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# CONSTANT VOLTAGE RECHARGE TIME FOR VRLA BATTERIES

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## INTRODUCTION

Within the industry it has been common practice to determine battery recharge time considering only the ampere-hours removed from the battery and the charging system current limitations ($I_c$) utilizing Equation 1:

Equation 1

$$R_t = \frac{Ah_r * K}{I_c}$$

Where
- $R_t$ = Recharge time in hours
- $Ah_r$ = Ampere hours removed during discharge
- $I_c$ = Current limit of the charger
- $K$ = a constant usually of between 1.07 and 1.25, and typically 1.20, which relates to the ampere-hour overcharge required to reach a full state of charge.

It has been generally accepted that these values of "K" were approximate and only appropriate for a small range of discharge rates and depths, and charging voltages and times. However, at the same time the "K" values of 1.07 to 1.25 have been widely applied as though the $I_c$ was a constant current rather than a current limit at constant voltage. As a result, inappropriate and sometimes more expensive chargers have been specified and unattainable recharge times have been anticipated.

A typical constant voltage – current limited recharging profile is shown in Figure 1. As will be noted in the figure, the charging current is "constant" only during the bulk phase of the cycle when the charger is working at its current limit ($I_c$). However, the charging current acceptance will decline below that of the charger current limit ($I_c$) when the battery has recovered to only approximately 85% to 90% state of charge. The point at which this decline in current acceptance occurs is a function of the prior discharge rate, depth of discharge, charging voltage and charger current limit ($I_c$) setting.

As a result of the many variables affecting recharge time, to accurately determine recharge time using Equation 1, a family of "K" values had to be determined through actual discharge - recharge testing.

