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IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

Sponsor

IEEE Standards Coordinating Committee 29
on Stationary Batteries

Approved 20 March 1997

IEEE Standards Board

Abstract: Methods for defining the dc load and for sizing a lead-acid battery to supply that load for stationary battery applications in full float operations are described. Some factors relating to cell selection are provided for consideration. Installation, maintenance, qualification, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this recommended practice. Design of the dc system and sizing of the battery charger(s) are also beyond the scope of this recommended practice.

Keywords: battery duty cycle, cell selection, dc load, full float operation, lead-acid batteries, rated capacity, sizing, stationary applications, valve-regulated lead-acid (VRLA) cell, vented battery

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Introduction

(This introduction is not part of IEEE Std 485-1997, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.)

The storage battery is of primary importance in ensuring the satisfactory operation of generating stations, substations, and other stationary applications. This recommended practice is based on commonly accepted methods used to define the load and to ensure adequate battery capacity. The method described is applicable to all installations and battery sizes.

The installations considered herein are designed for operation with a battery charger serving to maintain the battery in a charged condition as well as to supply the normal dc load.

This recommended practice was prepared by the Battery Sizing Working Group of Standards Coordinating Committee 29 (SCC29). It may be used separately, but when combined with IEEE Std 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications, and IEEE Std 484-1996, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications, it will provide the user with a general guide to designing, placing in service, and maintaining a lead-acid battery installation.

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IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

1. Overview

This recommended practice describes methods for defining the dc load and for sizing a lead-acid battery to supply that load for stationary battery applications in full float operations. Some factors relating to cell selection are provided for consideration.

Installation, maintenance, qualification, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this recommended practice. Design of the dc system and sizing of the battery charger(s) are also beyond the scope of this recommended practice.

2. References

This recommended practice shall be used in conjunction with the following publications.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.[1]

IEEE Std 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications (ANSI).

IEEE Std 484-1996, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications (ANSI).

IEEE Std 1184-1994, IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Systems (ANSI).

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[1] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3. Definitions

The following definitions apply specifically to this recommended practice. For other definitions, see IEEE Std 100-1996.[2]

3.1 battery duty cycle: The loads a battery is expected to supply for specified time periods.

3.2 cell size: The rated capacity of a lead-acid cell or the number of positive plates in a cell.

3.3 equalizing charge: A prolonged charge, at a rate higher than the normal float voltage, to correct any inequalities of voltage and specific gravity that may have developed between the cells during service.

3.4 full float operation: Operation of a dc system with the battery, battery charger, and load all connected in parallel and with the battery charger supplying the normal dc load plus any charging current required by the battery. (The battery will deliver current only when the load exceeds the charger output.)

3.5 period: An interval of time in the battery duty cycle during which the load is assumed to be constant for purposes of cell sizing calculations.

3.6 rated capacity (lead-acid): The capacity assigned to a cell by its manufacturer for a given discharge rate, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

3.7 valve-regulated lead-acid (VRLA) cell: A lead-acid cell that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds atmospheric pressure by a pre-selected amount. VRLA cells provide a means for recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

3.8 vented battery: A battery in which the products of electrolysis and evaporation are allowed to escape freely to the atmosphere. These batteries are commonly referred to as “flooded.”

4. Defining loads

4.1 General considerations

The duty cycle imposed on the battery by any of the conditions described herein will depend on the dc system design and the requirements of the installation. The battery must supply the dc power requirements when the following conditions occur:

a) Load on the dc system exceeds the maximum output of the battery charger;
b) Output of the battery charger is interrupted;
c) AC power is lost [may result in a greater dc power demand than b) above].

The most severe of these conditions, in terms of battery load and duration, should be used to determine the battery size for the installation.

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[2] Information on references can be found in Clause 2.

4.2 Load classification

The individual dc loads supplied by the battery during the duty cycle may be classified as continuous or noncontinuous. Noncontinuous loads lasting 1 min or less are designated “momentary loads” and should be given special consideration (see 4.2.3).

4.2.1 Continuous loads

Continuous loads are energized throughout the duty cycle. These loads are those normally carried by the battery charger and those initiated at the inception of the duty cycle. Typical continuous loads are as follows:

a) Lighting
b) Continuously operating motors
c) Converters (e.g., inverters)
d) Indicating lights
e) Continuously energized coils
f) Annunciator loads
g) Communication systems

4.2.2 Noncontinuous loads

Noncontinuous loads are energized only during a portion of the duty cycle. These loads may come on at any time within the duty cycle and may be on for a set length of time, be removed automatically or by operator action, or continue to the end of the duty cycle. Typical noncontinuous loads are as follows:

a) Emergency pump motors
b) Critical ventilation system motors
c) Fire protection systems actuations
d) Motor-driven valve operations (stroke time > 1 min)

4.2.3 Momentary loads

Momentary loads can occur one or more times during the duty cycle but are of short duration, not exceeding 1 min at any occurrence. Although momentary loads may exist for only a fraction of a second, it is common practice to consider each load will last for a full minute because the battery voltage drop after several seconds often determines the battery’s 1 min rating. When several momentary loads occur within the same 1 min period and a discrete sequence cannot be established, the load for the 1 min period should be assumed to be the sum of all momentary loads occurring within that minute. If a discrete sequence can be established, the load for the period should be assumed to be the maximum load at any instant. Sizing for a load lasting only a fraction of a second, based on the battery’s 1 min performance rating, results in a conservatively sized battery. Consult the battery manufacturer for ratings of discharge durations less than 1 min. Typical momentary loads are as follows:

a) Switchgear operations
b) Motor-driven valve operations (stroke time ≤ 1 min)
c) Isolating switch operations
d) Field flashing of generators
e) Motor starting currents
f) Inrush currents

When evaluating or justifying the size of an existing battery by means of a service test, the momentary load’s actual duration and sequence should be duplicated as accurately as practical.

4.2.4 Other considerations

The above lists of typical loads are not a full catalog of the dc loads at any one installation. Loads applied to the battery are normally typed as constant power, constant resistance, or constant current. However, for sizing purposes, loads are treated as constant power or constant current. The designer should review each system carefully to be sure all possible loads and their variations are included (see Annex B).

4.3 Duty cycle diagram

A duty cycle diagram showing the total load at any time during the cycle is an aid in the analysis of the duty cycle. To prepare such a diagram, all loads (expressed in either current or power) expected during the cycle are tabulated along with their anticipated inception and shutdown times. The total time span of the duty cycle is determined by the requirements of the installation.

4.3.1 Defined loads

Loads whose inception and shutdown times are known are plotted on the diagram as they would occur. If the inception time is known, but the shutdown time is indefinite, it should be assumed that the load will continue through the remainder of the duty cycle.

4.3.2 Random loads

Loads that occur at random should be shown at the most critical time of the duty cycle in order to simulate the worst-case load on the battery. These may be noncontinuous or momentary loads as described in 4.2.2 and 4.2.3. To determine the most critical time, it is necessary to size the battery without the random load(s) and to identify the section of the duty cycle that controls battery size. Then the random load(s) should be superimposed on the end of that controlling section as shown in Figure 1 (see 6.3.4).

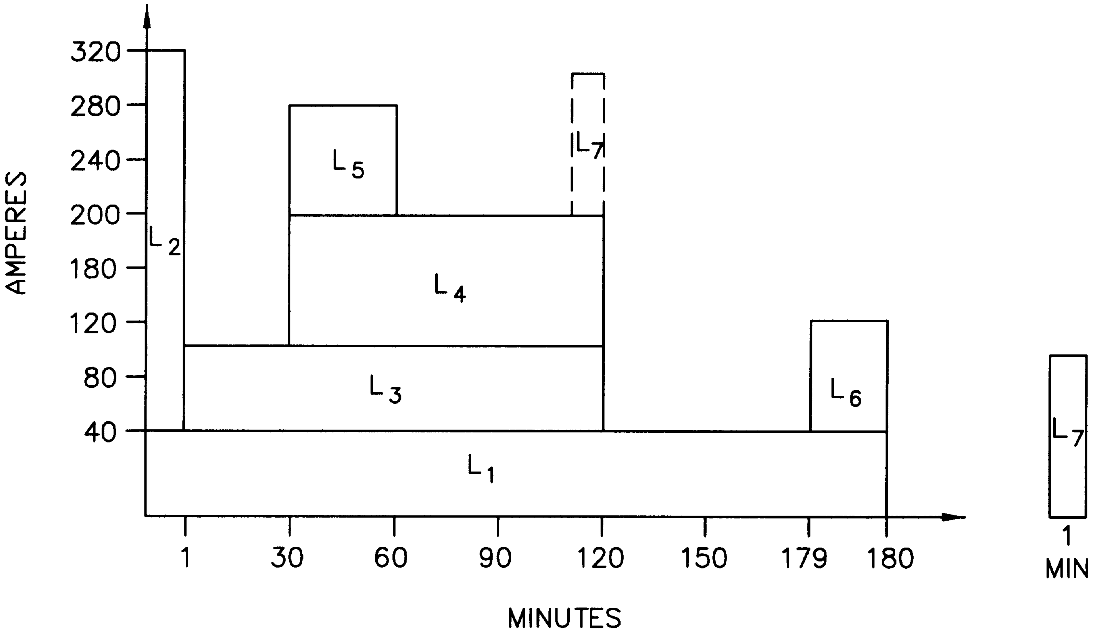


Figure 1—Diagram of a duty cycle

NOTE—This example is worked out in detail in Annex A. There it will be found that the first 120 min is the controlling portion of the duty cycle. Therefore, the random load is located on the duty cycle so that the random load ends at the end of the 120th min. This is indicated by the dashed lines.

