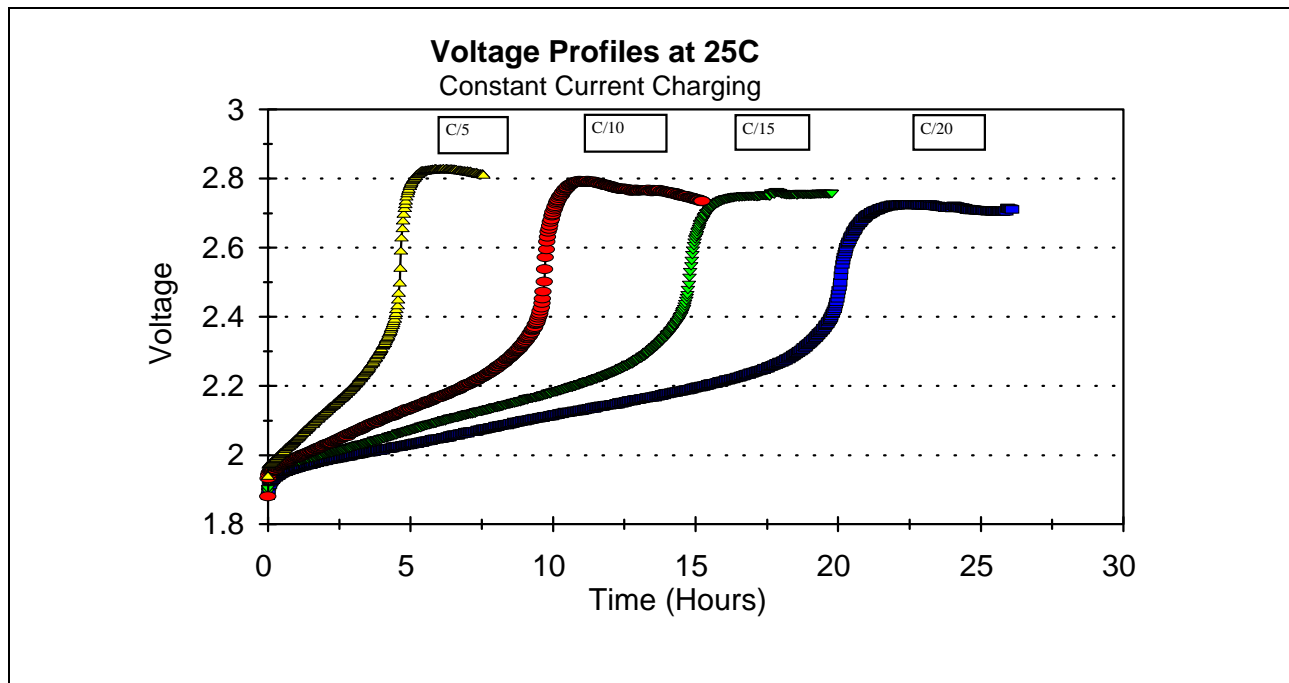
Figure V : Constant current charging at 25°C

While CC charging is a viable method of charging, it requires a greater degree of control to prevent serious overcharge. Continued application at rates above $0.002C_{10}$, after the cell is fully charged, will be detrimental to the life of the cell. In general, constant voltage charging is the preferred method of charge.

The large increase in voltage at the nearly fully charged state is a useful indicator for reducing the rates for a CC charger. If the rate is reduced to between $0.001C_{10}$ and $0.002C_{10}$, the cell can be left connected continuously. **However, we recommend that the charger switch into a CV mode at 2.27 vpc AFTER allowing the cells to rest for 30 minutes or more. The rest period should commence as soon as the voltage peak is reached.** The rest period is very important, unless the designer has test data that proves not having it is not detrimental to the cells.

Finally, these graphs and charts reflect data obtained from cells that had been cycled three times at the $0.20C_{10}$ rate. **These numbers should not be treated as specification values but rather as guidelines to follow when developing or using a constant current charger.**

Two-step CV charging

In many instances the battery user is not sure if the application would be of a cyclic or standby nature. In such cases a two-step CV charging scheme is particularly desirable. Just as we recommend in single level CV charging schemes, the inrush current should also be as high as practical in a two-step profile. Note that charge voltages should be temperature compensated, as discussed before.

In the first stage of a typical two-step design the charger puts out between 2.45 and 2.50 vpc constant voltage at 25°C. At the end of sixteen (16) hours the charger automatically switches to a float level of 2.25 to 2.30 vpc. The battery then stays on charge indefinitely at this level.

The two-step charger is in reality a variation on the intermittent charger profile discussed in a previous section. Instead of the charger shutting off after sixteen hours of charge at 2.45 vpc as in the case of an intermittent charger, it switches to a lower level float voltage.

The big advantage with this method of charge is that the system designer does not have to worry about undercharging the battery if the application transitions from a floating to a cyclic application; neither does he have to worry about consistently overcharging the battery in a floating situation.