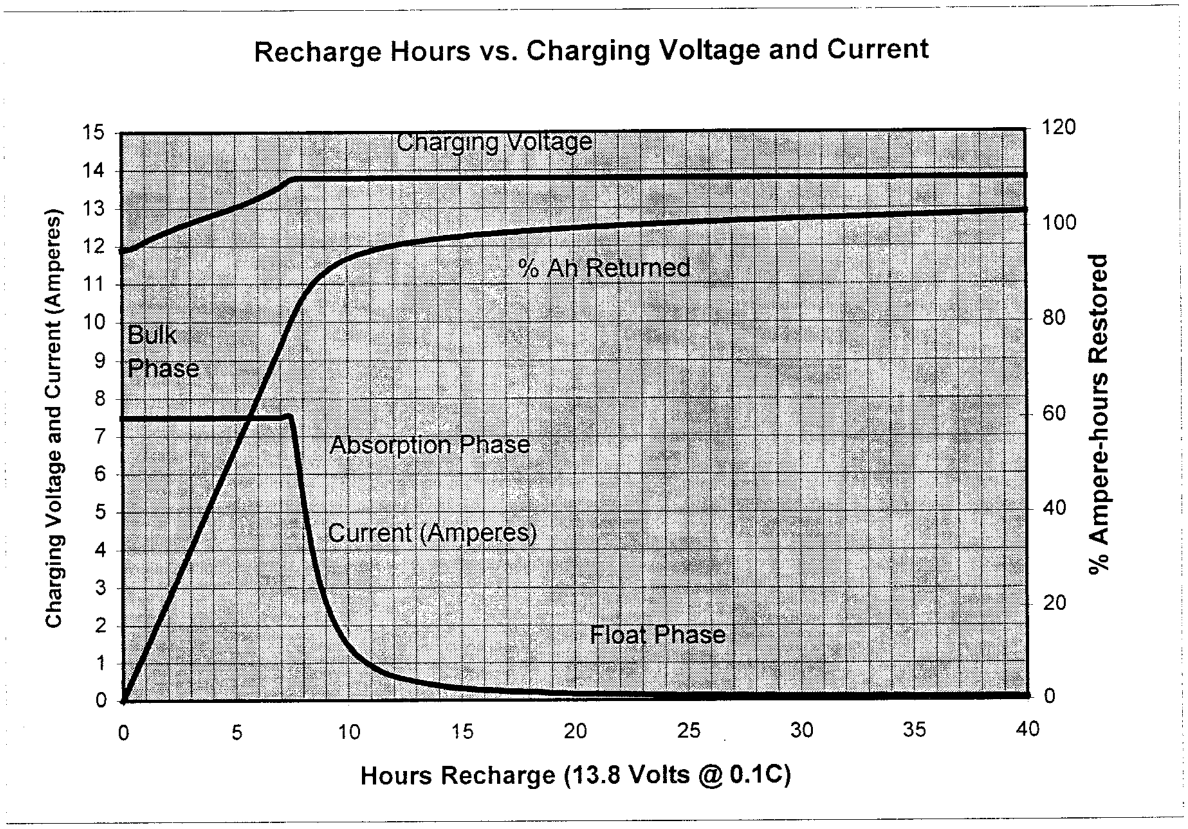


**Figure 1**

It has also been common of users to request that a 100% state of charge be attained within a predetermined time following discharge. Often this would require a more expensive charger. The most appropriate and less expensive requirement would be to demand 100% of the necessary standby operating time (autonomy) following a predetermined recharge period.

## THE TESTING

The testing was performed utilizing VRLA batteries with a $C_{20}$ (20 hour rated capacity) of from 24 to 100 Ah. There were a total of 48 cycles in which the batteries were discharged at rates of from 10 minutes through 20 hours resulting in depths of discharge of from 37% to 100%. The recharges were conducted at voltages of 2.25 through 2.47 v/c at selected current limits ranging from C/1 to C/10. The test cycles conducted are summarized in Table 1.

| Recharge Voltage | Number of Test Cycles | Range of Depth of Discharge | Recharge Current Limit |
|---|---|---|---|
| 14.7 | 7 | 37% to 100% | C/10 |
| 14.4 | 5 | 50% - 100% | C/10 |
| 14.4 | 3 | 89% - 90% | C/6.6 |
| 14.4 | 1 | 94% | C/2 |
| 13.8 | 5 | 37% - 100% | C/10 |
| 13.8 | 3 | 75% - 89% | C/6.6 |
| 13.8 | 5 | 41% - 84% | C/5 |
| 13.8 | 6 | 40% - 96% | C/2 |
| 13.8 | 5 | 38% - 93% | C/1 |
| 13.5 | 4 | 39% - 90% | C/10 |
| 13.5 | 4 | 40% - 79% | C/5 |
| 2.25 v/c to 2.45 v/c | Total = 48 | 50% to 100% DOD | 0.1C to 1C |

