TECHNICAL BULLETIN 41-2128

C&D TECHNOLOGIES

Charging Valve Regulated Lead Acid Batteries

Please Note: The information in this technical bulletin was developed for C&D Dynasty 12 Volt VRLA products. While much of the information herein is general, larger 2 Volt VRLA products are not within the intended scope.

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Valve Regulated Lead Acid Batteries
20 to 200 Ampere Hours

Lead Acid Battery Theory of Operation

Discharge and Charging Reactions

The lead acid battery is a truly unique device - an assembly of the active materials of a lead dioxide (PbO_2) positive plate, sulfuric acid (H_2SO_4) electrolyte and a sponge (porous) lead (Pb) negative plate which, when a load is connected between the positive and negative terminals, an electrochemical reaction occurs within the cell which will produce electrical energy (current) through the load as these active materials are converted to lead sulfate (H_2SO_4) and water (H_2O). When the load is removed and replaced by an appropriate DC current source, electrical energy (charging current) will flow through the battery in the opposite direction converting the active materials to their original states of lead dioxide, sulfuric acid and lead. This "recharging" of the battery restores the potential energy, making it again available to produce the electrical current during a subsequent discharge. This reversible electrochemical process is illustrated in Equations 1, 2 and 3.

1. $PbO_2 + 2\ H_2SO_4 + Pb = PbSO_4 + 2H_2O + PbSO_4$

2. Reaction at the Positive Plate $PbO_2 + 4H^+ + SO_4 + 2e^- = 2H_2O + PbSO_4$

3. Reaction at the Negative Plate $Pb + SO_4 = PbSO_4 + 2e^-$

In theory, this discharge and recharge process could continue indefinitely were it not for the corrosion of the grids onto which the lead dioxide (PbO_2) and lead (Pb) active materials are pasted, deterioration of the lead dioxide and sponge lead active materials of the positive and negative plates, and in the case of VRLA batteries, drying of the electrolyte. While internal local action and deep discharge do play a roll in grid corrosion and active material deterioration, and elevated operating temperatures do further aggravate the situation, it is most often that improper charging techniques are primarily responsible for premature battery failures.

Overcharging

It only requires between 107% and 115% of the ampere hours energy removed from a lead acid battery to be restored to achieve a fully charged system capable of delivering 100% of its rated capacity. For example, if 10 ampere hours of energy had been removed from a battery during discharge, then 10.7 ampere hours of energy would have to be replaced through the charging activity to restore 100% of capacity. Charging at too high a rate or forcing more than the 107% required into the battery constitutes overcharging and results in additional grid corrosion, gassing and consumption of the water in the electrolyte. This overcharging is a common cause of premature battery failure.

Vented Lead Acid Cells: Overcharging and Gassing

Once the plates of the battery are fully converted to their original lead dioxide (PbO_2) in the positive plate and sponge lead (Pb) in the negative plate, most of the additional ampere-hours or charging current are consumed in the electrolysis of the water in the electrolyte. In the vented (flooded) cell, this occurs at the positive and negative plates as shown in Equations 4, 5 and 6.

4. Positive Plate $H_2O - 2e^- = 1/2\ O_2 + 2H^+$
5. Negative Plate $2H^+ + 2e^- = H_2$
6. Net Reaction $H_2O = H_2 + 1/2\ O_2$

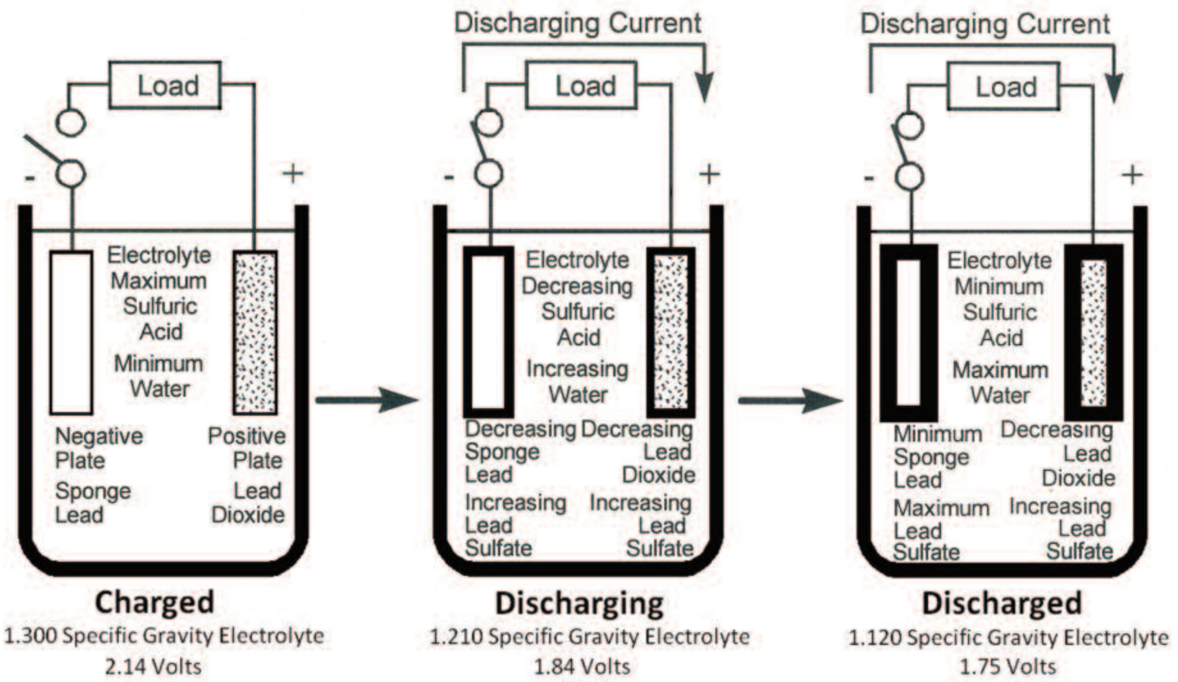
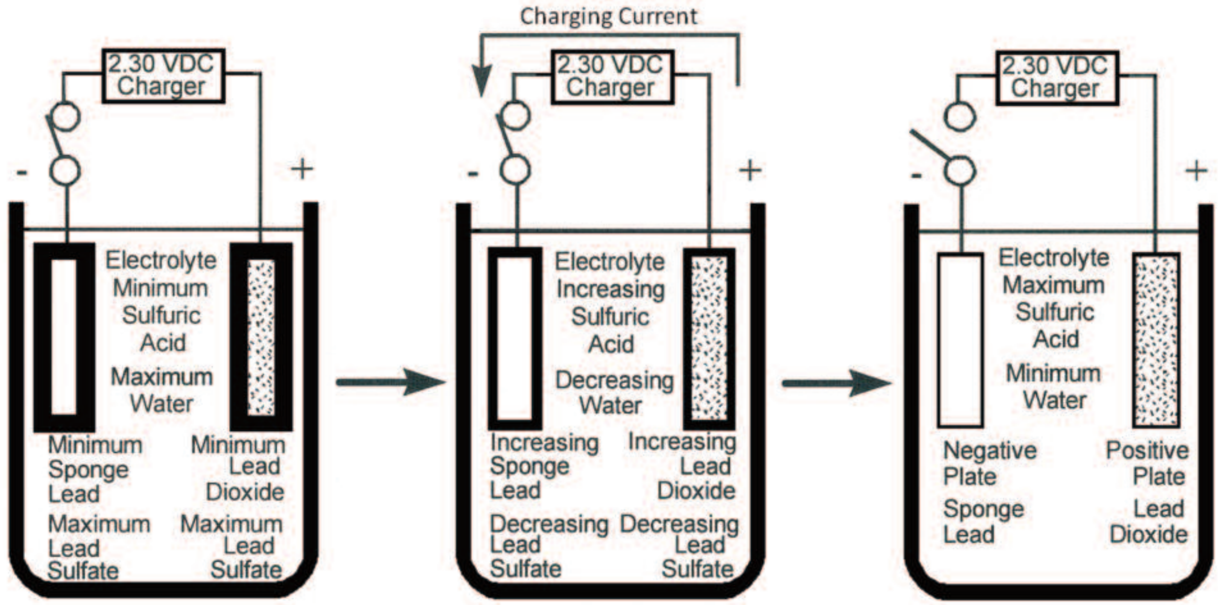


Figure 1 - Lead Acid Battery Discharge



Discharged
1.120 Specific Gravity Electrolyte
1.96 Volts

Charging
1.210 Specific Gravity Electrolyte
2.01 Volts

Charged
1.300 Specific Gravity Electrolyte
2.05 Volts

Figure 2 - Lead Acid Battery Recharge

As shown in Equation 8, the water (H_2O) in the electrolyte at the positive plate is broken down into oxygen gas (O_2), free hydrogen ions ($4H^+$) and free electrons ($4e^-$). The free electrons are "pulled" from the positive plate by the connected charger and "pumped" to the negative plate as noted in Equation 5. As the free hydrogen ions ($4H^+$) migrate through the electrolyte and contact the negative plate, where there is an excess of electrons, the hydrogen ions take on an electron, and hydrogen gas ($2H_2$) is formed. Being a vented cell with liquid electrolyte, the oxygen gas (O_2) generated at the positive plate and the hydrogen gas ($2H_2$) generated at the negative plate will percolate up through the electrolyte and into the surrounding atmosphere as the electrolyte level declines. Since the water that is gassed off can be replaced, this consequence of overcharging with have little impact on the life of the vented cell.

Valve Regulated Lead Acid (VRLA) Cells: Overcharging and Gassing

The VRLA battery is unique in that its electrolyte is immobilized and each cell contains a one way self resealing valve in the vent. The combination of these two features facilitate an oxygen recombination cycle which, under normal circumstances, will prevent the regular emission of gases and the need to replenish the electrolyte water supply. The electrolyte water is decomposed at the positive plate in the same manner as the vented (flooded) cell. See Equation 7:

7. $H_2O = H_2 + 1/2\ 0_2$

However, because the electrolyte is immobilized in a porous medium, such as an absorbent glass mat (AGM) separator that contains void spaces, the oxygen gas generated at the positive plate will diffuse through the separator material and contact the negative plate forming lead oxide (PbO) as noted in Equation 7.