4.3.3 Duty cycle example

Figure 1 is a diagram of a duty cycle made up of the following hypothetical loads expressed in amperes:

L_1	40 A for 3 h, continuous load;
L_2	280 A for the 1st min, momentary load, actually 5 s starting current to load L_3;
L_3	60 A from the 1st min through the 120th min, noncontinuous load;
L_4	100 A from the 30th min through the 120th min, noncontinuous load;
L_5	80 A from the 30th min through the 60th min, noncontinuous load;
L_6	80 A for the last minute, momentary load, actually a known sequence of: 40 A for the first 5 s, 80 A for the next 10 s, 30 A for the next 20 s;
L_7	100 A for 1 min, random load (Actually this consists of four 25 A momentary loads that can occur at any time within the duty cycle. Therefore, the assumption is that they all occur simultaneously.).

When the duty cycle includes constant power and constant current loads it is usually more convenient to convert the constant power load values to constant current values for sizing calculations (see Annex B).

5. Cell selection

This clause summarizes some factors that should be considered in selecting a cell design for a particular application. Various cell designs have different charge, discharge, and aging characteristics. Refer to IEEE Std 1184-1994 or vendor literature for a discussion of cell characteristics.

The following factors should be considered in the selection of the cell:

a) Physical characteristics, such as dimensions and weight of the cells, container material, intercell connectors, and terminals;
b) Planned life of the installation and expected life of the cell;
c) Frequency and depth of discharge;
d) Ambient temperature (Note that sustained high ambient temperatures result in reduced battery life. See IEEE Std 484-1996.);
e) Charging characteristics;
f) Maintenance requirements;
g) Cell orientation requirements (VRLA);
h) Ventilation requirements (VRLA);
i) Seismic characteristics.

6. Determining battery size

Several basic factors govern the size (number of cells and rated capacity) of the battery: the maximum system voltage, the minimum system voltage, correction factors, and the duty cycle. Since a battery is usually composed of a number of identical cells connected in series, the voltage of the battery is the voltage of a cell multiplied by the number of cells in series. The ampere-hour capacity of a battery is the same as the ampere-hour capacity of a single cell, which depends upon the dimensions and number of plates.

If cells of sufficiently large capacity are not available, then two or more strings (equal numbers of series-connected cells) may be connected in parallel to obtain the necessary capacity. The capacity of such a battery is the sum of the capacities of the strings. Consult the manufacturer for any limitation on paralleling.

Operating conditions can change the available capacity of the battery. For example,

a) The available capacity of the battery decreases as its temperature decreases.
b) The available capacity decreases as the discharge rate increases.
c) The minimum specified cell voltage at any time during the battery discharge cycle limits the available capacity of the battery.

6.1 Number of cells

The maximum and minimum allowable system voltage determines the number of cells in the battery. It has been common practice to use 12 cells, 24 cells, 60 cells, or 120 cells for nominal system voltages of 24 V, 48 V, 125 V, or 250 V, respectively. In some cases, it may be desirable to vary from this practice to more closely match the battery to system voltage limitations. It should be noted that the use of the widest possible voltage window, within the confines of individual load requirements, will result in the most economical battery. Furthermore, the use of the largest number of cells allows the lowest minimum cell voltage and, therefore, the smallest size cell for the duty cycle. The application of the following principles is illustrated in A.1.

6.1.1 Calculation of number of cells and minimum cell voltage

When the battery voltage is not allowed to exceed a given maximum system voltage, the number of cells will be limited by the cell voltage required for satisfactory charging or equalizing. This is

$$\frac{\text{maximum system voltage}}{\text{cell voltage required for charging}} = \text{number of cells}$$

Example: Assume 2.33 V/cell is required for equalize charging and that the maximum allowable system voltage is (1) 140 V, or (2) 135 V. Then

$$(1)\ \frac{140\ \text{V}}{2.33\ \text{V/cell}} = 60.09\ \text{cells (use 60 cells)}$$

$$(2)\ \frac{135\ \text{V}}{2.33\ \text{V/cell}} = 57.94\ \text{cells (use 58 cells)}$$

The minimum battery voltage equals the minimum system voltage plus cable voltage drop. The minimum battery voltage is then used to calculate the allowable minimum cell voltage.

$$\frac{\text{minimum battery voltage}}{\text{number of cells}} = \text{minimum cell voltage}$$

In an application with a wide voltage window, particularly when long discharge times are required, the minimum cell voltage recommended by the manufacturer for a given discharge time may be a factor. If so, reduce the number of cells in the above calculation so that the minimum cell voltage per cell does not fall below the recommended value.

Example: Assume that the minimum battery voltage for the examples above is 105 V. Then

$$\frac{105\text{ V}}{60\text{ cells}} = 1.75\text{ V/cell}$$

$$\frac{105\text{ V}}{58\text{ cells}} = 1.81\text{ V/cell}$$

This minimum cell voltage is then used in the sizing calculation.

6.1.2 Float voltage as limiting factor

To eliminate the need for frequent equalizing charges (refer to IEEE Std 450-1995), it may be desirable to establish a float voltage at the high end of the manufacturer’s recommended range. The float voltage must, however, be consistent with the maximum system voltage (see 6.1.1). This higher float voltage may then reduce the number of cells and may increase the cell size required for a given battery duty cycle.

6.1.3 Rounding off

If the calculations shown in 6.1.1 indicate a need for a fractional cell, the result should be rounded off to a whole number of cells. The minimum cell voltage, float voltage, and equalize voltage should then be recalculated and verified for adequacy of operation.

6.2 Additional considerations

Before proceeding to calculate the cell capacity required for a particular installation, the designer should consider factors that will influence cell size but that are not included in the general equation.

6.2.1 Temperature correction factor

The available capacity of a cell is affected by its operating temperature. The standard temperature for rating cell capacity is 25 °C (77 °F). If the lowest expected electrolyte temperature is below this standard temperature, select a cell large enough to have the required capacity available at the lowest expected temperature. If the lowest expected electrolyte temperature is above 25 °C (77 °F), it is a conservative practice to select a cell size to match the required capacity at the standard temperature and to recognize the resulting increase in available capacity as part of the overall design margin. Table 1 lists cell size correction factors for various temperatures for vented lead-acid cells with nominal 1.215 specific gravity. For unlisted temperatures within the range of Table 1, interpolate between adjacent values and round off to two decimal places. For VRLA cells, check with the manufacturers for the appropriate temperature correction factors.

6.2.2 Design margin

It is prudent to provide a capacity margin to allow for unforeseen additions to the dc system and less-than-optimum operating conditions of the battery due to improper maintenance, recent discharge, or ambient temperatures lower than anticipated, or a combination of these factors. A method of providing this design margin is to add 10–15% to the cell size determined by calculations. If the various loads are expected to grow at different rates, it may be more accurate to apply the expected growth rate to each load for a given time and to develop a duty cycle from the results.

The cell size calculated for a specific application will seldom match a commercially available cell exactly, and it is normal procedure to select the next higher capacity cell. The additional capacity obtained can be considered part of the design margin.

Note that the "margins" required by 6.3.1.5 and 6.3.3 of IEEE Std 323-1983 are to be applied during "qualification" and are not related to "design margin."

Table 1—Cell size correction factors for temperature

Electrolyte temperature		Cell size correction factor
(° F)	(° C)	
25	–3.9	1.520
30	–1.1	1.430
35	1.7	1.350
40	4.4	1.300
45	7.2	1.250
50	10.0	1.190
55	12.8	1.150
60	15.6	1.110
65	18.3	1.080
66	18.9	1.072
67	19.4	1.064
68	20.0	1.056
69	20.6	1.048
70	21.1	1.040
71	21.7	1.034
72	22.2	1.029
73	22.8	1.023
74	23.4	1.017
75	23.9	1.011
76	24.5	1.006
77	25.0	1.000
78	25.6	0.994
79	26.1	0.987
80	26.7	0.980
81	27.2	0.976
82	27.8	0.972
83	28.3	0.968
84	28.9	0.964
85	29.4	0.960
86	30.0	0.956
87	30.6	0.952
88	31.1	0.948
89	31.6	0.944
90	32.2	0.940
95	35.0	0.930
100	37.8	0.910
105	40.6	0.890
110	43.3	0.880
115	46.1	0.870
120	48.9	0.860
125	51.7	0.850

NOTE—This table is based on vented lead-acid nominal 1.215 specific gravity. However, it may be used for vented cells with up to a 1.300 specific gravity. For cells of other designs, refer to the manufacturer.

6.2.3 Aging factor

As a rule, the performance of a lead-acid battery is relatively stable throughout most of its life, but begins to decline with increasing rapidity in its latter stages, with the "knee" of its life versus performance curve occurring at approximately 80% of its rated performance.