**Table 1 – Summary of Discharge – Recharge Cycles Completed**

Although some of the test cycles utilized elevated charging voltages (14.7) and current limits (0.5C& 1.0C), in practice they must be limited to that which is recommended for the batteries as noted in Tables 2 and 3.

| Dynasty Series | Electrolyte Specific Gravity | Recommended Float Voltage / Cell | Recommended Equalization Voltage / Cell | Recommended Cycle Service Voltage / Cell |
|---|---|---|---|---|
| GC (Type A) | 1.280 (gel) | 2.25 to 2.30 v/c | 2.35 to 2.40 v/c | Not Recommended |
| GC (Type B) | 1.280 (gel) | 2.25 to 2.30 v/c | 2.35 to 2.40 v/c | 2.40 to 2.48 v/c |
| UPS (Std.) | 1.300 (AGM) | 2.26 to 2.30 v/c | 2.35 to 2.40 v/c | 2.40 to 2.48 v/c |
| UPS (Hi-Rate) | 1.300 (AGM) | 2.26 to 2.30 v/c | 2.35 to 2.40 v/c | Not Recommended |
| TEL | 1.300 (AGM) | 2.26 to 2.30 v/c | 2.35 to 2.40 v/c | Not Recommended |

**Table 2 – Recommended Charging Voltages as a Function of SG and Application**

The charging current limits expressed in Table 3 are based on a maximum allowable temperature rise of 18°F (10°C) during charging.

| **Maximum Rate Discharge Period to End Point Voltage** | **Approximate % Depth of Discharge Relative to 20 Hour Rated Capacity** | **Recommended Charging Current Limit Relative to Battery 20 Hour Rated Capacity** |
|---|---|---|
| 15 Minute | 45% | C/1 (100 amps per 100 AH) |
| 30 Minute | 55% | C/2 (50 amps per 100 AH) |
| 1 Hour | 60% | C/3 (33 amps per 100 AH) |
| 3 Hour | 75% | C/4 (25 amps per 100 AH) |
| 8 Hour | 90% | C/5 (20 amps per 100 AH) |
| 20 Hour | 100% | C/6 (17 amps per 100 AH) |