8. $Pb + 1/2O_2 = PbO$
9. $PbO + H_2SO_4 = PbSO_4 + H_2O$
10. $PbSO_4 + 2H^+ + 4e^- = Pb + H_2SO_4$

The lead oxide (PbO) then reacts with the sulfuric acid (H_2SO_4) in the electrolyte to partially discharge the negative plate forming lead sulfate ($PbSO_4$) and restoring the water (H_2O). However, as noted in Equation 11, the lead sulfate of the partially discharged negative reacts with the hydrogen ions ($2H^+$) from the positive plate and the free electrons ($4e^-$) being supplied by the charger to recharge the negative plate to its original form of lead (Pb) and restore the sulfuric acid (H_2SO_4) of the electrolyte. The net result, provided the rate of overcharge is not excessive, is the generation of hydrogen gas being suppressed, and there is no net loss of water from the electrolyte-a safer battery that does not require electrolyte maintenance. However, if the charging voltage is increased to such an extent that the resulting charging current generates the oxygen gas at a rate faster than what it can diffuse through the separator system, then the cell will revert to operation similar to that of a vented cell and will consume water and emit hydrogen. Naturally, this will lead to electrolyte dry-out and premature failure of the cell.

Lead Acid Batteries and Undercharging

Undercharging of the battery occurs when 107% to 115% of the removed ampere hours are not provided during the recharge. When not fully recharged, the residual lead sulfate ($PbSO_4$) remains on the positive and negative plates and eventually ‘hardens’. With successive cycles of undercharging, the layer of residual lead sulfate becomes thicker, the electrolyte specific gravity decreases, and the battery cycles down in capacity. In the ‘hardened’ condition, it may not be possible to convert the residual lead sulfate back into the original lead dioxide, sponge lead and sulfur acid active materials, even with higher voltage charging efforts. In this case, the battery will suffer a permanent loss in capacity.

Charging the Valve Regulated Lead Acid (VRLA) Battery

The basic requirement to charge a lead acid battery is to have a DC current source of a voltage higher than the open circuit voltage of the battery to be charged. Figure 3 illustrates the basic concept of charging.

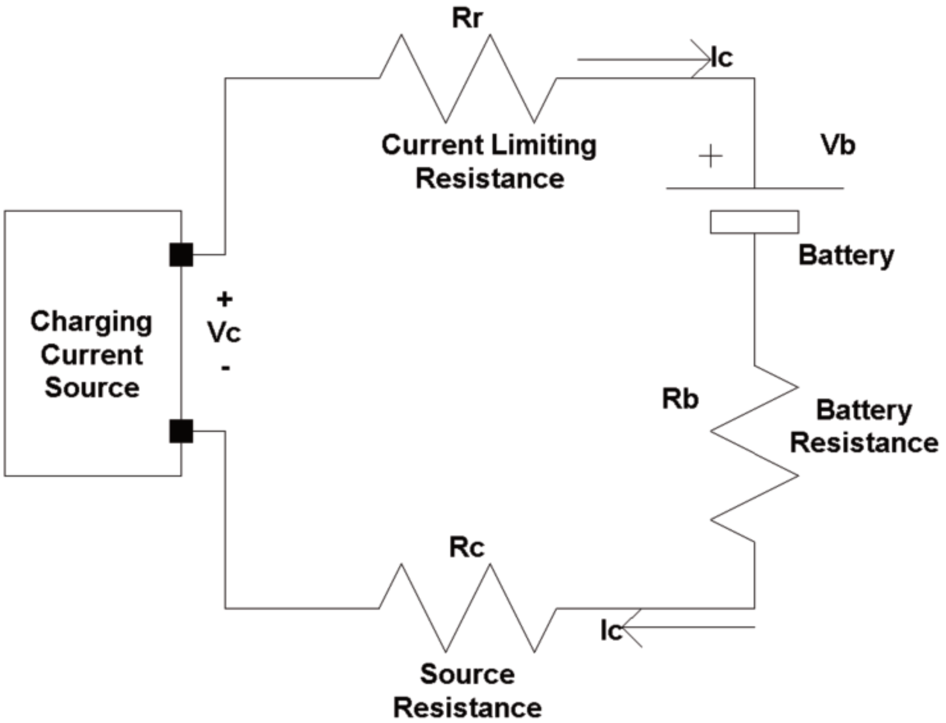


Figure 3 - Battery Charging

FIGURE 3: Battery Charging

The charging current will be the result of the difference between the voltage of the charger and the open circuit voltage of the battery, divided by the resistance of the charging circuit and battery.

$$Ic = \frac{(Vc - V_b)}{Rc+Rr+R_b}$$

The resistance of the battery and its change during charging is relatively small in comparison with that of the charger and charging circuit such that the charging current (Ic) is primarily a function of the difference between the charger output voltage and the open circuit voltage of the cell. Consequently, as the voltage of the cell rises during the recharge, approaching that of the charger output, the current acceptance of the cell decreases.

The charging source could be a constant voltage power supply, constant current power supply, tapering current power supply or one of several variations or combinations of these depending on the battery application, desired performance and life of the battery and economic constraints placed on the charging system. For optimum life, the rules are simple: do not overcharge and do not undercharge.

Constant Current Charging

Constant current charging is perhaps the easiest to visualize. The ampere-hours of energy restored is simply the product of the amperes accepted by the battery and the number of hours over which it was accepted. The constant current acceptance is achieved by having the charger applied voltage rise as the battery voltage rises during the charge. This is usually a matter of having sufficient output voltage from the current source and appropriate selection of the charging resistor Rr or use of an electronically controlled constant current source.

Single Rate Constant Current Charging

Occasionally, constant current charging at the C/3 to C/5 rate is proposed as a fast charging technique. Constant current charging at the C/4 rate (25 amperes for a 100 AH battery) is shown in Figure 4. However, constant current charging is not usually appropriate for the mass charge of the battery in that at these higher rates, as the battery approaches 80% state of charge, the applies voltage rises to well above 2.4 v/c, and its charge acceptance efficiency is reduced. Consequently, significant overcharging would occur until the charge were completed. The fact that the charger output voltage is rising dramatically at this time could be used as an indicator that the rate should be reduced to the normal float voltage to minimize overcharging; however, this will also increase the total time to complete the recharge. This method of charging can result in significant gassing and heating of the battery being charged and is not normally recommended with VRLA batteries. Typically, a constant voltage-limited current charge will result in a faster, more efficient and less abusive recharge.

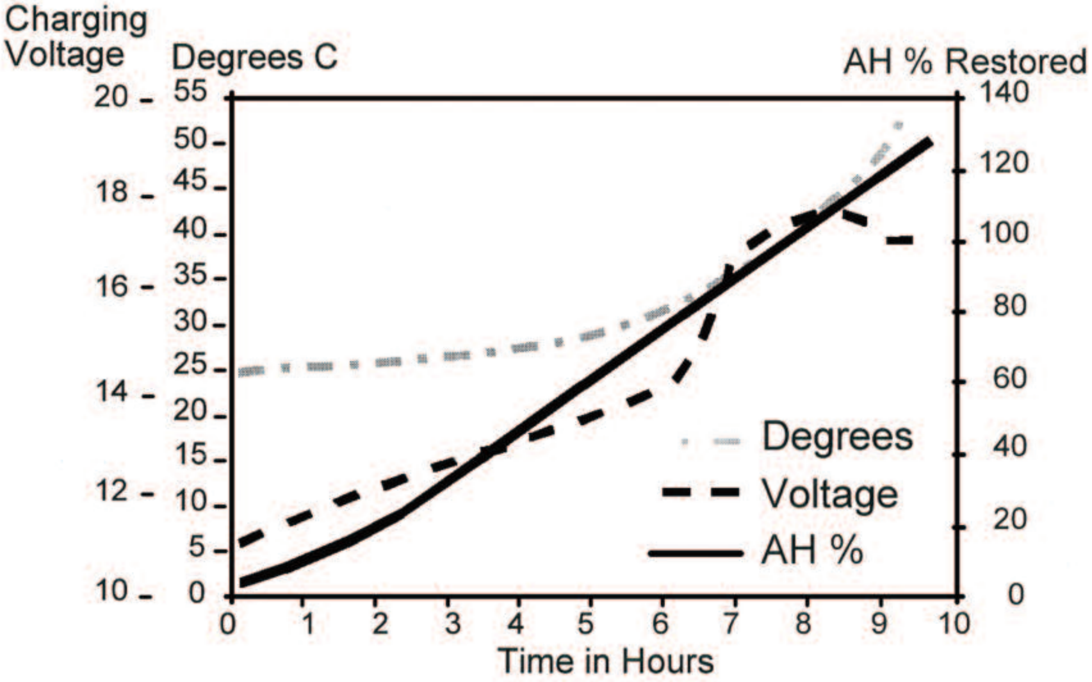


FIGURE 4: Constant Current Charging at C/4 Rate

Lower rate constant current charging can be used sparingly in special circumstances under controlled conditions. For example, it can be useful when providing a freshening charge for batteries in inventory or charging following a capacity test in the lab. In this situation, the series connected string of batteries can be constant current charged at the C/20 rate until approximately 115% of the required ampere-hours of energy are accepted by the batteries. As noted in Figure 5, the applied voltage will rise to approximately 2.4 v/c when the battery is approximately 90% recharged, at which time the voltage will continue to rise to approximately 2.7 v/c when the battery is fully recharged, having received 110% to 115% of the ampere-hours previously removed. Obviously, this technique should be used sparingly in that it too will result in a degree of overcharging and gassing.