IEEE Std 450-1995 recommends that a battery be replaced when its actual performance drops to 80% of its rated performance because there is little life to be gained by allowing operation beyond this point. Therefore, to ensure that the battery is capable of meeting its design loads throughout its service life, the battery's rated capacity should be at least 125% (1.25 aging factor) of the load expected at the end of its service life.

Exceptions to this rule exist. For example, some manufacturers recommend that vented batteries with Planté, modified Planté, and round plate designs be replaced when their measured capacity drops below 100% of their rated capacity (1.00 aging factor). These designs maintain a fairly constant capacity throughout their life.

6.2.4 Initial capacity

Batteries may have less than rated capacity when delivered. Unless 100% capacity upon delivery is specified, initial capacity can be as low as 90% of rated capacity. This will rise to rated capacity in normal service after several charge-discharge cycles or after several years of float operation.

If the designer has provided a 1.25 aging factor, there is no need for the battery to have full rated capacity upon delivery because the capacity normally available from a new battery will be above the duty cycle requirement. When a 1.00 aging factor is used, the designer should ensure that the initial capacity upon delivery is at least 100%, or that there is sufficient margin in the sizing calculation to accommodate a lower initial capacity.

Example: If the cells have 90% initial capacity and the margin is greater than 11%, then no additional compensation for initial capacity is required.

6.3 Cell size

This subclause describes and explains a proven method of calculating the cell capacity necessary for satisfactory performance on a given duty cycle. The application of this method to a specific duty cycle, using an optional preprinted worksheet to simplify the calculations, is demonstrated in A.2. Instructions for the proper use of the worksheet are given in 6.4.

6.3.1 Initial calculation

Equation (1) (see 6.3.2) requires the use of a capacity rating factor C_t (6.3.3) that is based on the discharge characteristics of a particular plate type and size. Thus, the initial calculation must be based on a trial selection of positive plate type and capacity. Depending on the results of this initial calculation, it may be desirable to repeat the calculation for other types or sizes of plates to obtain the optimum cell type and size for the particular application. In addition, it may be desirable to repeat the calculation to take into account any differences in performance per plate within a given series of cells. Use the capacity from the first calculation as a guide for selecting additional types to size.

6.3.2 Sizing methodology

The cell selected for a specific duty cycle must have enough capacity to carry the combined loads during the duty cycle. To determine the required cell size, it is necessary to calculate, from an analysis of each section of the duty cycle (see Figure 2), the maximum capacity required by the combined load demands (current versus time) of the various sections. The first section analyzed is the first period of the duty cycle. Using the capacity rating factor (see 6.3.3) for the given cell type, a cell size is calculated that will supply the required current for the duration of the first period. For the second section, the capacity is calculated assuming that the current A_1, required for the first period, continued through the second period; this capacity is then adjusted for the change in current (A_2–A_1) during the second period. In the same manner, the capacity is calculated for each subsequent section of the duty cycle. This iterative process is continued until all sections of the duty cycle have been considered. The calculation of the capacity F_S required by each section S, where S can be any integer from 1 to N, is expressed mathematically in equation (1). F_S will be expressed as watt-hours, ampere-hours, or number of positive plates, depending upon which C_t is used (see 6.3.3).

$$F_S = \sum_{P=1}^{P=S} \frac{A_P - A_{(P-1)}}{C_t} \qquad (1)$$

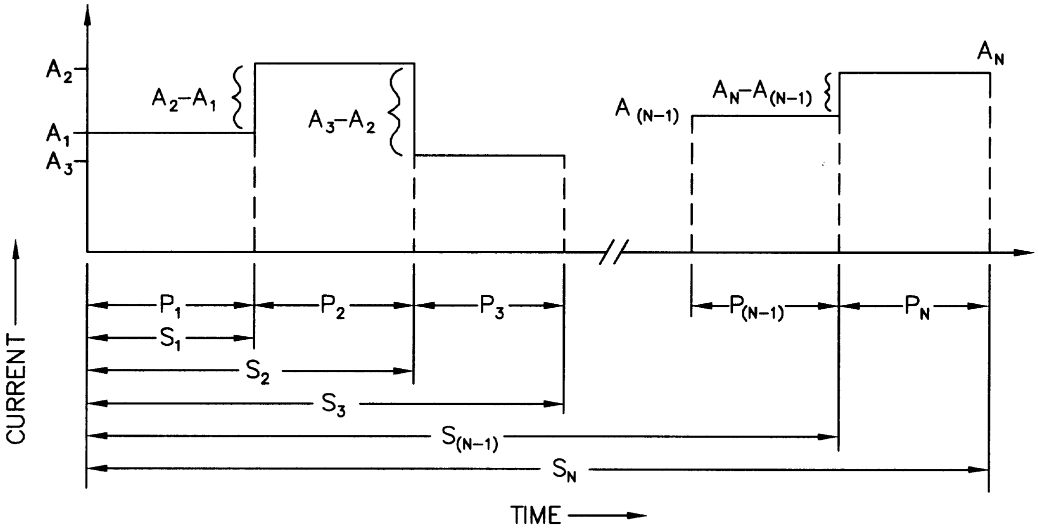


Figure 2—Generalized duty cycle

The maximum capacity (max F_S) calculated determines the uncorrected cell size that can be expressed by the following general equation:

$$F = \max_{S=1}^{S=N} F_S \tag{2}$$

where

F	is the cell size (uncorrected for temperature, aging, and design margin);
S	is the section of the duty cycle being analyzed. [Section S contains the first S periods of the duty cycle (e.g., section S_5 contains periods S_1 through S_5). See Figure 2 for a graphical representation of “section.”];
N	is the number of periods in the duty cycle;
P	is the period being analyzed;
A_P	are the amperes required for period P;
t	is the time in minutes from the beginning of period P through the end of Section S;
C_t	is the capacity rating factor (see 6.3.3) for a given cell type, at the t minute discharge rate, at 25 °C (77 °F), to a definite minimum cell voltage;
F_S	is the capacity required by each section.

If the current for period $P + 1$ is greater than the current for period P, then section $S = P + 1$ will require a larger cell than section $S = P$. Consequently, the calculations for section $S = P$ can be omitted.

6.3.3 Capacity rating factor

There are two terms for expressing the capacity rating factor C_t of a given cell type in cell sizing calculations. One term R_t, is the number of amperes that each positive plate can supply for t minutes, at 25 °C (77 °F), to a definite minimum cell voltage. Therefore $C_t = R_t$ and, combining equations (1) and (2)

$$\mathrm{F} = \max_{S=1}^{S=N} F_S = \max_{S=1}^{S=N} \sum_{P=1}^{P=S} \frac{A_P - A_{(P-1)}}{R_t} \tag{3}$$

The other term K_t, is the ratio of rated ampere-hour capacity [at a standard time rate, at 25 °C (77 °F) and to a standard minimum cell voltage] of a cell, to the amperes that can be supplied by that cell for t minutes at 25 °C (77 °F) and to a given minimum cell voltage. Therefore, $C_t = 1/K_t$ and equation (3) can be rewritten as

$$\mathrm{F} = \max_{S=1}^{S=N} F_S = \max_{S=1}^{S=N} \sum_{P=1}^{P=S} [A_P - A_{(P-1)}]K_t \tag{4}$$

R_t is not equal to $1/K_t$ because of the different units applied to each factor. However, R_t is proportional to $1/K_t$. The values may be obtained from battery manufacturers for each positive plate design and various minimum cell voltages.

Batteries experience a voltage dip during the early stage of discharge, following which the voltage shows some recovery. The designer should ensure that this effect has been taken into account in the manufacturer's published capacity rating factor.

6.3.4 Sizing to include random loads

When equipment loads that occur at random are included as part of the battery duty cycle, it is necessary to calculate the cell size required for the duty cycle without the random load(s) and then add to this the cell size required for the random load(s) only.

6.3.5 Plate conversion

When used with the factor R_t (amperes per positive plate), the general equation expresses the cell size as the number of positive plates. In the manufacturer's literature, the cell size will be listed as the total number of positive and negative plates. The conversion from number of positive plates to the total number of plates is

$$\text{total number of plates} = 1 + (2 \times \text{number of positive plates}) \tag{5}$$

6.4 Cell sizing worksheet

A worksheet, given in Figure 3, has been designed and may be used to simplify the manual application of the procedure described in 6.3. Examples of its use will be found in Annex A. Instructions for proper use of the worksheet are as follows:

a) Fill in necessary information in the heading of the chart. The temperature and voltage recorded are those used in the calculations. The voltage used is the minimum battery voltage divided by the number of cells in the battery.

b) Fill in the amperes and the minutes in columns (2) and (4) as indicated by the section heading notations.

c) Calculate and record the changes in amperes as indicated in column (3). Record whether the changes are positive or negative.

d) Calculate and record the times from the start of each period to the end of the section as indicated in column (5).

e) Record in column (6) the capacity factors (R_t or K_t, from the manufacturer's literature) for each discharge time calculated in column (5).

f) Calculate and record the cell size for each period as indicated in column (7). Note the separate subcolumns for positive and negative values.

g) Calculate and record in column (7) the subtotals and totals for each section as indicated.

h) Record the maximum section size (the largest total from column (7) on line (8), the random section size on line (9), and the uncorrected size (US) on lines (10) and (11).

i) Select the correction factor from Table 1 or from the manufacturer's published data for the temperature shown in the main heading and record it on line (12).