**Table 3 – Recommended Maximum Charging Current ($I_c$) VS. Depth of Discharge (DOD)**

## DATA ANALYSIS AND RESULTS

Initially, the 90%, 95% and 100% state of charge was calculated. For each cycle to a specific depth of discharge, the recharge time to 90%, 95% and 100% state of charge was then noted for the relevant charging voltage and current limit. These recharge times were then plotted vs. depth of discharge as noted in Figure 2.

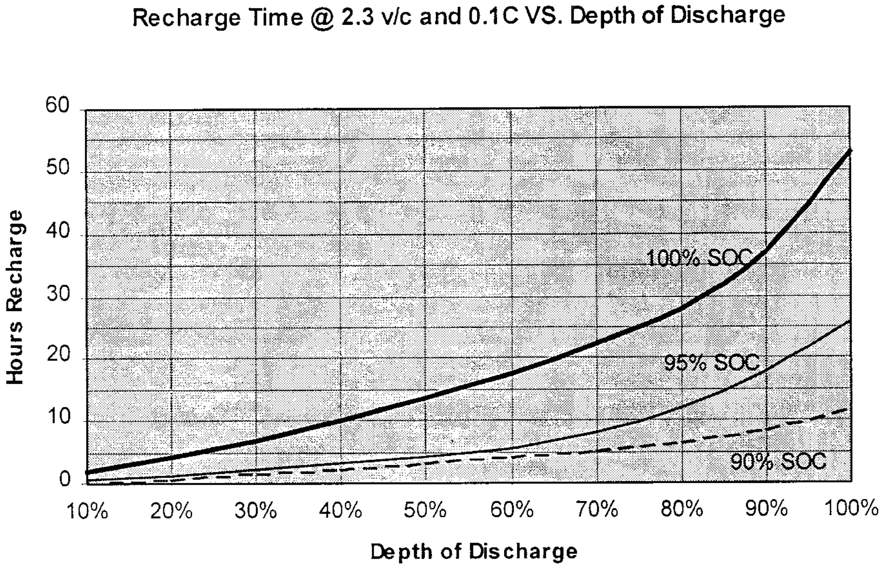


**Figure 2**

As noted in Figure 2, it can require twice as long to attain 95% state of charge (SOC) and four times as long to attain 100% as it does to reach 90% state of charge. With this in mind, it can be much less expensive and more convenient in many cases to size the battery to provide the required autonomy at 90% or 95% of rating than to provide a charger with greater output current capability in an effort to reduce recharge time.

Based on the recharge times from the Figure 2, the "K" values were then calculated, using Equation 1, and plotted vs. depth of discharge (DOD) as noted in Figure 3.

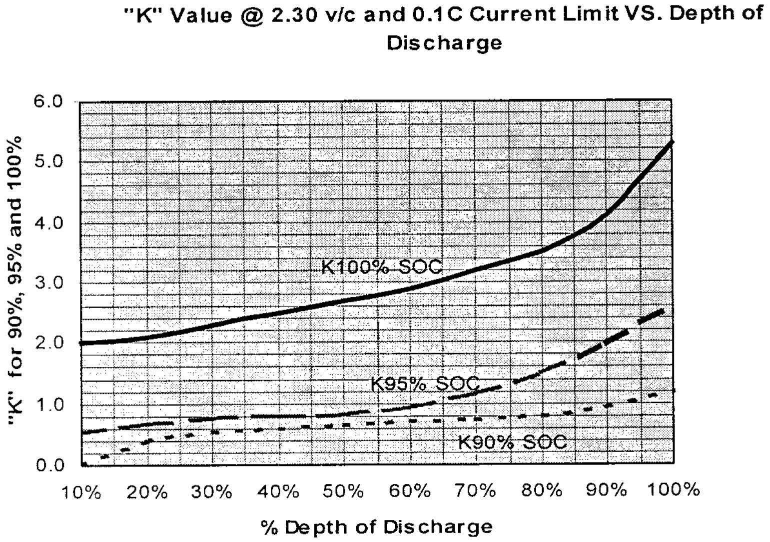


**Figure 3**

A wide variance in the appropriate "K" values is apparent in Figure 3. Note for example that the typical "K" value of 1.2 is valid only for the 70% DOD as $K_{90}$ and 100% for $K_{95}$. If recharging from this same 70% DOD to 100% state of charge, the $K_{100}$ would be 3.2. As noted here, even at the same charging voltage and current limit there is a wide variation in the value of "K" as a function of the DOD and the desired state of charge to which the battery is to be restored.