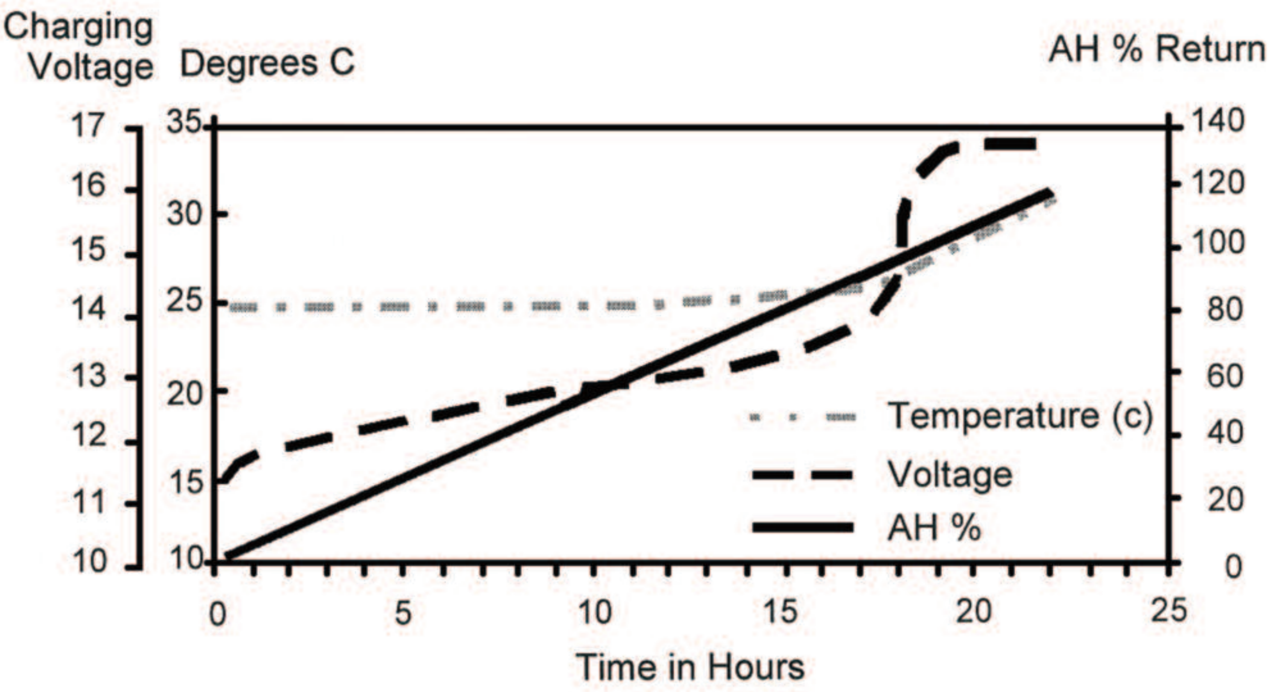


FIGURE 5: Constant Current Charging at C/20 Rate

Once fully charged, the VRLA battery can be maintained in a readiness state using a constant current trickle charge of approximately the C/500 to C/1000 rate. Obviously this low rate is not sufficient to recharge the battery following discharge, but it will maintain the battery, offsetting self discharge, while not overcharging the battery at a rate exceeding the oxygen recombination rate. The value of the constant trickle current is approximately the same as that which would flow normally when a constant float voltage of 2.25 v/c is used. This constant current trickle charge technique can be used to limit the current available to a string of batteries, even though it may have shorted cells, to prevent overcharging and heating that could result in thermal runaway.

Multi-Rate Constant Current Charging

VRLA batteries are increasingly being used in traction applications such as for wheelchairs and robotic devices. In these applications, it is often desirable to charge the battery as quickly as possible while not abusing the battery, yet at the same time allowing for a limited overcharge for cell equalization purposes. In some cases a multi-rate constant current technique can be utilized, which states that a lead acid battery can accept current at a rate equal to the ampere hours capacity required to attain full charge and without significant overheating. For example, if a 100 ampere hour battery were completely discharged, it could initially accept 100 amperes of charging current. However, when 10 ampere hours have been accepted, it could only accept 90 amperes. And once 90 ampere hours had been restored, leaving 10 ampere hours yet required, it could accept only 10 amperes.
An approximation of this rule of thumb can be achieved by using successively lower constant current rates with the current rate switching point to be controlled by the voltage rise associated with each rate as shown in Table 1.

STEP	Current as a function of battery rated AH capacity @ 20 hr. rate	Volts/cell at which the current rate is switched to next lower level
1	C/2	2.45 v/c
2	C/4	2.45 v/c
3	C/8	2.45 v/c
4	C/16	2.45 v/c
5	C/32	2.4 v/c
6	C/500 to C/1000 OR constant float voltage OR disconnect charging source	2.25 to 2.3 v/c

TABLE 1. MULTI-RATE, CONSTANT CURRENT CHARGING

The region in Table 1 indicates a maximum current allowed of C/2 (50 amperes per 100 AH of rated capacity), and a switching voltage of 2.45 v/c. Naturally, lower currents may be used, which will reduce battery heating, resulting in greater recharge efficiency and lengthen the recharge time. The temperature rise of the battery should not exceed 10°C during the recharge. Once approximately 107% to 115% of the ampere hours removed have been restored, the trickle charging constant current should be set to approximately C/500 to C/1000. If using a constant float voltage, it should be set to between 2.25 and 2.30 volts per cell. Another option is to simply disconnect the charging source from the battery at this time. For example, Figure 6 illustrates profile of the voltage, current, and percent ampere hours returned during the recharge of a 31 ampere hour capacity battery that was discharged to a 70% depth of discharge.

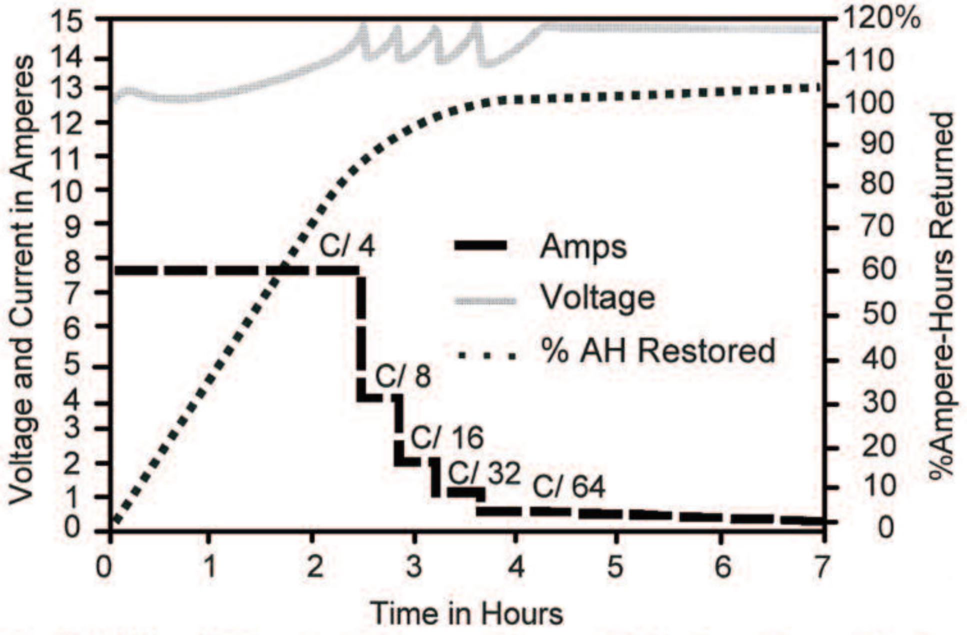


FIGURE 6: Multi-Level Constant Current Charge Following 4 hour Discharge(14.7 VDC Switch Level)

In this case, the maximum current allowed was C/4 or 7.5 amps for a 31 ampere hour battery. While the time required to restore the capacity removed is approximately the same as that noted in Figure 11, where a constant voltage of 2.45 v/c with a current limit of C/4 was utilized, the temperature rise of only 3°C using the multi-rate constant current technique is somewhat less abusive. A maximum rate of C/2 or possibly even C could have been used with a further reduction in recharge time and acceptable battery heating.

When using the multi-rate constant current technique, which is automatically controlled, it is recommended that the charger also provide for a manually controlled equalization at 2.4 v/c in the event that the battery should experience a gradual decline in performance due to the accumulated effects of frequent cycling and possible undercharging.

Taper Current Charging

The tapered current charger is often used with lower capacity (less than 20 ampere-hours) VRLA batteries used in portable power applications due to its low cost. However, this is at some sacrifice in battery cycle life.

The taper current charger is typically only a transformer followed by full wave rectification. The transformer design is such that it has sufficient resistance to limit the current available to the battery. Therefore, as the charger is applied to a discharged battery demanding current, the applied voltage sags, thus limiting the current available, as noted in Figure 7. As the battery voltage rises and the battery demands less current, the charger applied voltage also rises and to some maximum level (typically 2.5 v/c) when the battery has attained a full state of charge. The charger components have to be selected such that when the battery has attained a state of full charge, the current acceptance by the battery is approximately C/50 so as to limit the degree of overcharge should the charger remain applied beyond the point of full charge. Naturally, this design criteria also tends to limit the current available during the bulk charge period of the process.

Tapered current chargers are never recommended for float charging the VRLA battery in that they provide no voltage regulation and the applied current, once a full charge is attained, is variable. This will result in gassing, premature dry-out and capacity loss of the battery.

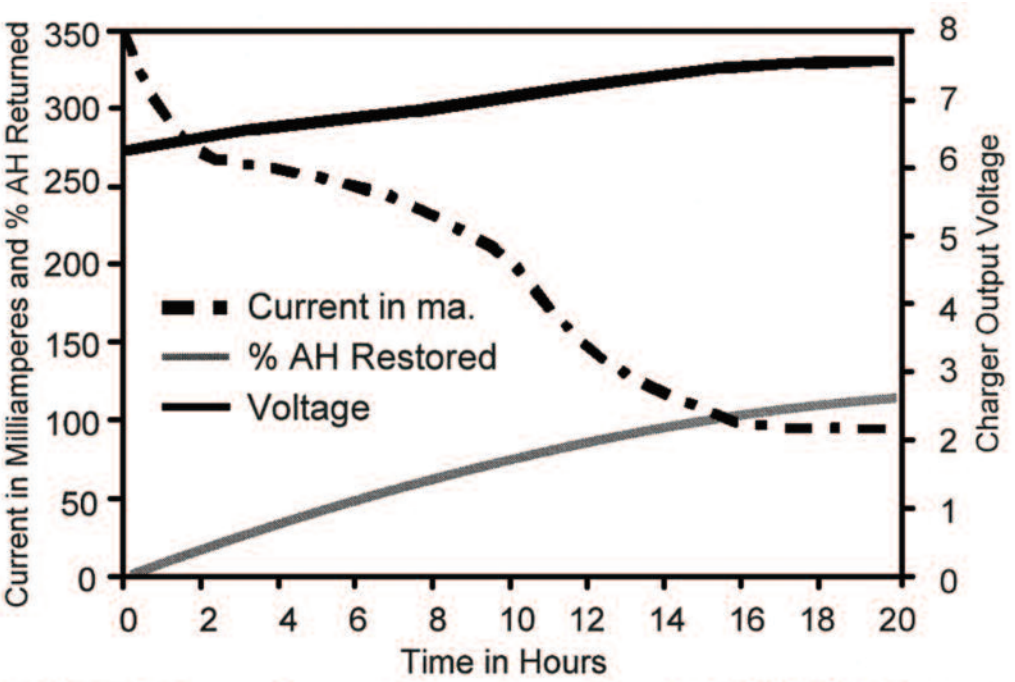


FIGURE 7: Taper Current Charging of 6 volt 4 AH VRLA Battery

Constant Voltage - Unlimited Current Charging

The constant voltage-unlimited current charging technique will typically provide the fastest recharge, and least abusive conditions of the lead acid battery. Unlimited current in this case means current availability of 5°C or greater.