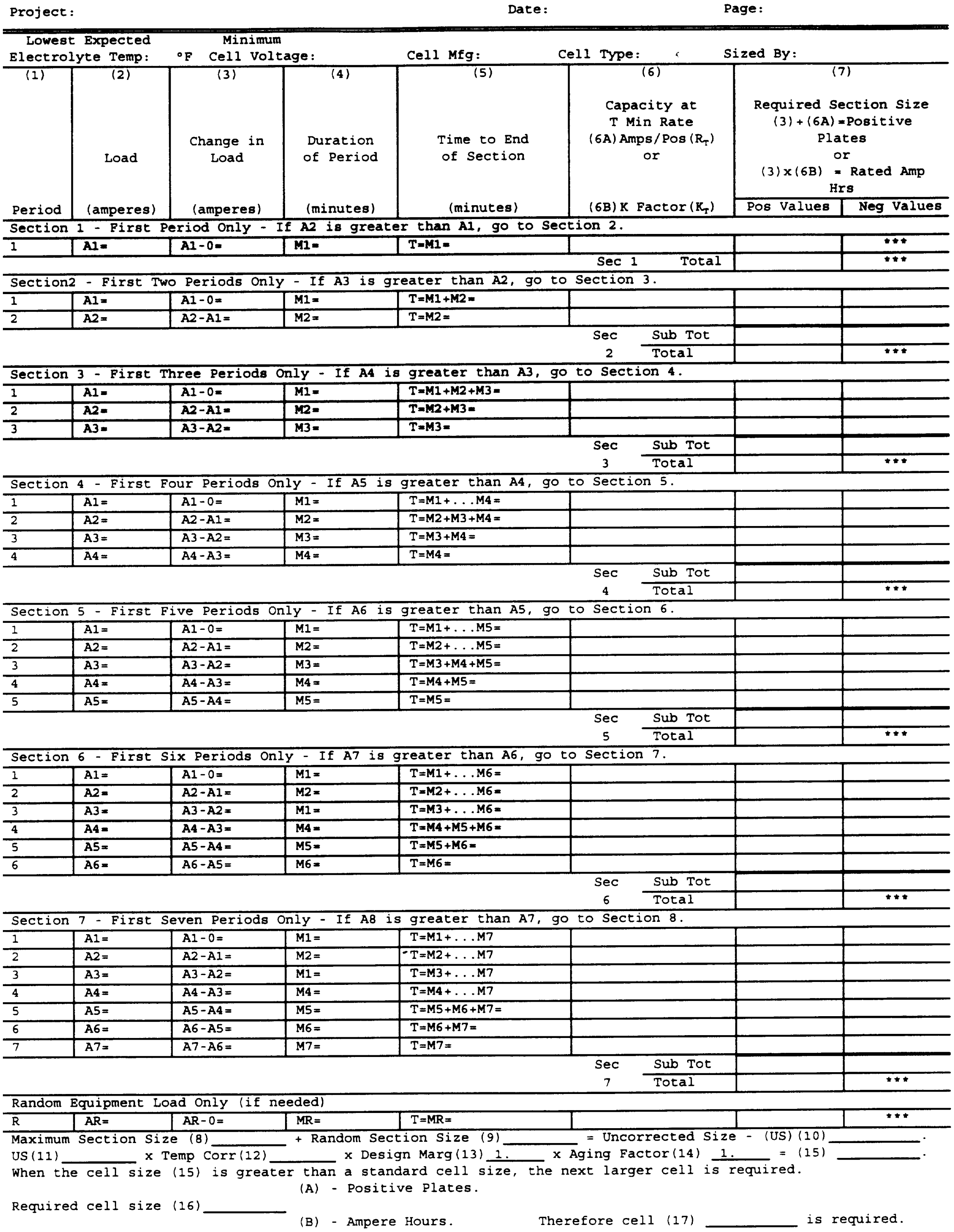
j) Enter the design margin on line (13) and the aging factor on line (14). Combine lines (11), (12), (13), and (14) as indicated and record the result on line (15).

k) When line (15) is in terms of ampere-hours and does not match the capacity of a commercially available cell, the next larger cell is required. When line (15) shows a fractional number of positive plates, use the next larger integer. Show the result on line (16).

l) From the value on line (16), 6.3.5, and the manufacturer's literature, determine the commercial designation of the required cell and record it on line (17).

7. Cell voltage/time profile calculation

The battery sizing procedure and methods described above ensure that, for the specified battery duty cycle and the cell size selected, the average cell voltage will not drop below the specified minimum (e.g., 1.75 V or 1.81 V) at any point in the duty cycle. It is therefore not normally necessary to calculate the cell or battery terminal voltage because it will be above the predetermined allowable minimum through the discharge period. If the need for such information should arise, Annex C describes one method of calculating the voltage at various points in the battery duty cycle utilizing the typical discharge characteristic curves published by the battery manufacturer.



Project: Date: Page:

Lowest Expected Electrolyte Temp: °F Minimum Cell Voltage: Cell Mfg: Cell Type: Sized By:

(1)	(2)	(3)	(4)	(5)	(6)	(7)	
	Load	Change in Load	Duration of Period	Time to End of Section	Capacity at T Min Rate (6A) Amps/Pos (R_T) or	Required Section Size (3)+(6A)=Positive Plates or (3)x(6B) = Rated Amp Hrs	
Period	(amperes)	(amperes)	(minutes)	(minutes)	(6B) K Factor (K_T)	Pos Values	Neg Values
Section 1 - First Period Only - If A2 is greater than A1, go to Section 2.							
1	A1=	A1-0=	M1=	T=M1=			***
					Sec 1 Total		***
Section2 - First Two Periods Only - If A3 is greater than A2, go to Section 3.							
1	A1=	A1-0=	M1=	T=M1+M2=			
2	A2=	A2-A1=	M2=	T=M2=			
					Sec Sub Tot		
					2 Total		***
Section 3 - First Three Periods Only - If A4 is greater than A3, go to Section 4.							
1	A1=	A1-0=	M1=	T=M1+M2+M3=			
2	A2=	A2-A1=	M2=	T=M2+M3=			
3	A3=	A3-A2=	M3=	T=M3=			
					Sec Sub Tot		
					3 Total		***
Section 4 - First Four Periods Only - If A5 is greater than A4, go to Section 5.							
1	A1=	A1-0=	M1=	T=M1+...M4=			
2	A2=	A2-A1=	M2=	T=M2+M3+M4=			
3	A3=	A3-A2=	M3=	T=M3+M4=			
4	A4=	A4-A3=	M4=	T=M4=			
					Sec Sub Tot		
					4 Total		***
Section 5 - First Five Periods Only - If A6 is greater than A5, go to Section 6.							
1	A1=	A1-0=	M1=	T=M1+...M5=			
2	A2=	A2-A1=	M2=	T=M2+...M5=			
3	A3=	A3-A2=	M3=	T=M3+M4+M5=			
4	A4=	A4-A3=	M4=	T=M4+M5=			
5	A5=	A5-A4=	M5=	T=M5=			
					Sec Sub Tot		
					5 Total		***
Section 6 - First Six Periods Only - If A7 is greater than A6, go to Section 7.							
1	A1=	A1-0=	M1=	T=M1+...M6=			
2	A2=	A2-A1=	M2=	T=M2+...M6=			
3	A3=	A3-A2=	M1=	T=M3+...M6=			
4	A4=	A4-A3=	M4=	T=M4+M5+M6=			
5	A5=	A5-A4=	M5=	T=M5+M6=			
6	A6=	A6-A5=	M6=	T=M6=			
					Sec Sub Tot		
					6 Total		***
Section 7 - First Seven Periods Only - If A8 is greater than A7, go to Section 8.							
1	A1=	A1-0=	M1=	T=M1+...M7			
2	A2=	A2-A1=	M2=	T=M2+...M7			
3	A3=	A3-A2=	M1=	T=M3+...M7			
4	A4=	A4-A3=	M4=	T=M4+...M7			
5	A5=	A5-A4=	M5=	T=M5+M6+M7=			
6	A6=	A6-A5=	M6=	T=M6+M7=			
7	A7=	A7-A6=	M7=	T=M7=			
					Sec Sub Tot		
					7 Total		***
Random Equipment Load Only (if needed)							
R	AR=	AR-0=	MR=	T=MR=			***

Maximum Section Size (8)__________ + Random Section Size (9)__________ = Uncorrected Size - (US)(10)____________.

US(11)__________ x Temp Corr(12)_________ x Design Marg(13)_1.____ x Aging Factor(14) _1.____ = (15) ____________.

When the cell size (15) is greater than a standard cell size, the next larger cell is required.

(A) - Positive Plates.

Required cell size (16)__________

(B) - Ampere Hours. Therefore cell (17) ___________ is required.