This is further illustrated in Figure 4, where the recharge times are shown for different charging voltages and current limits and Figure 5 which notes the resulting calculated "K" factors.

In Figure 4, where recharge time is plotted against DOD for various charging voltages and current limits, it will be noted that higher charging voltage can be more effective in the reduction of recharge time than higher charging current limits. Note that at a 90% depth of discharge, it only requires 18 hours to attain a 95% state of charge when using 2.3 v/c charging voltage and 0.1C (10 amperes per 100 Ah) charging current limit. However, 28 hours are required when using 2.25 v/c and 0.2C (20 amperes per 100 Ah).Using the recharge times of Figure 4, the "K" factors were calculated using Equation 1 and were plotted vs. depth of discharge in Figure 5. Use of a family.of "K" curves at various charging voltages and charging current limits allows for extrapolation between the curves should it be desired to determine a recharge time at a somewhat different voltage or current limit than that presented.

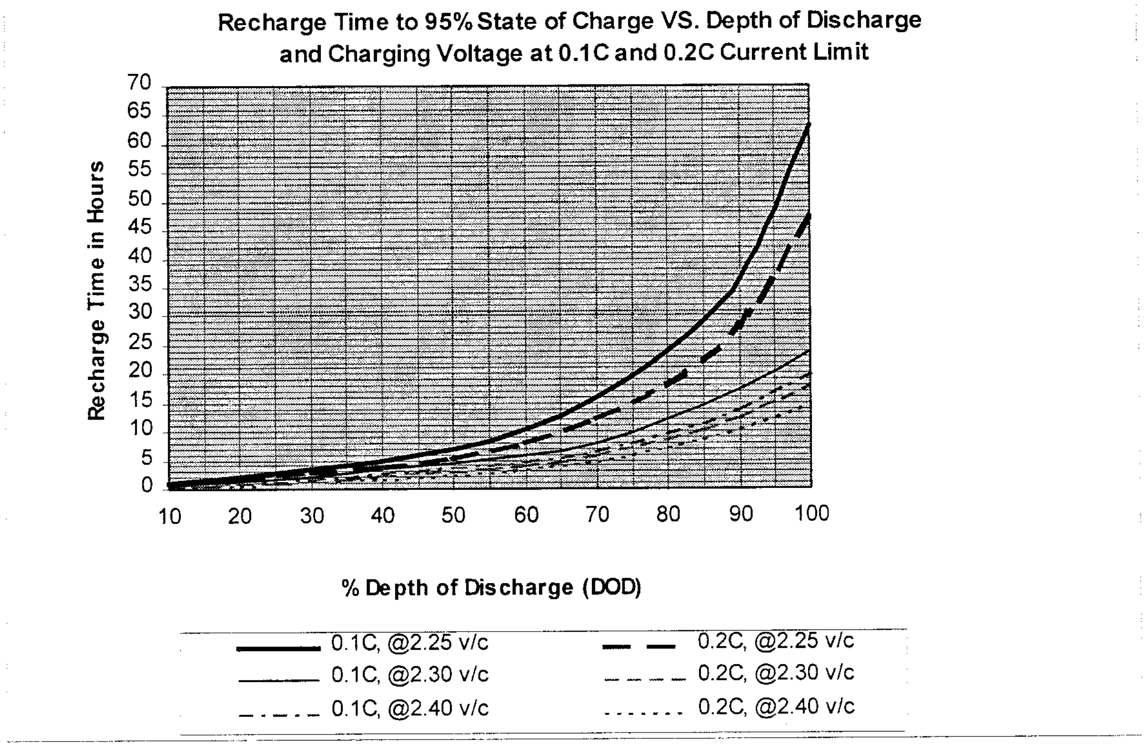


**Figure 4**

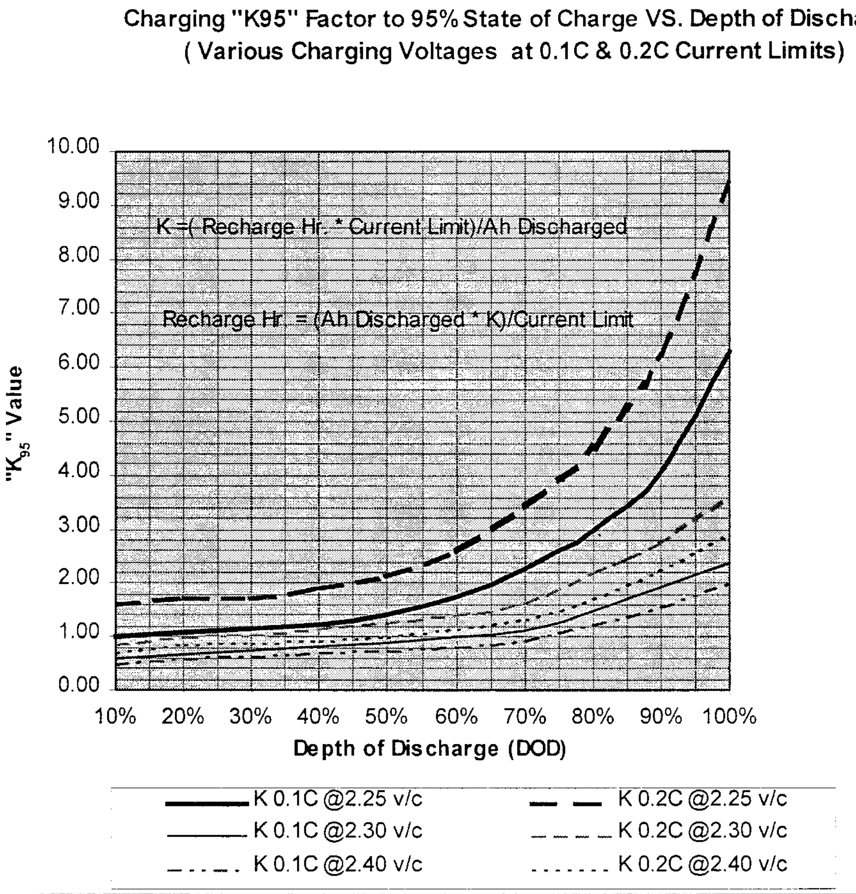


**Figure 5**

The recharge time and "K" factors to attain 90% and 95% SOC were also determined for typical high rate (10 through 90 minute) UPS discharges using a charging voltage of 2.3 v/c and current limits of 0.5C and 1.0C (Figures 6 & 7). In practice, the 1C and 0.5C rates should be limited to use at 45% and 55% or less DOD respectively to prevent excessive heating of the battery during recharge.

With constant power discharges, the DOD was determined by calculating the average current during the discharge and ampere-hours removed relative to the 20 hour rated capacity ($C_{20}$).