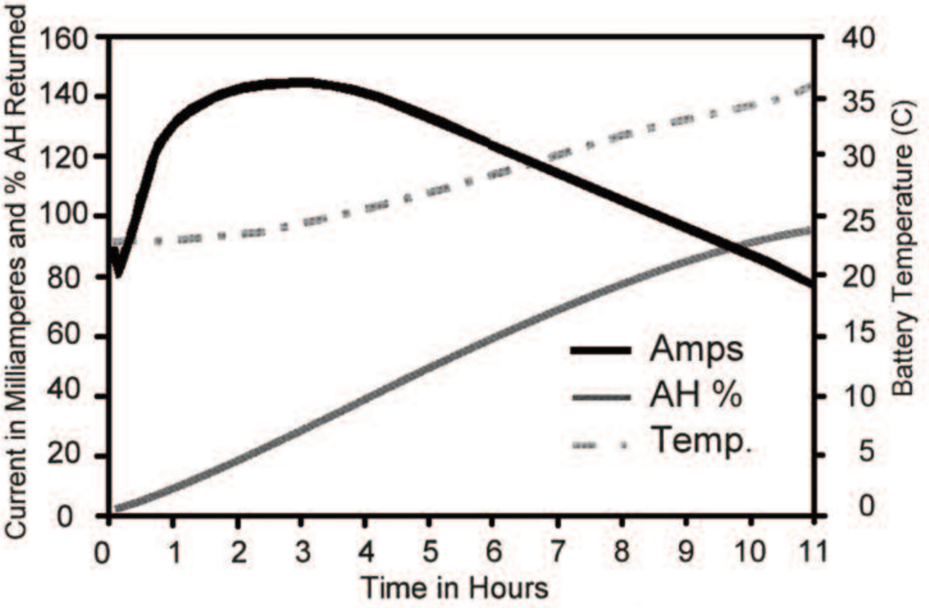


FIGURE 8: 12 Volt 33 AH VRLA Battery Inrush Current and Temperature @ 13.8 VDC Following 8 hour Discharge

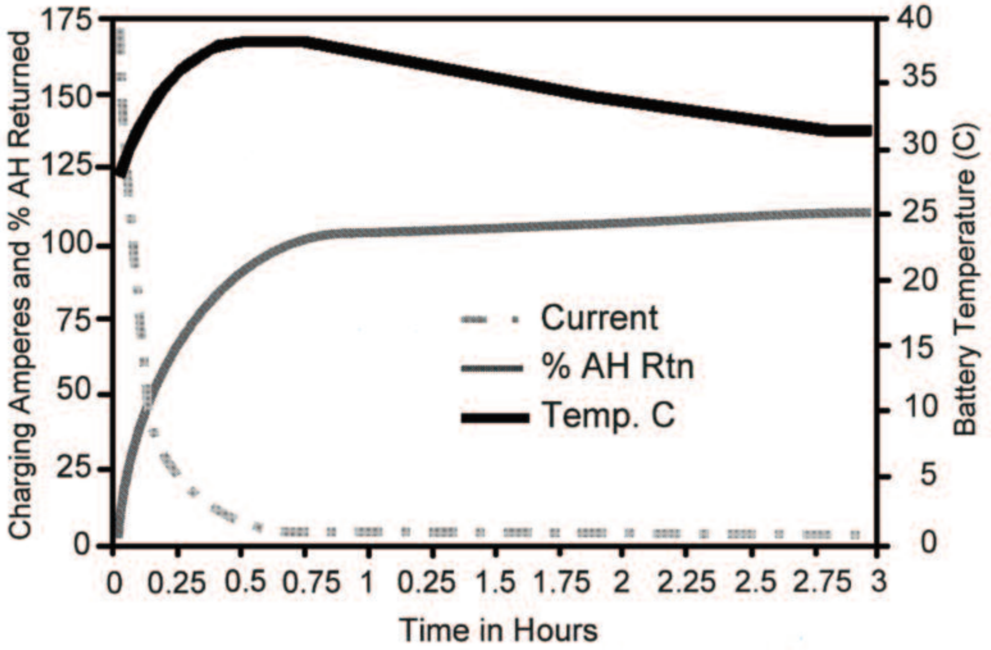


FIGURE 9: 12 Volt 33 AH VRLA Battery Inrush Current and Temperature @ 13.8 VDC Following 15 minute Discharge

This type of charging profile is illustrated in Figure 8 for a recharge following an eight hour (100% DOD) discharge. Figure 9 illustrates a recharge following a 15 minute (40% DOD) discharge. However, the components for a charger of this type are both massive and expensive. Further, the very high initial current accepted by the battery will cause excessive heating (I^2R_b) of the battery and can be detrimental to the active materials in the plates of the battery.

This type of charging, with resulting high inrush current, could occur in systems where a common rectifier capable of high output load currents, supplies both the critical load and the batteries. If the critical load is disabled when the batteries are charged, the entire rectifier output will be available to the battery. Figure 10 indicates the level of initial current which could be accepted by the battery under these conditions. Naturally, the inrush current will be a function of the rectifier/charger constant voltage output and the battery depth of discharge.

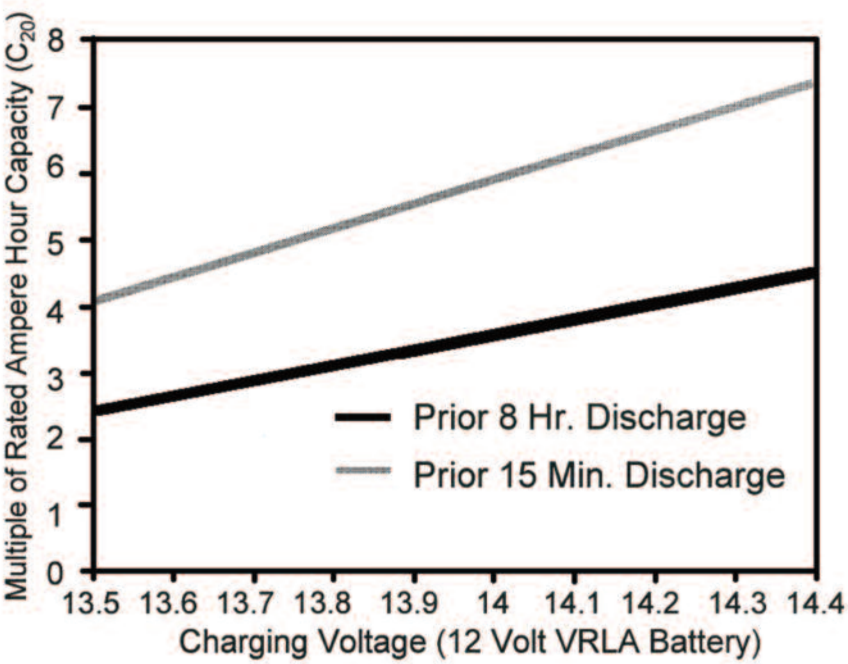


FIGURE 10: VRLA Battery Inrush Current as a Multiple of AH Rated Capacity

Modified Constant Voltage-Limited Current Charging

The modified constant voltage charger is essentially a regulated voltage power supply that is current limited. This is the most commonly recommended method of charging VRLA batteries. As noted in Figure 11, the charger output voltage initially sags as the current demanded by the battery exceeds the charger current limit. However, as the battery state of charge and voltage rises during the recharge, the current demand declines below the current limit and the charger output voltage rises to its regulated design value. This signals the completion of the "Bulk Charging Phase" of the process. The current acceptance is very low once the battery has attained a 95% state of charge and approaches the final float value asymptotically. This characteristic is responsible for the extended charging period when 100% state of charge is required. It is usually more practical to just oversize the battery to the requirements by 5% to 10% and consider the time until the load requirements are met rather than the time to attain 100% state of charge.

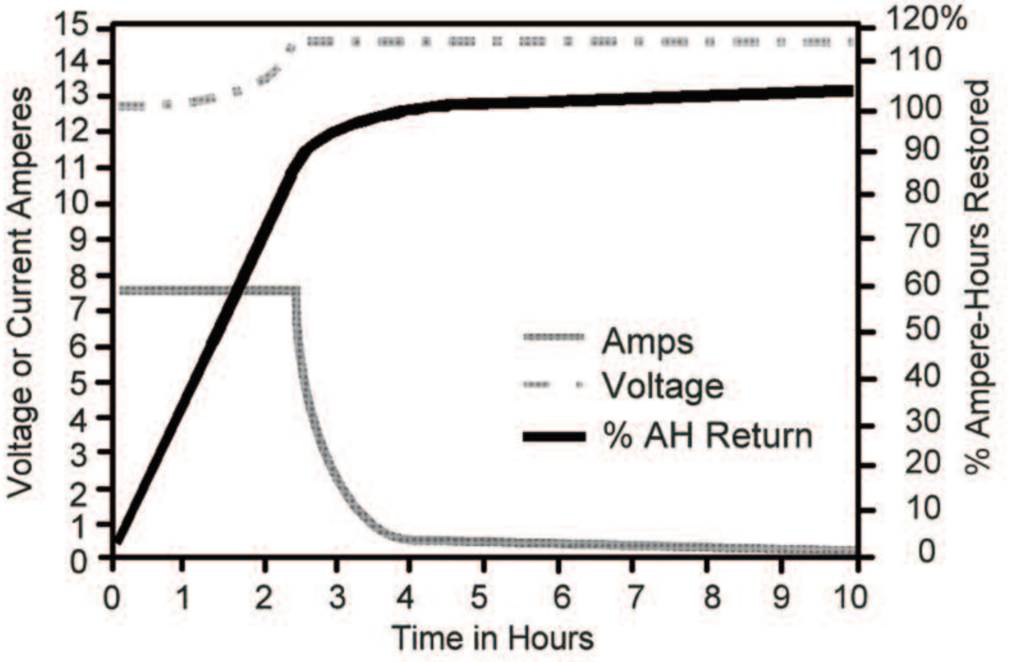


FIGURE 11: Recharge at Constant 14.7 VDC with C/4 Current Limit

Charging Voltages vs. Electrolyte Specific Gravity (SG)

The electrolyte specific gravity will determine the cell open circuit and minimum charging voltages. The open circuit voltage of a lead acid cell is equal to the specific gravity of the electrolyte plus approximately 0.84. For example, a lead acid battery with an electrolyte SG of 1.210 will have an open circuit voltage of 1.210 VDC + 0.84 = 2.05VDC. Naturally, the higher the specific gravity of the electrolyte, the higher the cell open circuit voltage and required minimum charging voltage. Typical values are noted in Table 2.

Recharging Time vs. Charging Voltage and Depth of Discharge (DOD)

The simplest way to reduce charging time is to increase the output voltage of the charger. This will increase the voltage difference between the charger and the discharged cell open circuit voltage and result in a greater current acceptance for a longer period of time, as noted in Figure 12.