Figure 3—Cell sizing worksheet

Annex A

(informative)

Battery and cell sizing examples

In A.1 and A.2, use the same duty cycle discussed in 4.3.3 and the lowest expected electrolyte temperature is 18.3 °C (65 °F). Clause A.1 provides several examples of calculations selecting the number of cells to be used in the battery and shows how the number of cells affects the required cell capacity. Clause A.2 shows how the cell sizing worksheet can be used to calculate the required cell size.

A.1 Required number of cells

<u>Example 1</u>

The following example describes two cases where system design affects the number of cells. For both cases the voltage window is 105–140 V and the battery manufacturer recommends a float voltage of 2.25 V/cell and equalizing at 2.33 V/cell.

Case 1.

The battery and charger are continuously connected to the loads.

$$\text{Number of cells} = \frac{140\ \text{V}}{2.33\ \text{V/cell}} = 60.1\ \text{(use 60 cells)}$$

$$\text{End-of-discharge voltage} = \frac{105\ \text{V}}{60\ \text{cells}} = 1.75\ \text{V/cell}$$

This case is worked out in detail in Figure A.1. and results in a corrected size of 1010.4 Ah at the 8 h rate using 1.75 minimum cell voltage.

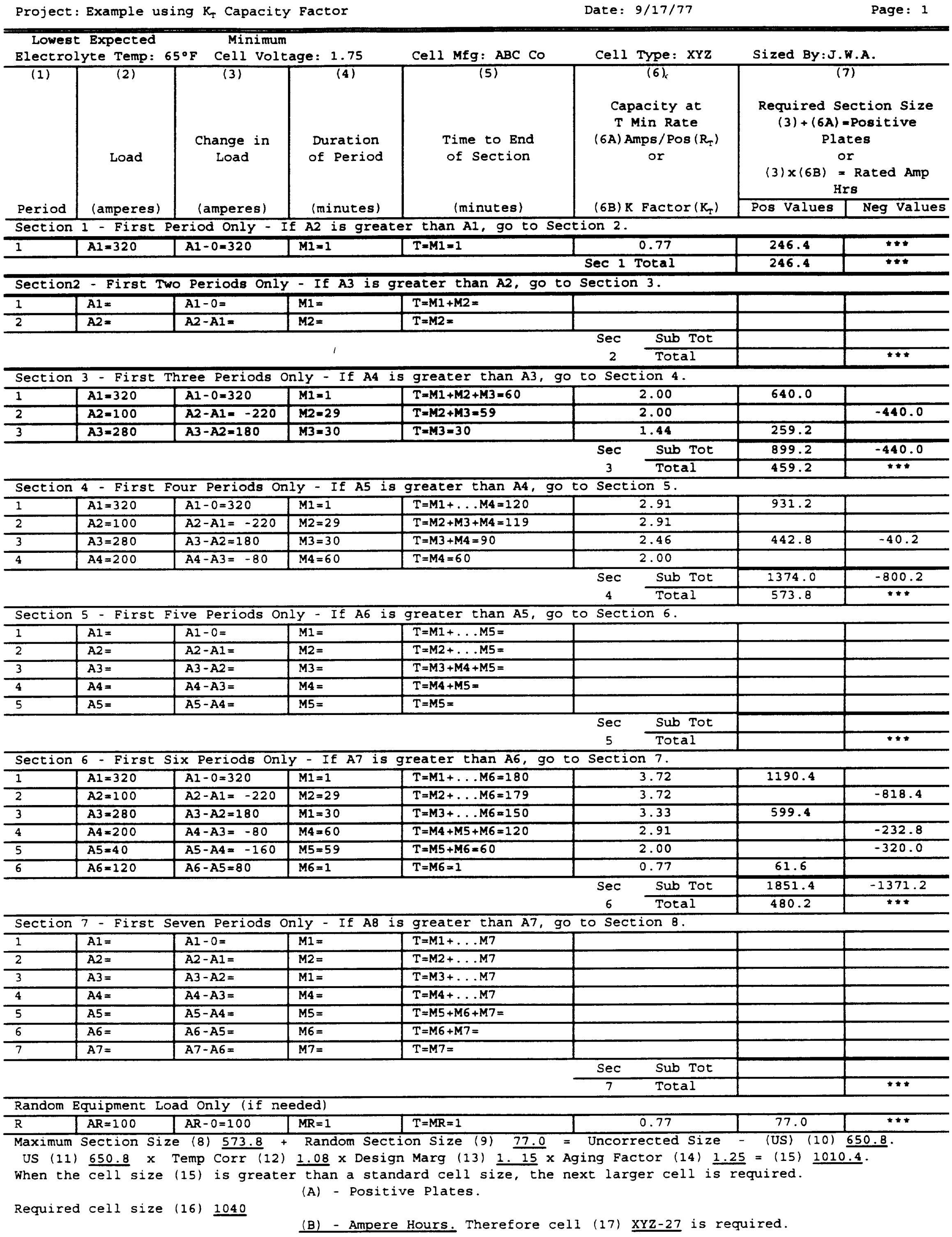
Case 2.

The battery and charger are isolated from the loads during equalizing.

$$\text{Number of cells} = \frac{140\ \text{V}}{2.25\ \text{V/cell}} = 62.2\ \text{(use 62 cells)}$$

$$\text{End-of-discharge voltage} = \frac{105\ \text{V}}{62\ \text{cells}} = 1.69\ \text{V/cell}$$

A cell sizing worksheet is not provided for this example, but calculations show that the corrected cell size is 944 Ah at the 8 h rate. The reduction in the end-of discharge voltage results in about a 7% reduction in corrected cell capacity with only a 3% increase in the number of cells. The equalizing voltage while isolated would be 144.5 V.



Project: Example using K_T Capacity Factor   Date: 9/17/77   Page: 1

Lowest Expected Electrolyte Temp: 65°F   Minimum Cell Voltage: 1.75   Cell Mfg: ABC Co   Cell Type: XYZ   Sized By:J.W.A.

(1) Period	(2) Load (amperes)	(3) Change in Load (amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate (6A) Amps/Pos (R_T) or (6B) K Factor (K_T)	(7) Required Section Size (3)+(6A)=Positive Plates or (3)x(6B) = Rated Amp Hrs	
						Pos Values	Neg Values
Section 1 - First Period Only - If A2 is greater than A1, go to Section 2.							
1	A1=320	A1-0=320	M1=1	T=M1=1	0.77	246.4	***
					Sec 1 Total	246.4	***
Section2 - First Two Periods Only - If A3 is greater than A2, go to Section 3.							
1	A1=	A1-0=	M1=	T=M1+M2=			
2	A2=	A2-A1=	M2=	T=M2=			
					Sec Sub Tot		
					2 Total		***
Section 3 - First Three Periods Only - If A4 is greater than A3, go to Section 4.							
1	A1=320	A1-0=320	M1=1	T=M1+M2+M3=60	2.00	640.0	
2	A2=100	A2-A1= -220	M2=29	T=M2+M3=59	2.00		-440.0
3	A3=280	A3-A2=180	M3=30	T=M3=30	1.44	259.2	
					Sec Sub Tot	899.2	-440.0
					3 Total	459.2	***
Section 4 - First Four Periods Only - If A5 is greater than A4, go to Section 5.							
1	A1=320	A1-0=320	M1=1	T=M1+...M4=120	2.91	931.2	
2	A2=100	A2-A1= -220	M2=29	T=M2+M3+M4=119	2.91		
3	A3=280	A3-A2=180	M3=30	T=M3+M4=90	2.46	442.8	-40.2
4	A4=200	A4-A3= -80	M4=60	T=M4=60	2.00		
					Sec Sub Tot	1374.0	-800.2
					4 Total	573.8	***
Section 5 - First Five Periods Only - If A6 is greater than A5, go to Section 6.							
1	A1=	A1-0=	M1=	T=M1+...M5=			
2	A2=	A2-A1=	M2=	T=M2+...M5=			
3	A3=	A3-A2=	M3=	T=M3+M4+M5=			
4	A4=	A4-A3=	M4=	T=M4+M5=			
5	A5=	A5-A4=	M5=	T=M5=			
					Sec Sub Tot		
					5 Total		***
Section 6 - First Six Periods Only - If A7 is greater than A6, go to Section 7.							
1	A1=320	A1-0=320	M1=1	T=M1+...M6=180	3.72	1190.4	
2	A2=100	A2-A1= -220	M2=29	T=M2+...M6=179	3.72		-818.4
3	A3=280	A3-A2=180	M1=30	T=M3+...M6=150	3.33	599.4	
4	A4=200	A4-A3= -80	M4=60	T=M4+M5+M6=120	2.91		-232.8
5	A5=40	A5-A4= -160	M5=59	T=M5+M6=60	2.00		-320.0
6	A6=120	A6-A5=80	M6=1	T=M6=1	0.77	61.6	
					Sec Sub Tot	1851.4	-1371.2
					6 Total	480.2	***
Section 7 - First Seven Periods Only - If A8 is greater than A7, go to Section 8.							
1	A1=	A1-0=	M1=	T=M1+...M7			
2	A2=	A2-A1=	M2=	T=M2+...M7			
3	A3=	A3-A2=	M1=	T=M3+...M7			
4	A4=	A4-A3=	M4=	T=M4+...M7			
5	A5=	A5-A4=	M5=	T=M5+M6+M7=			
6	A6=	A6-A5=	M6=	T=M6+M7=			
7	A7=	A7-A6=	M7=	T=M7=			
					Sec Sub Tot		
					7 Total		***
Random Equipment Load Only (if needed)							
R	AR=100	AR-0=100	MR=1	T=MR=1	0.77	77.0	***

Maximum Section Size (8) 573.8 + Random Section Size (9) 77.0 = Uncorrected Size - (US) (10) 650.8.
US (11) 650.8 x Temp Corr (12) 1.08 x Design Marg (13) 1. 15 x Aging Factor (14) 1.25 = (15) 1010.4.
When the cell size (15) is greater than a standard cell size, the next larger cell is required.
(A) - Positive Plates.
Required cell size (16) 1040
(B) - Ampere Hours. Therefore cell (17) XYZ-27 is required.