Moreover, the combination of superior charge acceptance of CYCLON® and Genesis® batteries and the higher voltage at the beginning of the charge cycle ensures that the cells are brought to a high state of charge relatively quickly. Thus PLT batteries with a two-step CV charger forms an attractive package for standby applications in areas where the reliability of utility power is questionable.

Taper current charging

Although taper current chargers are among the least expensive types, their lack of voltage regulation can be detrimental to the life of any cell or battery. While CYCLON® and Genesis® products have a superior ability to withstand charge voltage variations, some caution in using taper chargers is recommended.

A taper charger contains a transformer for voltage reduction and a half-wave or full-wave rectifier for converting the a.c. input into a d.c. output. The output characteristics are such that as the voltage of the battery rises during charge, the charging current decreases.

Basically, the turns ratio from primary to secondary determines the output voltage at no load, and the wire size in the secondary determines the current at a given voltage. The transformer is essentially a constant voltage device that depends entirely on the a.c. (input) line voltage regulation for its output voltage regulation.

Because of the crude method of regulation, any changes in input line voltage directly affect the charger output. Depending on the charger design, the output-to-input voltage change can be more than a direct ratio. For example, a 10% line voltage change can produce a 13% change in the output voltage.

There are several charging parameters that must be met. The parameter of main concern is the recharge time to 100% nominal capacity for a cyclic application. This parameter can primarily be defined as the charge rate available to the cell when it is at 2.20 volts (representing the charge voltage at which approximately 50% of the charge has been returned at normal charge rates between $0.1C_{10}$ and $0.05C_{10}$) and 2.50 volts (representing the voltage point at which the cell is in overcharge).

Given the charge rate at 2.20 volts, the recharge time, T_{rchg} for a taper current charger can be estimated by the following equation:

$$T_{rchg} = \frac{1.10 \times C_D}{C_{2.2V}}$$

In the equation above for the recharge time using a taper charger, C_D represents the discharged capacity in ampere-hours while $C_{2.2V}$ is the charge current delivered at 2.20 vpc. The 1.10 multiplier represents the 10% overcharge that is recommended for a complete recharge. It is also recommended that the charge current rate at 2.50 volts be in the neighborhood of $0.01C_{10}$ to ensure that the battery is recharged at normal rates and that it will not be severely overcharged if the charger is left connected for extended time periods.

End of charge detection

There are several ways to answer the question **"How do I know when to turn off the charger?"** that is often asked by a charger designer. This section will attempt to provide some guidelines that the designer can implement.

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Time-based shutoff

This is perhaps the easiest way to determine end of charge, and is commonly used in single step CV charging. In a typical design, the CV charger is set at 2.45 to 2.50 vpc at 25°C and charges the battery for 16 to 24 hours, at the end of which period it shuts off. In an intermittent charge implementation, another timer may be used to turn the charger on after a two or three week delay.

Although this is an easy way of determining end of charge this assumes that the designer has accurate knowledge of his application's battery usage profile. For example, if the battery only sees shallow cycling, say 50% DOD or less, repeatedly charging it for 16 to 24 hours at 2.45 vpc will amount to overcharging of the battery.

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Current detection

If the charge current under CV conditions is stable over three (3) hours or more, it may be reasonably inferred that the battery has reached end of charge and the charger may be shut off.

Another viable method is to switch to a lower CV setting once a relatively high (of the order of $0.01C_{10}$) charge current is detected. Charging continues for a few hours at the lower CV level and is then terminated.

It is important to avoid looking for the charge current to drop to a specific low level before shutting off the charge because of its dependence on several factors such as battery age, temperature and duty cycle.

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Final thoughts & comments

All of the preceding material is a combination of test data and estimates based on our long experience with VRLA batteries utilizing the PLT technology. It is therefore important to not treat the material provided as product specification; rather, it should be viewed as guidelines derived from our experience with PLT batteries.

We realize that there may be instances where the system designer implements a charger that does not precisely match any of the types covered in this guide; however, we believe that by sifting through the information available in this guide the designer should get enough pointers to come up with a charger that matches the CYCLON® or Genesis® battery very well with the specific application.

We hope that one particularly important message — our strong preference for CV charging as opposed to CC charging — has come through from all of the material presented in this guide. This statement should not be construed to imply that CC charging is unacceptable; we recognize that some situations call for CC charging for some portion of the charge cycle, as exemplified by our IUI algorithm. Rather, we have tried to emphasize our preference for CV charging since the potential for damaging levels of overcharge is much less under CV charging regimes than under CC charging conditions.

Finally, it should be pointed out that the responsibility for verifying that a charger is appropriate for a particular application ultimately lies with the designer of the system. However, Hawker Energy Products Inc. will provide the technical support necessary to design an application-specific charger, and indeed prefers to be an active partner in the entire system design process. While this does not guarantee the performance of our batteries in a particular application, we believe that it is the best way to ensure that you get maximum benefit from these high performance VRLA products.