TABLE 2. ELECTROLYTE SG vs. CELL OCV AND CHARGING VOLTAGE

ELECTROLYTE SPECIFIC GRAVITY	CELL OPEN CIRCUIT VOLTAGE	PER CELL MINIMUM AVG. FLOAT VOLTAGE	PER CELL MAXIMUM AVG. FLOAT VOLTAGE	FLOAT SERVICE PER CELL AVG. EQUALIZATION/ FRESHENING VOLTAGE	CYCLE SERVICE PER CELL AVG. CHARGING VOLTAGE
1.215	2.055	2.170	2.250	2.330	2.390
1.225	2.065	2.180	2.260	2.340	2.400
1.240	2.080	2.200	2.280	2.360	2.420
1.250	2.090	2.210	2.290	2.370	2.430
1.280	2.120	2.240	2.300	2.400	2.460
1.300	2.140	2.260	2.300	2.400	2.480

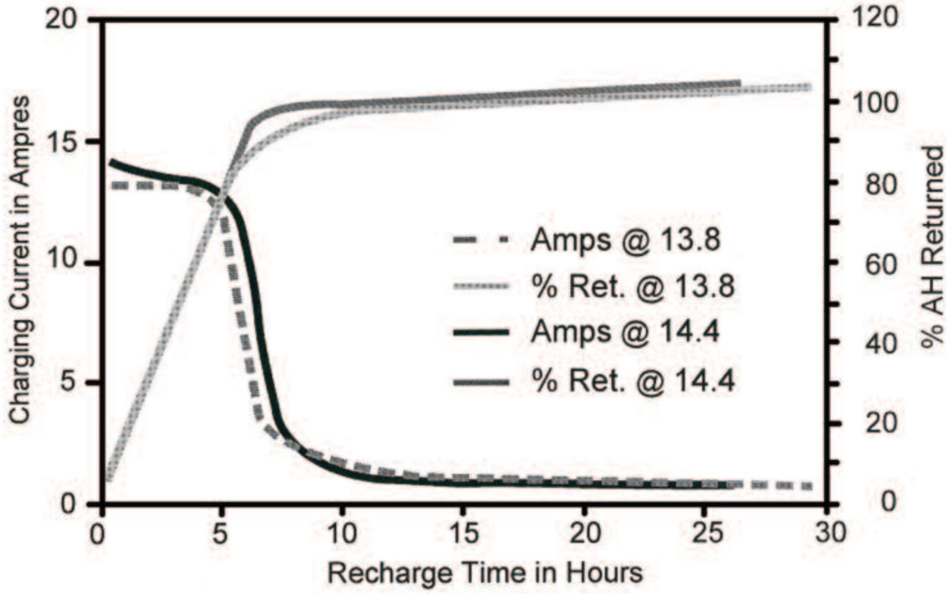
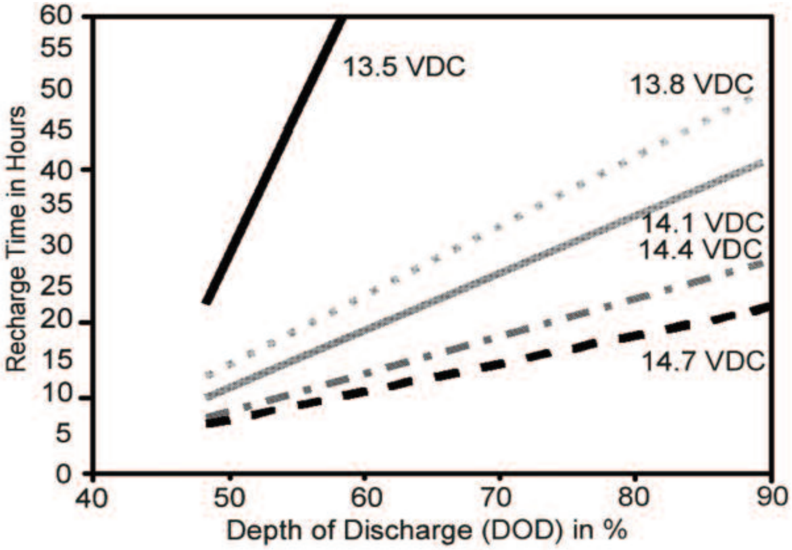


FIGURE 12: TEL12-90 Constant Voltage—Current Limited C/6 Recharge



Note: Current Limited to C/ 5

FIGURE 13: VRLA Battery Recharge Time vs. DOD and Charging Voltage (to 107% AH removed)

This results in the greatest ampere hours of energy being restored to the cell in the shortest period of time. This is also illustrated in Figure 13. For example, if a 100 ampere hour cell were discharged 55 ampere hours (55% DOD) it would require approximately 47 hours to fully restore the capacity with a 20 ampere (C/5) charger set at 13.5 VDC (2.25 v/c). However, if the charger output were adjusted to 13.8 VDC (2.3 v/c) only 18 hours would be required. If the charger had a fast charge feature set at 14.4 VDC (2.4 v/c), the recharge time would be reduced to approximately 10 hours. At 14.7 VDC (2.44 v/c) the time would be further reduced to approximately 8 hours.

Two questions are in order at this point:

1. Is it important that the battery be restored to 100% state of charge in the shortest time in that it would be at approximately 95% state of charge in half the above indicated times?

2. What, if any, are the negative effects of using the higher charging voltages?

Temperature Rise vs. Charging Voltage and Depth of Discharge

Use of the higher charging voltage extends the period of time that the maximum current available will be accepted by the battery. Naturally, this will result in a shorter recharge time. However, the battery will generate heat during the recharge period as a result of the oxygen recombination cycle, which is an exothermic reaction, and due to the resistance of the cell. During this period, the main source of heating is due to the cell resistance, (R_b) and the heat generated is proportional to the square of the charging current (I^2) as noted in the equations:

$$\text{Watts of Heat} = I^2R_i$$

$$\text{BTU/Hr.} = \text{Watts} \times 3.413$$

Naturally, the longer the heat is generated the higher the battery temperature will become. Figure 14 illustrates the temperature rise of the 100 ampere hour capacity VRLA battery of the previous example when charged at 20 amperes (C/5) at various voltages.

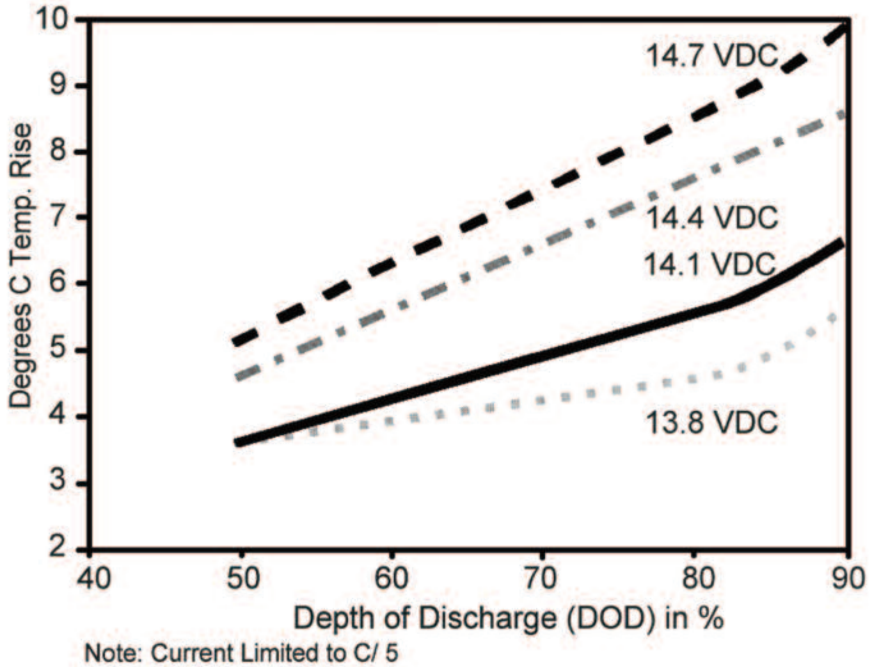


FIGURE 14: VRLA Battery Temperature Rise vs. Charging Voltage and DOD

As would be expected, the deeper the preceding discharge, the longer it will take to recharge the battery and the higher will be the battery temperature toward the end of recharge. Naturally, when higher charging voltages are used, resulting in higher current acceptance for a longer period and reduced recharge time, a higher battery temperature can be expected. To avoid complications that could lead to thermal runaway, the VRLA battery temperature rise during charging should be limited to 10°C (18°F) and it should not be charged at temperatures above 50°C (122°F).

Current Limit and Depth of Discharge (DOD) vs. Recharge Time and Temperature

Recharge time can also be reduced by increasing the available current to the battery to be charged. Figure 15 illustrates the time required to restore 107% of the ampere-hours removed from the cell as a function of the available current and cell depth of discharge.

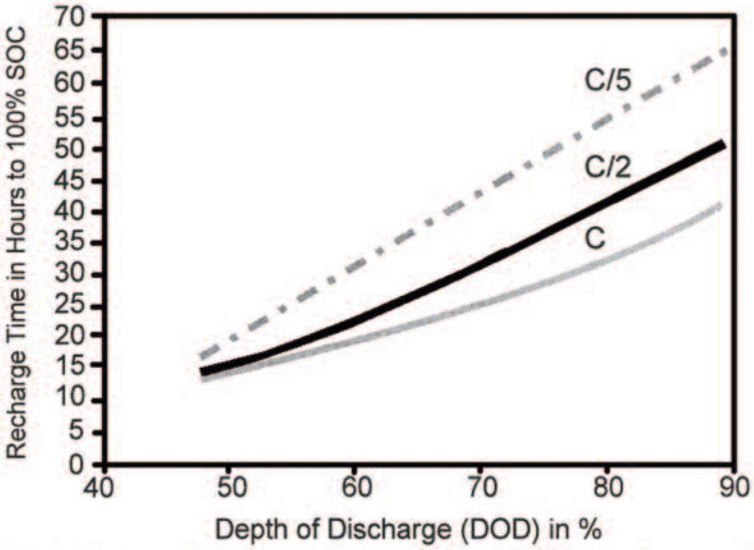


FIGURE 15: VRLA Battery Recharge Time @ 13.8 VDC vs. Current Limit and DOD

For example, if a 100 ampere hour capacity cell were previously discharged 80 ampere hours and recharged at 2.3 V/C with a 20 ampere charger (C/5) the recharge time would be approximately 55 hours while use of a 100 ampere charger would result in the shorter recharge time of approximately 32 hours. Notice however, that in Figure 16, this would also result in significantly higher battery temperatures.