Figure A.1—Sample worksheet using K_t capacity factors

Example 2

Same conditions as Example 1, Case 1, except that the dc system voltage limits are now 105–135 V.

$$\text{Number of cells} = \frac{135\ \text{V}}{2.33\ \text{V/cell}} = 57.9\ \text{(use 58 cells)}$$

$$\text{End-of-discharge voltage} = \frac{105\ \text{V}}{58\ \text{cells}} = 1.81\ \text{V/cell}$$

A cell sizing worksheet is not provided for this example, but calculations show that the corrected cell size is 1186 Ah at the 8 h rate. In comparison to Example 1, the increase in the minimum cell voltage results in a 17% increase in the corrected cell size with only a 3% reduction in the number of cells required.

A.2 Required cell capacity

Table A.1 can be constructed from the battery duty cycle diagram in Figure A.2. This table will be of value in filling out the cell sizing worksheet.

Figure A.3 is a hypothetical composite rating curve for the XYZ cell manufactured by the ABC Company. The graph gives values for both types of capacity rating factors for discharges started at 25 °C (77 °F) and terminated when the average cell voltage reaches 1.81 V, 1.75 V, or 1.69 V. Figure A.4 shows the way in which the cell sizing worksheet and the R_t rating factor would be used to size the XYZ cell for the Figure 1 duty cycle. Figure A.1 shows the application of the K_t rating factor to the same problem.

Table A.1—Sample cell sizing data

Period	Loads	Total amperes	Duration (min)
1	$L_1 + L_2$	320	1
2	$L_1 + L_3$	100	29
3	$L_1 + L_3 + L_4 + L_5$	280	30
4	$L_1 + L_3 + L_4$	200	60
5	L_1	40	59
6	$L_1 + L_6$	120	1
R	L_7	100	1