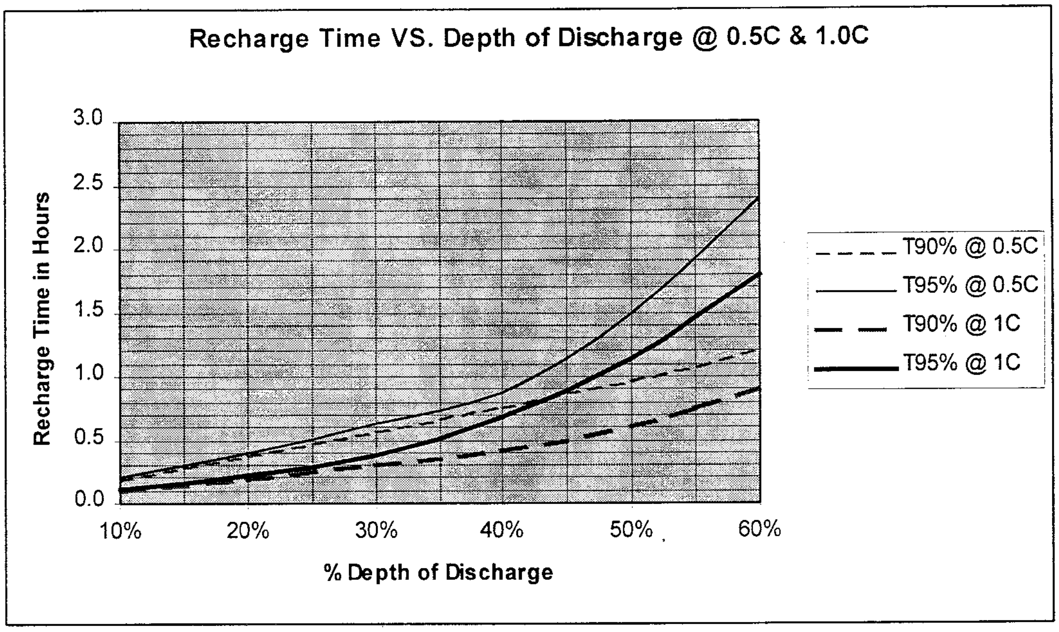


**Figure 6**

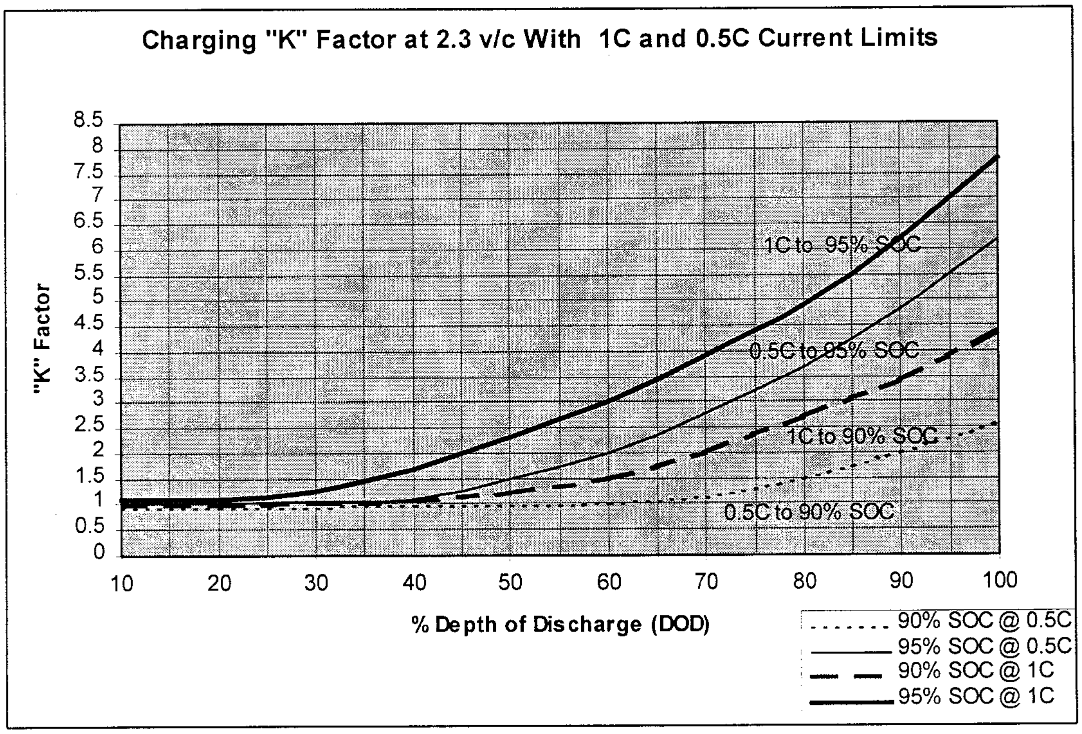


**Figure 7**

When the depth of discharge is related to that attained when the battery is discharged at specific rates to specified end point voltages, as in Table 4, curves of recharge time vs. discharge time at rating can be generated. These curves greatly simplify the question of "how long does it take to recharge the battery?". Examples are shown in Figures 8 and 9.