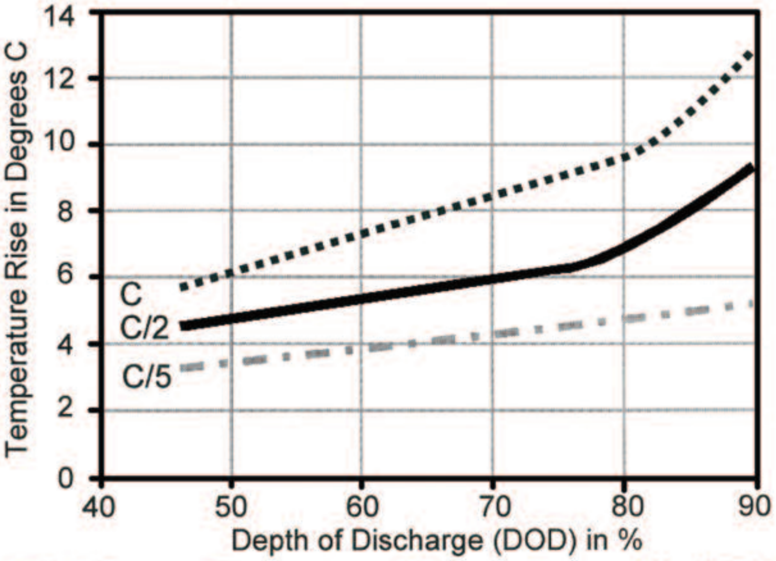


FIGURE 16: VRLA Battery Temperature Rise vs. Current Limit @ 13.8 VDC and DOD

Again, the VRLA battery temperature rise during charging should be limited to 10°C (18°F). It should not be charged at temperatures above 50°C (122°F). The implication of this is that for high rate UPS applications, typically operated at the 10 to 30 minute discharge rate, resulting in a depth of discharge (DOD) of approximately 50%, a higher charging current of C to C/2 (100 to 50 amperes for a 100 ampere-hour battery) can be utilized. However, for telecommunications types of applications, where the battery is more deeply discharged (e.g., 80% to 100% DOD) at the five to eight hour rate, the current should be limited to C/5 (20 amperes for a 100 ampere hour capacity battery) or less. A guide is provided in Table 3.

TABLE 3: MAXIMUM ALLOWABLE CHARGING CURRENT LIMIT AS A FUNCTION OF RATE AND DEPTH DISCHARGE

Current Limit as a function of 20 hr. Rated Capacity	Approximate Max. Rate Discharge Period	% Depth of Discharge as a function of the 20 hr. Rated Capacity
C/1	15 minutes	45%
C/2	30 minutes	55%
C/3	1 hour	60%
C/4	3 hour	75%
C/5	8 hour	90%

Charging Voltage vs. Gassing

Under normal float charging conditions , that is when floating at the recommended low float voltage or float constant trickle current, and at 25°C (77°F) the recombination efficiency of the VRLA cell is such that nearly all the oxygen generated at the positive plate is recombined at the negative plate, and there is minimal water loss from the electrolyte while hydrogen generation is suppressed.

However, when the battery is already fully charged and the float voltage (or current) is increased to above that required to compensate for self-discharge, the rate of oxygen generation will increase to greater than that of its diffusion rate through the separator and electrolyte medium, and the cell will gas both oxygen and hydrogen resulting from the electrolysis of the water in the electrolyte. As noted in Figure 17, this excessive gassing starts to occur at approximately 2.35 V/C and increases with increasing charging voltage. Obviously, use of the higher charging voltages for extended periods can lead to premature dry-out and resulting loss of capacity.

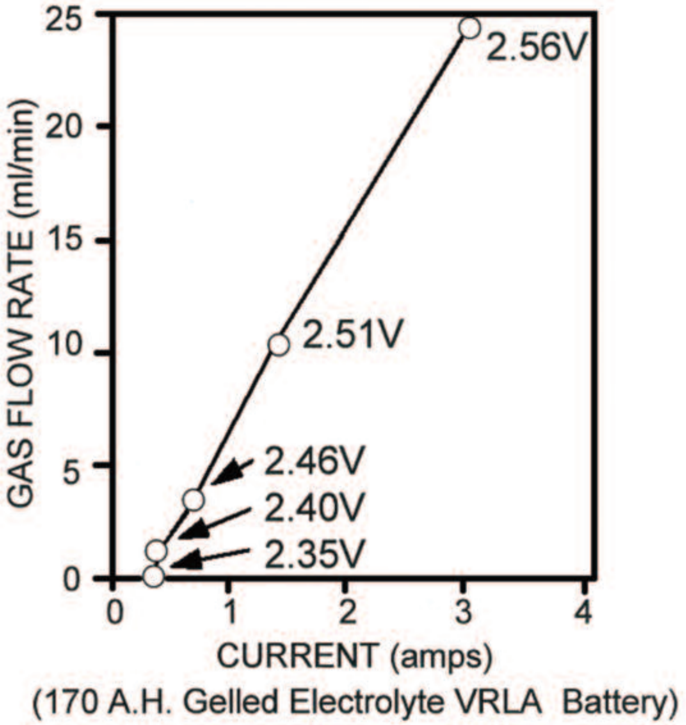


FIGURE 17: VRLA Cell Gassing Rate vs. Float Charging Voltage

Charging Voltage vs. Current Acceptance

As seen previously, as the charging voltage is increased, the current acceptance will increase accordingly. As noted in Figure 18, the float current will approximately double for each 0.05 V/C increase in the float charging voltage. Also note that the AGM type of VRLA battery has a float current approximately twice that of the gelled electrolyte batteries. This reflects its higher oxygen recombination efficiency and lower internal resistance. The significance is twofold:

1. The higher the charging voltage, the higher the float current and the more heat is generated by the VRLA battery due to increased rate of oxygen recombination.

2. AGM VRLA batteries having twice the float current and greater recombination efficiency than the gelled battery will also generate more internal heat during float. Figure 18 further illustrates the need to utilize the recommended charging voltages and avoid excessively high float voltages if premature dry-out and excessive cell heating is to be avoided.

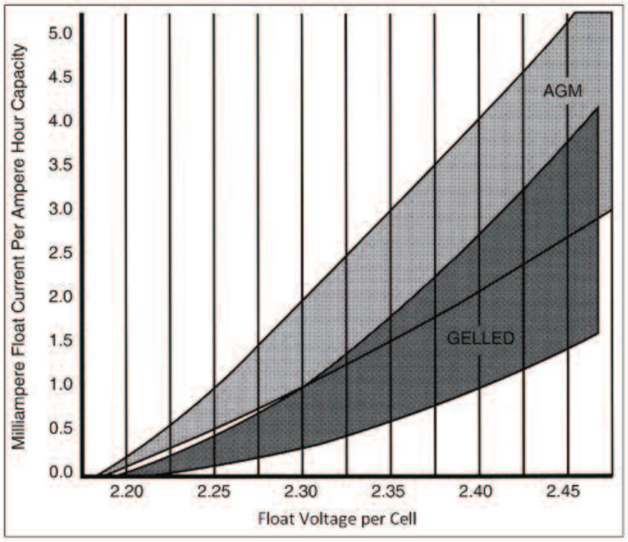


FIGURE 18: VRLA Battery Float Current vs. Float Voltage

The temperature of the battery environment has a significant impact on the VRLA battery float current when maintained at a constant float voltage. The float current will approximately double for each 10°C (18°F) temperature rise. This is equivalent to increasing the float charging voltage by 0.05 V/C and will have similar negative results: Increased heating, gassing and premature dry-out of the cell. Additionally, when in the warmer environment, the capability of the battery to dissipate the heat is reduced and the risk of thermal runaway is increased.

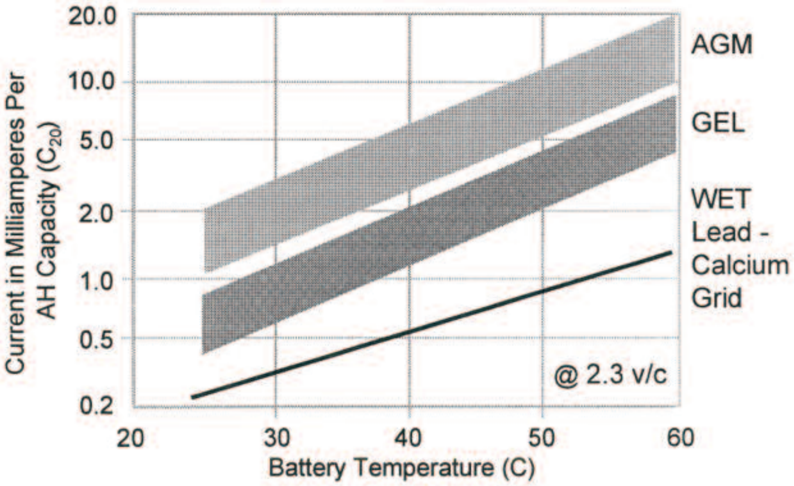


FIGURE 19: VRLA Battery Float Current vs. Temperature

VRLA Battery Float Voltage and Temperature Compensation

If it is known that the battery is to be operated at an elevated but constant temperature, the impact of the increased float current can be minimized by utilizing a lower float voltage. The temperature compensation to be employed is -.005 V/C per degree Celsius (.0028 V/C per degree Fahrenheit) and is illustrated in Figure 20.

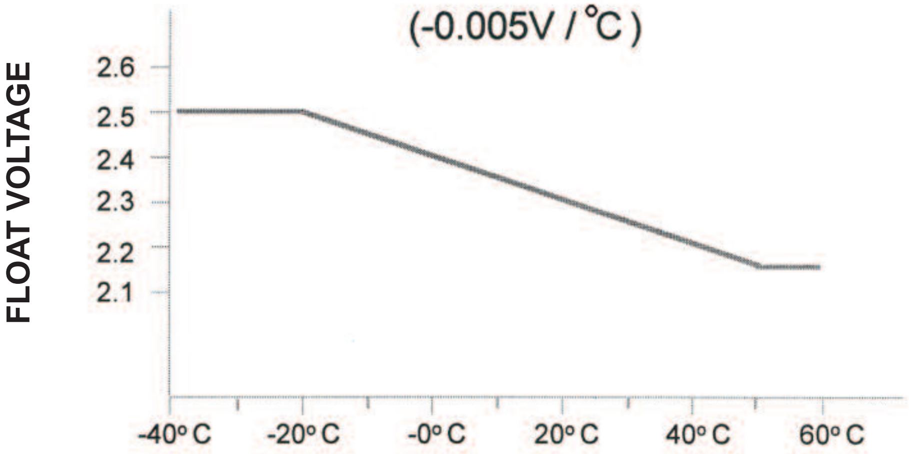


FIGURE 20: VRLA Battery Charging Voltage Temperature Compensation

If minor excursions in temperature are expected about a norm, the float charging voltage can be set to the midpoint of the recommended range. For example, if the recommended range is 2.25 to 2.30 V/C at 25°C, setting the float voltage to 2.275 V/C would accommodate the temperature range of 20°C to 30°C.