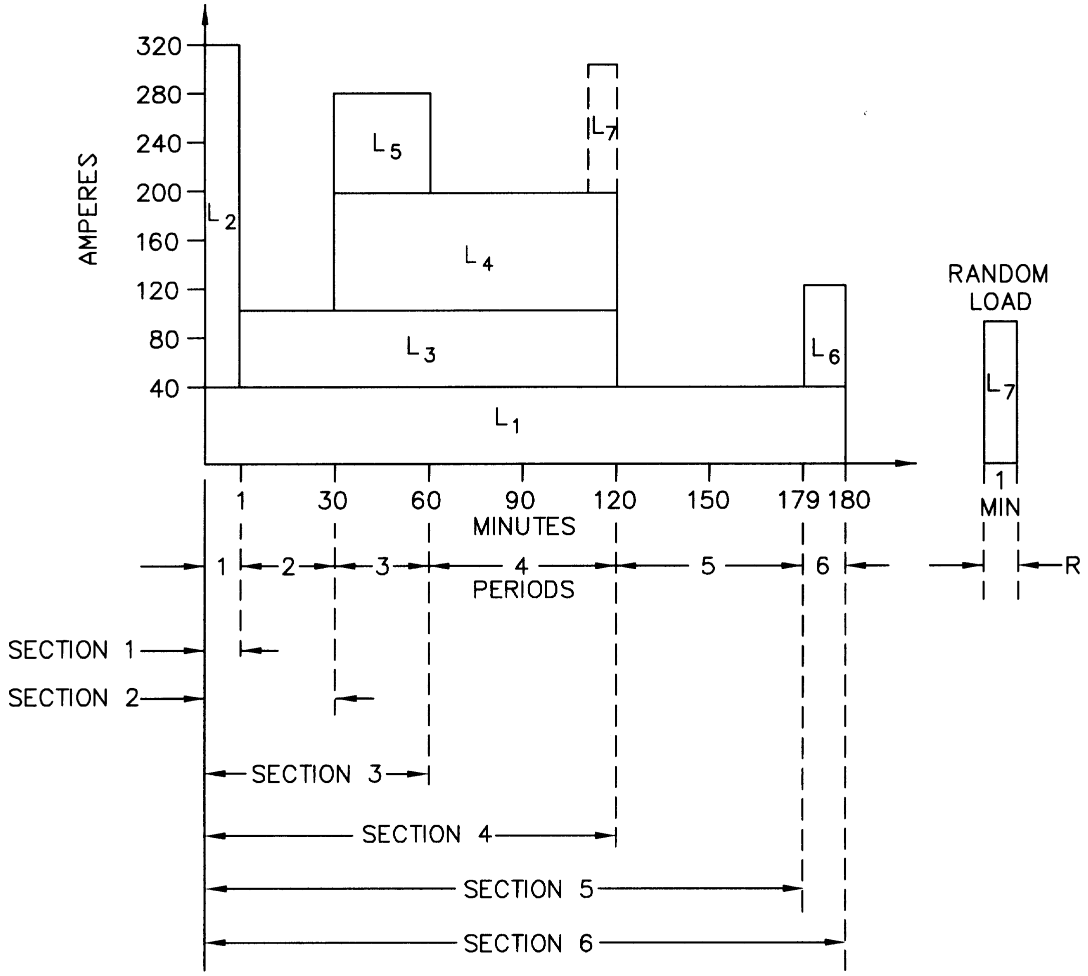


Figure A.2—Battery duty cycle diagram

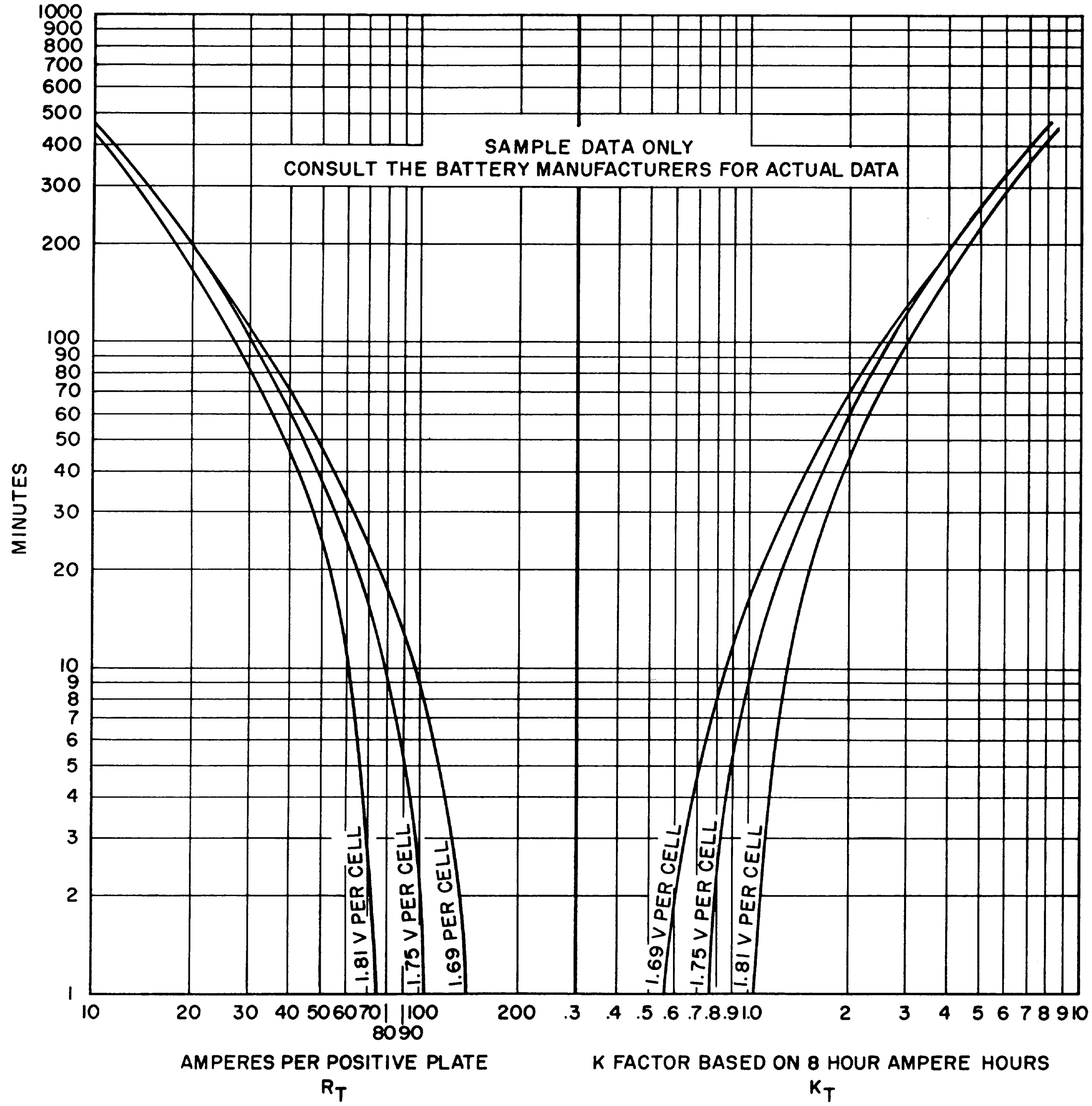
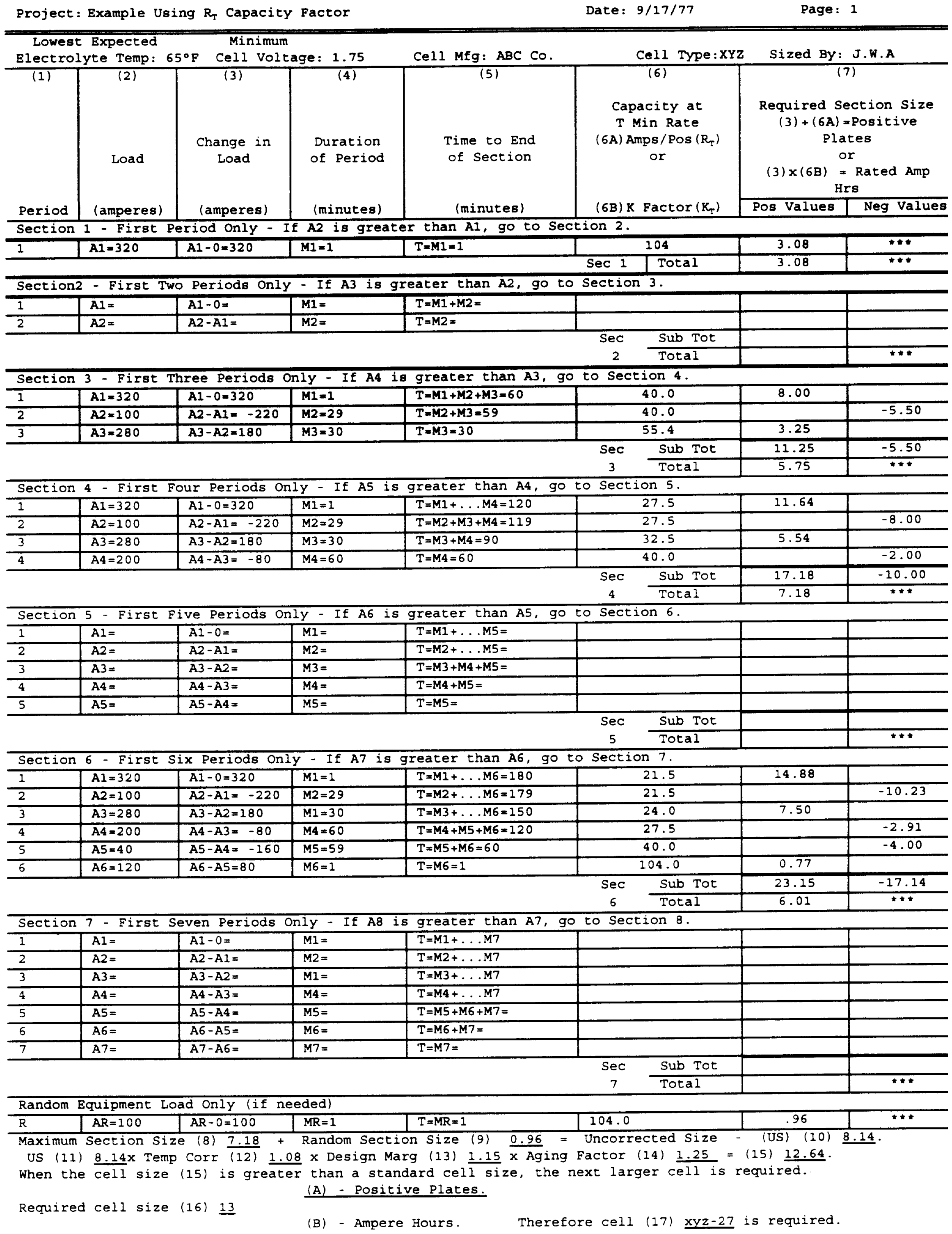


Figure A.3—Hypothetical composite rating curve for XYZ cell manufactured by ABC Company



Project: Example Using R_T Capacity Factor Date: 9/17/77 Page: 1

Lowest Expected Electrolyte Temp: 65°F Minimum Cell Voltage: 1.75 Cell Mfg: ABC Co. Cell Type:XYZ Sized By: J.W.A

(1) Period	(2) Load (amperes)	(3) Change in Load (amperes)	(4) Duration of Period (minutes)	(5) Time to End of Section (minutes)	(6) Capacity at T Min Rate (6A) Amps/Pos (R_T) or (6B) K Factor (K_T)	(7) Required Section Size (3)+(6A)=Positive Plates or (3)x(6B) = Rated Amp Hrs	
						Pos Values	Neg Values
Section 1 - First Period Only - If A2 is greater than A1, go to Section 2.							
1	A1=320	A1-0=320	M1=1	T=M1=1	104	3.08	***
					Sec 1 Total	3.08	***
Section2 - First Two Periods Only - If A3 is greater than A2, go to Section 3.							
1	A1=	A1-0=	M1=	T=M1+M2=			
2	A2=	A2-A1=	M2=	T=M2=			
					Sec Sub Tot		
					2 Total		***
Section 3 - First Three Periods Only - If A4 is greater than A3, go to Section 4.							
1	A1=320	A1-0=320	M1=1	T=M1+M2+M3=60	40.0	8.00	
2	A2=100	A2-A1= -220	M2=29	T=M2+M3=59	40.0		-5.50
3	A3=280	A3-A2=180	M3=30	T=M3=30	55.4	3.25	
					Sec Sub Tot	11.25	-5.50
					3 Total	5.75	***
Section 4 - First Four Periods Only - If A5 is greater than A4, go to Section 5.							
1	A1=320	A1-0=320	M1=1	T=M1+...M4=120	27.5	11.64	
2	A2=100	A2-A1= -220	M2=29	T=M2+M3+M4=119	27.5		-8.00
3	A3=280	A3-A2=180	M3=30	T=M3+M4=90	32.5	5.54	
4	A4=200	A4-A3= -80	M4=60	T=M4=60	40.0		-2.00
					Sec Sub Tot	17.18	-10.00
					4 Total	7.18	***
Section 5 - First Five Periods Only - If A6 is greater than A5, go to Section 6.							
1	A1=	A1-0=	M1=	T=M1+...M5=			
2	A2=	A2-A1=	M2=	T=M2+...M5=			
3	A3=	A3-A2=	M3=	T=M3+M4+M5=			
4	A4=	A4-A3=	M4=	T=M4+M5=			
5	A5=	A5-A4=	M5=	T=M5=			
					Sec Sub Tot		
					5 Total		***
Section 6 - First Six Periods Only - If A7 is greater than A6, go to Section 7.							
1	A1=320	A1-0=320	M1=1	T=M1+...M6=180	21.5	14.88	
2	A2=100	A2-A1= -220	M2=29	T=M2+...M6=179	21.5		-10.23
3	A3=280	A3-A2=180	M1=30	T=M3+...M6=150	24.0	7.50	
4	A4=200	A4-A3= -80	M4=60	T=M4+M5+M6=120	27.5		-2.91
5	A5=40	A5-A4= -160	M5=59	T=M5+M6=60	40.0		-4.00
6	A6=120	A6-A5=80	M6=1	T=M6=1	104.0	0.77	
					Sec Sub Tot	23.15	-17.14
					6 Total	6.01	***
Section 7 - First Seven Periods Only - If A8 is greater than A7, go to Section 8.							
1	A1=	A1-0=	M1=	T=M1+...M7			
2	A2=	A2-A1=	M2=	T=M2+...M7			
3	A3=	A3-A2=	M1=	T=M3+...M7			
4	A4=	A4-A3=	M4=	T=M4+...M7			
5	A5=	A5-A4=	M5=	T=M5+M6+M7=			
6	A6=	A6-A5=	M6=	T=M6+M7=			
7	A7=	A7-A6=	M7=	T=M7=			
					Sec Sub Tot		
					7 Total		***
Random Equipment Load Only (if needed)							
R	AR=100	AR-0=100	MR=1	T=MR=1	104.0	.96	***

Maximum Section Size (8) 7.18 + Random Section Size (9) 0.96 = Uncorrected Size - (US) (10) 8.14.

US (11) 8.14x Temp Corr (12) 1.08 x Design Marg (13) 1.15 x Aging Factor (14) 1.25 = (15) 12.64.

When the cell size (15) is greater than a standard cell size, the next larger cell is required.

(A) - Positive Plates.

Required cell size (16) 13

(B) - Ampere Hours. Therefore cell (17) xyz-27 is required.