| Discharge Rate (Hours) | % Depth of Discharge | Hourly Discharge Rate | % Depth of Discharge | Hourly Discharge Rate | % Depth of Discharge | Hourly Discharge Rate | % Depth of Discharge |
|---|---|---|---|---|---|---|---|
| 0.083* | 29.0% | 4 | 78.3% | 11 | 92.0% | 18 | 98.0% |
| 0.25* | 47.5 | 5 | 81.0 | 12 | 93.5 | 19 | 99.0 |
| 0.5* | 58.4 | 6 | 84.0 | 13 | 95.0 | 20 | 100.0 |
| 0.75* | 63.1 | 7 | 86.0 | 14 | 96.0 | 24 | 100.4 |
| 1* | 67.5 | 8 | 88.0 | 15 | 96.5 | 72 | 103.0 |
| 2 | 69.5 | 9 | 89.4 | 16 | 96.8 | 100 | 104.0 |
| 3 | 75.4 | 10 | 90.8 | 17 | 97.5 | | |

Note: * to 1.65 v/c

**Table 4 - Discharge Rate VS. Depth of Discharge**

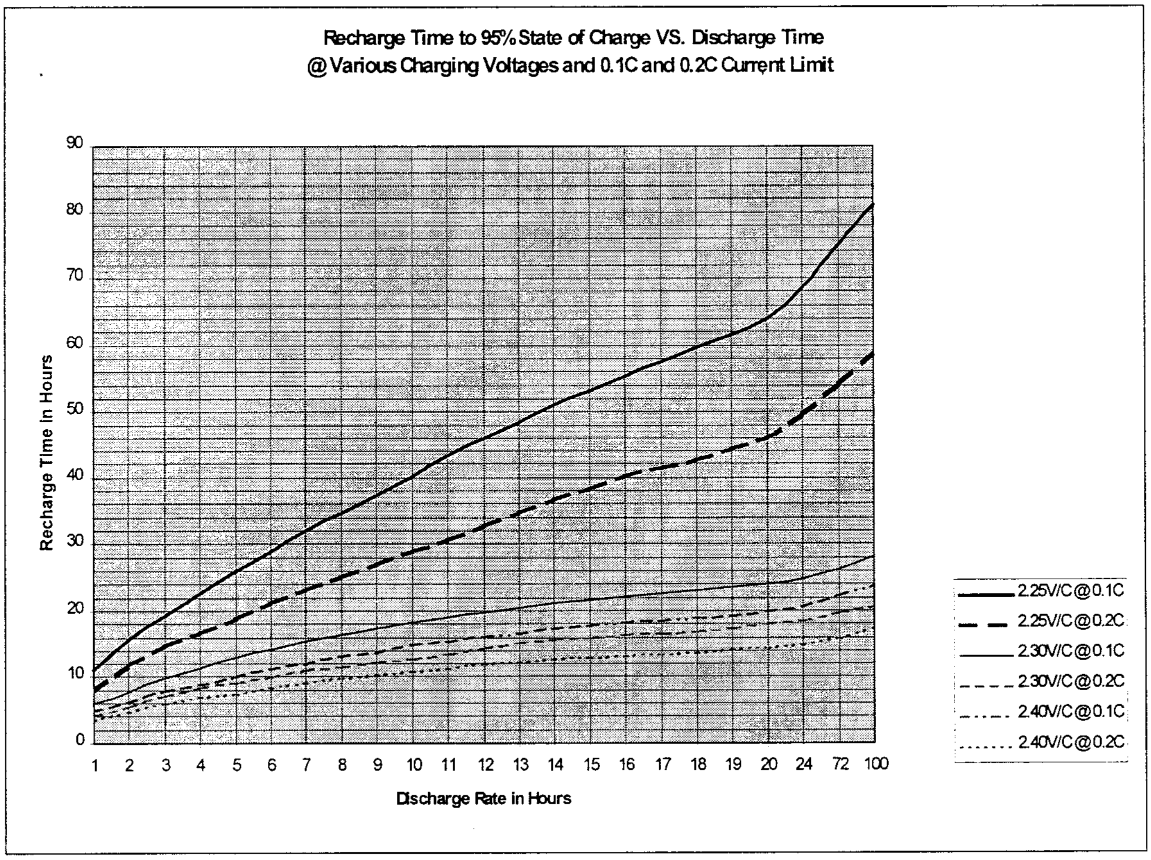


**Figure 8**

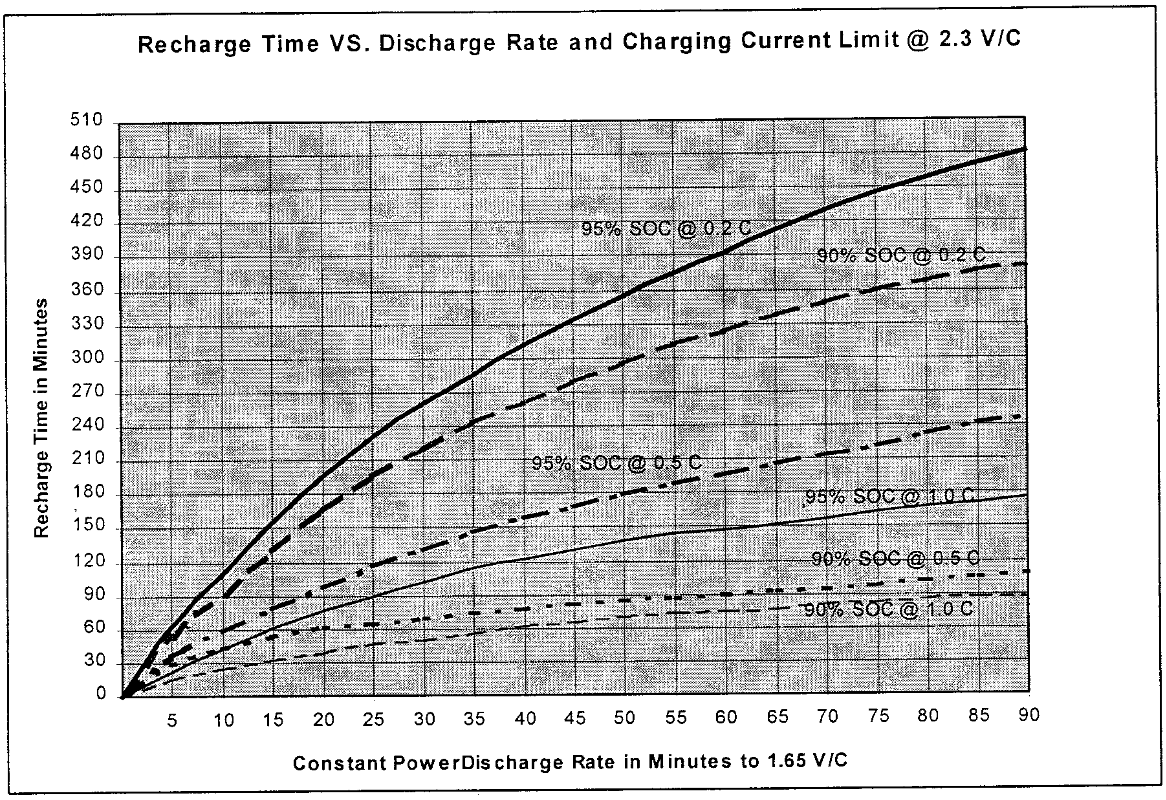


**Figure 9**

## Summary

This is obviously a "work in process" in that the database is currently limited to that derived from only 48 discharge-recharge cycles. However, this is sufficient to illustrate the need for empirical data to establish more accurate "K" factors as a function of charging voltage, current limit and rate and depth of discharge for optimum selection of charging parameters and accurate determination of recharge time.

## CONCLUSIONS

1. In constant voltage charging the "K" factor of Equation 1 is not a constant but varies with depth of discharge(DOD), charging current limit ($I_c$) and charging voltage. As a result, an appropriate family of "K" value curves must be determined empirically.

2. Use of a higher than minimum (2.3 v/c vs. 2.25 v/c) charging voltage can reduce the required charger current limit ($I_c$) and expense with a reduction in recharge time.

3. Required autonomy following recharge for a prescribed time can often be met more economically by oversizing (5% or more) the battery rather than the charger.

4. Knowledge of the recharge family of "K" curves is required to most efficiently optimize the charger and battery as a system.

5. With empirically derived family of "K" curves and the relationship between depth of discharge and discharge rate, curves can be generated that accurately indicate the recharge time vs. the discharge rate when recharging at a given voltage and current limit.