If the battery and charging system are located outdoors and are exposed to temperature extremes, incorporation of automatic temperature compensation of the charging voltage should be considered for optimum recharge time during the cold periods and to minimize the risk of thermal runaway during hot periods. Where extremes are involved, it may also be worthwhile to consider insulation of the enclosure interior, mechanical ventilation, battery heating pads and/or buried battery vaults.

Charger DC Output and AC Ripple Voltage and Current

The achievement of optimum life from a VRLA battery system can also be related to the quality of the DC output voltage of the charger. The output should be as pure DC as is practical for the application and life expectations. When the output contains a significant AC component this can cause additional heating of the battery. If the AC component is sufficiently large, during a portion of the waveform the charging voltage could actually dip below the battery OCV and slightly discharge the battery-thus affecting the battery active materials. An excessive AC ripple voltage induces an AC ripple current which results in additional heating of the battery and a resulting decrease in the expected life of the system.

For best results, the AC ripple voltage on the charger output should be less than 1.4% p-p (peak to peak) of the battery DC charging voltage. For example, if the DC charging voltage is 54 VDC, the AC ripple voltage should be no more than 0.76 volts p-p. With four equivalent 12 VDC batteries connected in series, this ripple voltage will be evenly distributed across the four units (0.19 volts p-p per battery). With a digital voltmeter reading the RMS value, this would be .067 volts rms. (voltage p-p/2 x .707).

The maximum AC ripple voltage should never exceed 4% p-p (1.4% rms) of the battery DC charging voltage to ensure that the battery will not be cycled.

The AC ripple voltage will induce an AC ripple current and the value of this current will be related to the value of the voltage and the relatively low impedance of the battery (I=V/R). This AC ripple current will cause additional heating of the battery which could affect the battery life, if significant. The AC ripple current should be limited to 0.05C for best results. For example, a 100 ampere-hour capacity (C) battery should experience less than 5 AC amperes ripple current for best results. The actual heating effect will be:

I^2R_b

For example, the heating effect with a UPS12-370 with an internal resistance of 0.0025 ohms and experiencing a four ampere average AC ripple current would be:

4 amperes^2 x .0025 ohms = 0.04 watts
0.04 watts x 3.413 = 0.136 BTU/hr.

The AC ripple voltage and current can be measured as shown in Figure 21.

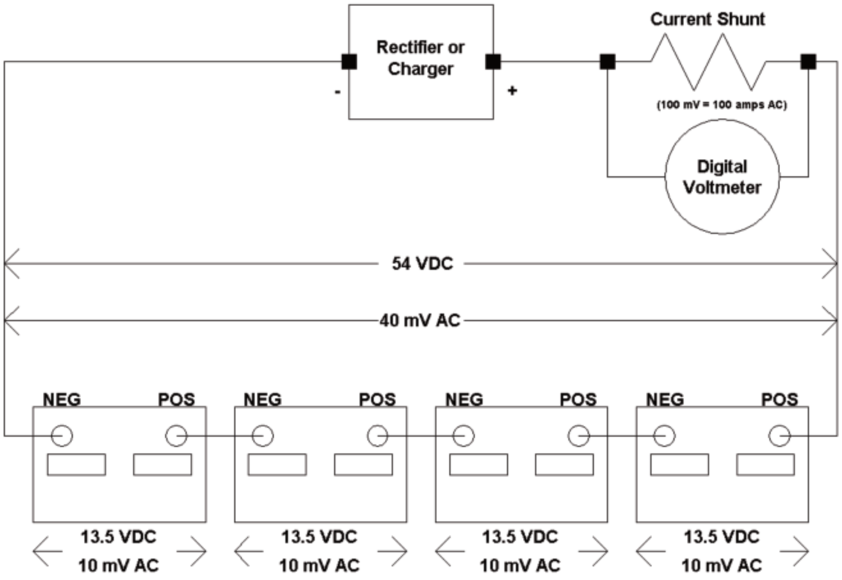


Figure 21 - Measurement of AC Ripple Voltage and Current

The preceding comments assume that the AC ripple voltage is a sine wave; however, this is not always that case. The better way to ensure the negative portion of the AC ripple voltage does not extend below the battery OCV is to observe it on an oscilloscope.

Thermal Runaway and VRLA Battery Charging

Thermal runaway is the condition when heat is generated within the battery at a rate greater than that at which it can be dissipated. Should this condition exist for an extended period of time, the battery will experience accelerated dry-out and temperature elevation to the point where the plastic container could deform and even melt. The VRLA battery is more susceptible to thermal runaway than the vented (wet) cells because the oxygen recombination cycle, which is much more pronounced in the VRLA battery, is an exothermic reaction which generates heat in addition to that normally generated due to charging inefficiencies such as the I^2R losses within the cells.

The conditions conductive to thermal runway are those which either singly or in combination either increase the generation of heat within the cell or minimize the dissipation of heat from the cell. Those conditions which increase the generation of heat within the cells are as follows:

1. High charging voltage resulting in elevated charging current and gassing
2. Unlimited or too high charging current limit
3. Excessively high float current
4. High temperature battery operating conditions

When an appropriate constant voltage is used to float charge the batteries the current acceptance is such that it would not be a cause for thermal runaway in a normally operating system. However, if the system is not maintained and is allowed to operate with shorted cells, the constant voltage float current could increase dramatically and this could lead to thermal runaway in the remaining good cells and premature failure of the entire string.

As noted in Figure 19, as the temperature of the battery increases, it will draw increased current. Naturally, this accelerates the generation of heat and can cascade into a thermal runaway condition.

The conditions that minimize the dissipation of heat from the battery are:

1. High temperature operating environment.
2. Lack of adequate ventilation about the batteries.

Certain characteristics and features can be incorporated into the constant voltage battery charger which either minimizes the risk of thermal runaway, or at a minimum, terminate the charging current should a thermal runaway condition occur. These include:

1. Temperature compensation of the float charging voltage
2. Use of the lowest practical initial current limit for the bulk charge
3. Use of a current limit on the float voltage-limited to approximately 1 ma/AH for gelled batteries and 2 ma/AH for AGM batteries.
4. Battery charging current disconnect should the temperature of the battery reach 122°F (50°C) or greater or should the difference between the ambient and the battery reach 18°F (10°C).

Charging Parallel Strings of VRLA Batteries

Equal voltage strings of VRLA batteries may be operated in parallel to provide proportionally greater ampere-hour capacity and autonomy for the critical load. For example, two 24 cell strings of 90 ampere-hour capacity batteries can be operated in parallel to provide a total of 180 ampere-hours capacity. In this situation, under normal conditions, each string would accept one half the total charging current and supply one half the total load current during discharge.

When operating parallel strings, each of the strings should contain a separate circuit breaker or fuse to provide for individual string disconnect during maintenance and to provide for opening of the string should shorted cells or a significant short to ground occur within the string. The circuit breaker should be sized to allow for the battery inrush current upon initial charging or approximately 150% of the anticipated charging or discharging current, whichever is larger.

Ideally, strings charged in parallel would contain steering diodes as shown in Figure 22 for both the charging and discharging currents. This will prevent a string with shorted cells from drawing current from the normal strings operating in parallel.

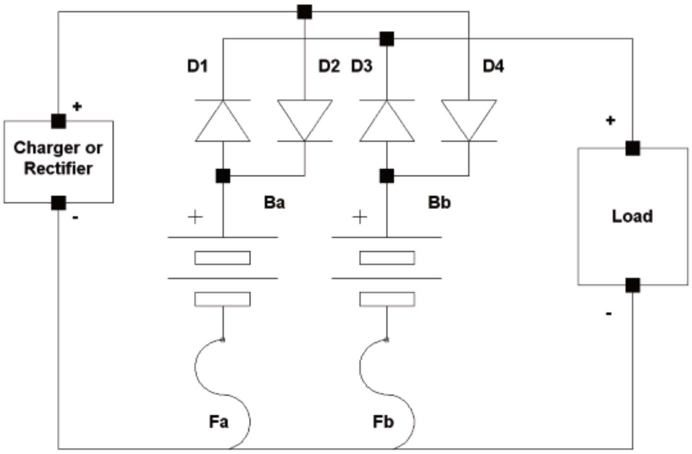


Figure 22 - Parallel Strings of VRLA Batteries with Steering Diodes

Summary of Charging Methods for Valve Regulated Lead Acid Batteries

The following summarizes the previous discussion concerning charging methods. The summary is, in most cases, divided into the method employed during the specific phase (bulk, absorption or float) of the charging regime. The bulk phase is the initial portion of the charge, during which the battery is accepting large quantities of energy and the voltage is steadily rising. Following this is the absorption phase when the battery begins to plateau and approaches a fully charged state. This occurs as the majority of the materials in the battery are converted into their fully charged state, and the battery can no longer accept the high, initial rates of charging energy. The final phase is the float phase. This occurs when the battery is virtually fully charged and the input energy is primarily used to sustain this fully charged state. This is often called a ‘trickle charge’. The actual charging regime selected will be a combination of the following individual methods. For example, methods 7 and 8 and 9 are the preferred method.

#	Charging Method	Advantages	Disadvantages	Comments
1	Taper current	Economic - lowest possible cost charger	Slower than modified constant voltage. Results in overcharging with unregulated voltage when connected after fully charged. Must be supervised. Excessive gassing and reduced life.	Acceptable for "cycle" applications when charger cost is the driving factor. Max. allowable peak voltage of 2.5 V/C. Never recommended for float service applications
2	Constant current bulk charging phase	Possibly economic	Can result in heating and gassing depending on the rate and duration. Overcharging will result in dry-out and reduced life.	Not normally recommended. When used, limit current to C/5 or less and switch to lower voltage/rate when voltage rises to 2.45 V/C.

	Charging Method	**Advantages**	**Disadvantages**	**Comments**
3	Constant current absorption charging phase	Possibly economic	Can result in heating and gassing depending on the rate and duration. Overcharging will result in dry-out and reduced life.	Not normally recommended. When used, limit current to C/5 or less and switch to lower voltage/rate when voltage rises to 2.45 V/C.
4	Constant current float (trickle) charging phase	Limited current minimizes the potential of thermal runaway, even with shorted cells in the string of batteries.	Increased circuitry	Recommended to maintain a fully charged battery. Limit the "trickle" current to 0.002 amps per AH capacity for AGM batteries, and 0.001 amps per AH capacity for gelled electrolyte batteries.
5	Multi-rate constant Current Charge	Fast charge, automatically controlled	Increased circuitry.	Recommended in cycle service application. Bulk charge current should be limited to C/2 and temperature rise to 10℃.
6	Constant voltage unlimited bulk charging phase	Fastest possible recharge materials.	Excessive heating, gassing and drying. Abusive with respect to the plate active materials. Reduced life.	Unlimited current not recommended. Limit the initial current with respect to depth of discharge and a maximum temperature rise of 10°C. See Figure 15.
7	Constant voltage limited current bulk charging phase	Fast recharge with acceptable heating. Preserves life expectations	None	Recommended. Limit initial current max. per figure 14 for a max. temperature rise of 10° C at 2.3 to 2.4 V/C at 25°C.

	Charging Method	Advantages	Disadvantages	Comments
8	Constant voltage limited current absorption charging phase	Reasonable recharge time. Minimizes excessive gassing and drying. Preserves life expectations	None Extended time to reach full SOC.	Recommended. Limit voltage to 2.25 to 2.30 V/C at 25°C.
9	Constant voltage float charging phase	Maintains battery in fully charged condition using the same voltage as the absorption charging phase (2.25 to 2.30 V/C at 25°C). No additional cost.	No protection from excessive string current should there be shorted cells in the string. Extended time to reach full SOC.	Recommended. Limit voltage to 2.25 to 2.30 V/C at 25°C.

Criterion for Charging VRLA Batteries in Float (Standby) Service:

1. Do not exceed 2.40 volts per cell for constant voltage equalize/freshening charge.
2. Do not exceed 2.30 volts per cell @ 25°C (77°F) for the final constant float voltage if this voltage level is also relied upon to drive the bulk and absorption phases of the charging operation.
3. Do not use below 2.25 volts per cell @ 25°C (77°F) for the final constant float voltage if this voltage level is also relied upon to drive the bulk and absorption phases of the charging operation.
4. If the final float voltage is not used to drive the bulk and absorption phase of the charging operation, once the battery is fully charged, a final float voltage as low as 2.2 V/C may be used to maintain the battery.
5. Do not exceed the recommended initial bulk charging current recommendation.
6. Utilize temperature compensation of the charging voltage, especially where wide temperature variations and extremes are anticipated.
7. If constant current is to be employed for the final "trickle" charge, it should not exceed 1 milli ampere per ampere hour of capacity for the gelled battery or 2 milli ampere per ampere hour of capacity for the AGM battery.
8. Approximately 107% to 115% of the ampere-hours removed during the discharge must be restored to reach 100% state of charge.

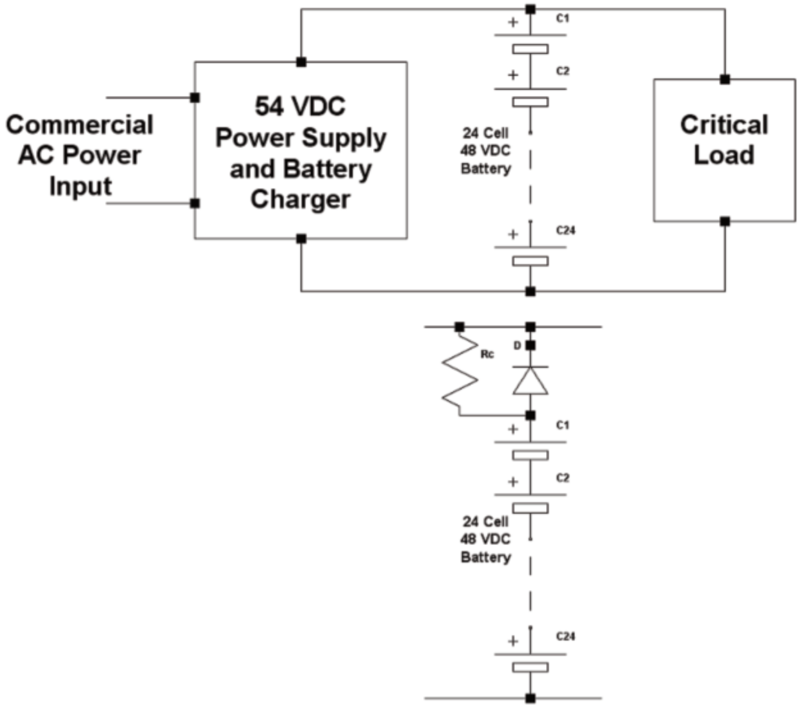


Figure 23 - Typical Float Service Application

The typical float service application is shown in Figure 23. The system power supply provides a regulated voltage output, which is used to both power the critical load during normal operation and provide the float charging voltage and current for the standby power battery. Naturally, since the battery system and the critical load are connected in parallel, the critical load must be capable of operating at the voltage required to charge the battery . When the current capability of the power supply is marginal, it may be advisable to utilize a charging current limiting resistor and blocking diode, as shown. The current limiting resistor (R_c) can be calculated as:

$$R_c = \frac{\text{Float voltage per Cell - 2.0 Volts}}{\text{Desired Ampere Current Limits}}$$

There are many situations where the critical load may not be recommended for operation at an input voltage as high as that required to charge the battery. For example, as shown in Figure 24, the critical load maximum allowable input voltage is 52.8 VDC. This would be an acceptable voltage for charging 24 cells with a specific gravity of 1.215, but it is inadequate to charge a 24 cell battery, such as a VRLA battery, which has an electrolyte specific gravity of 1.300. In this case, a 23 cell battery system could be charged within its recommended range of 2.296 volts per cell; however, if a 23 cell system were not used, a scheme using counter EMF cells as shown in Figure 24, could be used.

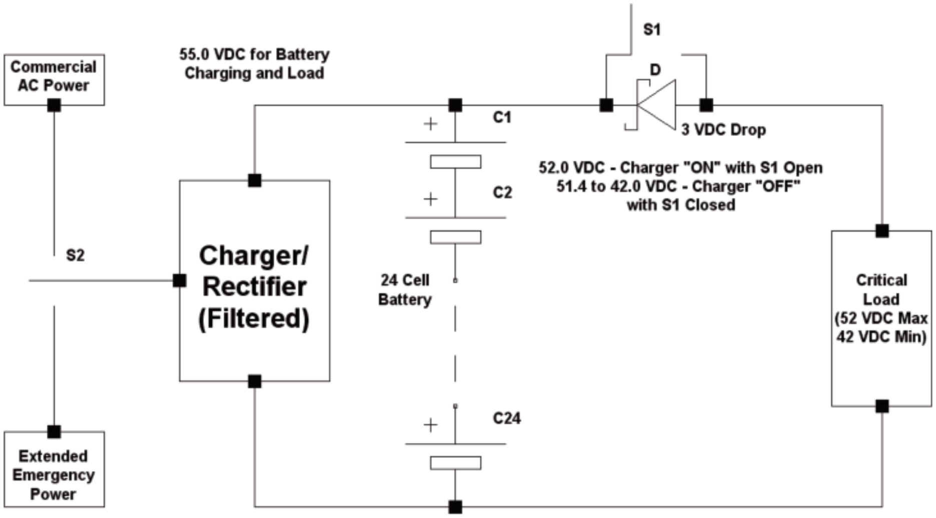


Figure 24 - Float Service Application with Counter EMF Cells

The scheme in Figure 24 allows the battery to be charged at the higher required voltage of 55.0 VDC, while the counter EMF cell drops the voltage of the critical load to an acceptable 52.0 VDC. When commercial power is lost, the switch in parallel with the counter EMF cell closes, eliminating any voltage drop between the battery and the critical load, allowing full use of the battery's capacity. The scheme, as shown in Figure 25, would be utilized when a standby power system was being added to an existing system or when the float charging scheme had unique characteristics of charging voltage and current which would not be suitable to impress directly upon the critical load. The switch that connects the battery system to the critical load in the event of a power outage might simply by a relay as in the case of an emergency lighting system where switching time is less of a consideration or a blocking diode or transistorized switch in the case where the transfer must be instantaneous.

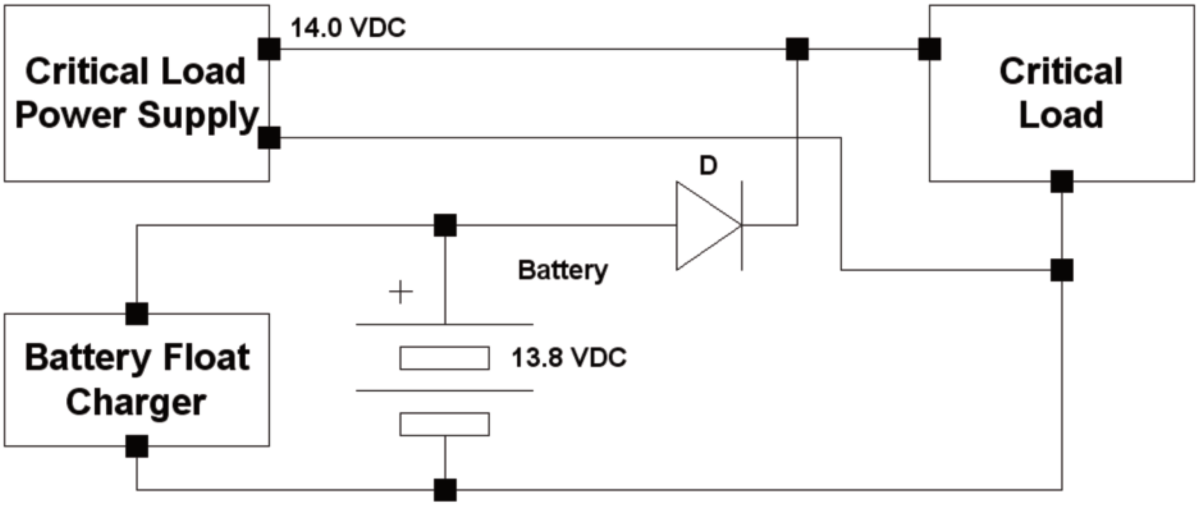


Figure 25 - Auxiliary Standby Power Float Service System

Summary

The preceding information is presented to assist the engineer in the design of an appropriate charging system for the VRLA battery in specific applications. No one charging scheme is optimum for all applications, and it is up to the designer to select those charging techniques which is most appropriate for the specific battery application and are optimum from a battery performance, life and economic standpoint. In that a variety of charging techniques are possible, each with unique results in terms of the battery performance and life, the proposed design should be thoroughly tested and evaluated during bulk, absorption, and float phases of charging in terms of:

1. DC charging voltage value and regulation when using voltage techniques
2. DC charging current rates and regulation when using constant current techniques
3. DC voltage switching levels and stability when using multi-level constant voltage or constant current techniques
4. AC ripple voltage
5. AC ripple current
6. Battery temperature
7. Charging time to 85, 90, 95 and 100% state of charge

C&D TECHNOLOGIES, INC.
1400 Union Meeting Road
P.O. Box 3053 • Blue Bell, PA 19422-0858
(215) 619-2700 • Fax (215) 619-7899 • (800) 543-8630
customersvc@cdtechno.com
www.cdtechno.com