Figure A.4—Sample worksheet using R_t capacity factor

Annex B

(informative)

Converting constant power to constant current

Loads applied to the battery are normally typed as constant power, constant resistance, or constant current. The designer should review each system carefully to ensure that all possible loads and their variations have been included.

Battery voltage decreases as the battery discharges (as will the voltage at the loads). The amount by which the battery voltage decreases depends on the internal battery resistance and the load placed on the battery.

For constant power loads, current increases with a voltage decrease. Inverters and dc/dc power supplies are usually constant power; they are internally regulated to maintain a constant output voltage as the input voltage decreases. As a result, the dc input current will increase as the input voltage decreases. If the constant power load is remote from the battery, the voltage drop may be increased by the cable resistance and the resulting input current will be higher. It is desirable to consider the increase in load current as battery voltage declines. This can be calculated as follows:

$$I_{\mathrm{AVG}} = \frac{P}{E_{\mathrm{AVG}}}$$

where

I_{AVG} is the average discharge current (A) for the discharge period;
P is the discharge load (W);
E_{AVG} is the average discharge voltage for the discharge period.

Since the average battery voltage is dependent on cell designs and load duration, and, without information from the manufacturer, is often unknown, a conservative method of converting watts to amperes assumes a constant current for the entire load duration as equal to the current being supplied by the battery at the end of the discharge period (minimum volts, maximum amperes). Thus

$$I_{\mathrm{MAX}} = \frac{P}{E_{\mathrm{MIN\ LOAD}}}$$

where

I_{MAX} is the discharge current at the end of the discharge period;
P is the discharge load (W);
$E_{\mathrm{MIN\ LOAD}}$ is $E_{\mathrm{MIN\ BATT}}$ – voltage drop;
$E_{\mathrm{MIN\ BATT}}$ is the minimum battery voltage.

Example: For a 24 cell battery operating in a nominal 48 V system with a minimum battery voltage of 42 V and a voltage drop from the battery to the load of 2 V, a constant power load of 5000 W will discharge the battery at a rate no greater than

$$I_{\mathrm{MAX}} = \frac{5000\ \mathrm{W}}{40\ \mathrm{V}} = 125\ \mathrm{A}$$

For constant resistance loads, current decrease as the voltage decreases. DC motor starting, emergency lighting, relays, contactors, and indicating lights are usually constant resistance. A constant resistance load may be conservatively estimated as a constant current load as follows:

$$I_{\mathrm{MAX}} = \frac{E_{\mathrm{OC}}}{R_{\mathrm{AVG}}} \text{ or } I_{\mathrm{MAX}} = \frac{W_R}{E_{\mathrm{OC}}}$$

where

E_{OC} is the battery open circuit voltage (typically 0.85 + nominal specific gravity);
R_{AVG} is the average resistance;
W_R is the rated power value.

Similarly, as for power loads, the load current can be calculated using the average battery voltage. System voltage drop to the loads can also be considered.

However, if the battery requires significant motor starts at the beginning of the cycle, the battery voltage may be calculated from initial data using an estimate of the rated motor starting current, and then checking that the initial voltage will support that level of current, iterating the level of current and voltage until a satisfactory solution is obtained.

For constant current loads, current is approximately constant as the voltage decreases. Running dc motors can be approximated as constant current. Within the normal battery voltage range, the flux is fairly constant in the motor. Modeling a dc motor as a constant current load is conservative if the voltage maintains the motor in saturation.

Annex C

(informative)

Calculating cell voltage during discharge

The battery sizing procedure and methods described in this recommended practice ensure that, for the specified battery duty cycle and the cell size selected, the average cell voltage will not drop below the specified minimum at any point in the duty cycle. It is not therefore normally necessary to calculate the cell or battery terminal voltage because it will be above the predetermined allowable minimum throughout the discharge period. If the need for such information should arise, a method of calculating the voltage at various points in the battery duty cycle, utilizing the battery manufacturer's typical discharge characteristic curves, is described below.

C.1 Method

Two types of typical discharge characteristic curves in common use are "fan" curves and "S" curves, typical examples of which are shown in Figures C.1 and C.2, respectively. Although these two curves have different coordinates and appearance, the data provided in each is identical.

The method of calculation (using either curve) is an iterative process and consists of the following:

a) Keeping a cumulative total of the ampere-hours "removed" from the cell during each discharge segment/period,

b) Identifying the discharge current at that time, and

c) Using this information, along with the battery manufacturer's typical discharge characteristics, to determine the cell terminal voltage at various points in the duty cycle.

The voltage/time profile is then a plot of these cell voltages versus time for the entire duty cycle. To determine the voltage just before and just after a step change in the discharge rate, keep the cumulative ampere-hours constant and determine the voltage based on the two different (before and after) discharge rates. The battery terminal voltage at each point is equal to the average cell voltage multiplied by the number of cells connected in series.

To determine the voltage profile for cells at other than 25 °C (77 °F) electrolyte temperature and/or less than 100% of rated capacity, multiply the current for each period during the duty cycle by the same correction factors used to size a battery per this recommended practice. For example, to predict the performance of a cell at 15.6 °C (60 °F) and 80% of its rated capacity, multiply each current value in the duty cycle by the temperature correction factor and the aging factor to determine the cell voltage. Similarly, if the cell performance (in amperes per positive plate) is not a constant value for all sizes of a given type of cell, the current for each period during the duty cycle should be adjusted by using the appropriate correction factor as provided by the battery manufacturer.

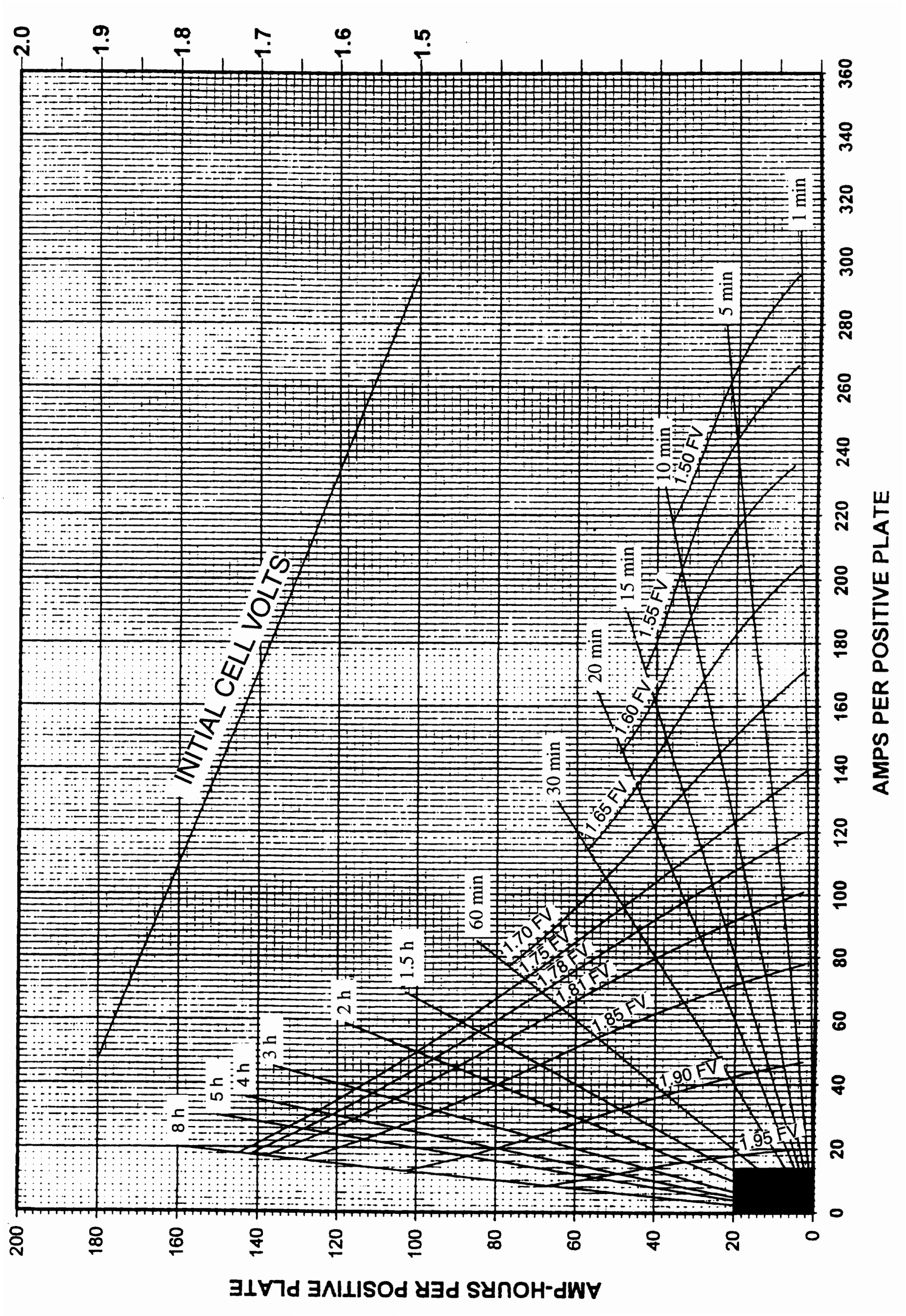


Figure C.1—Discharge characteristics of ABC-type cell

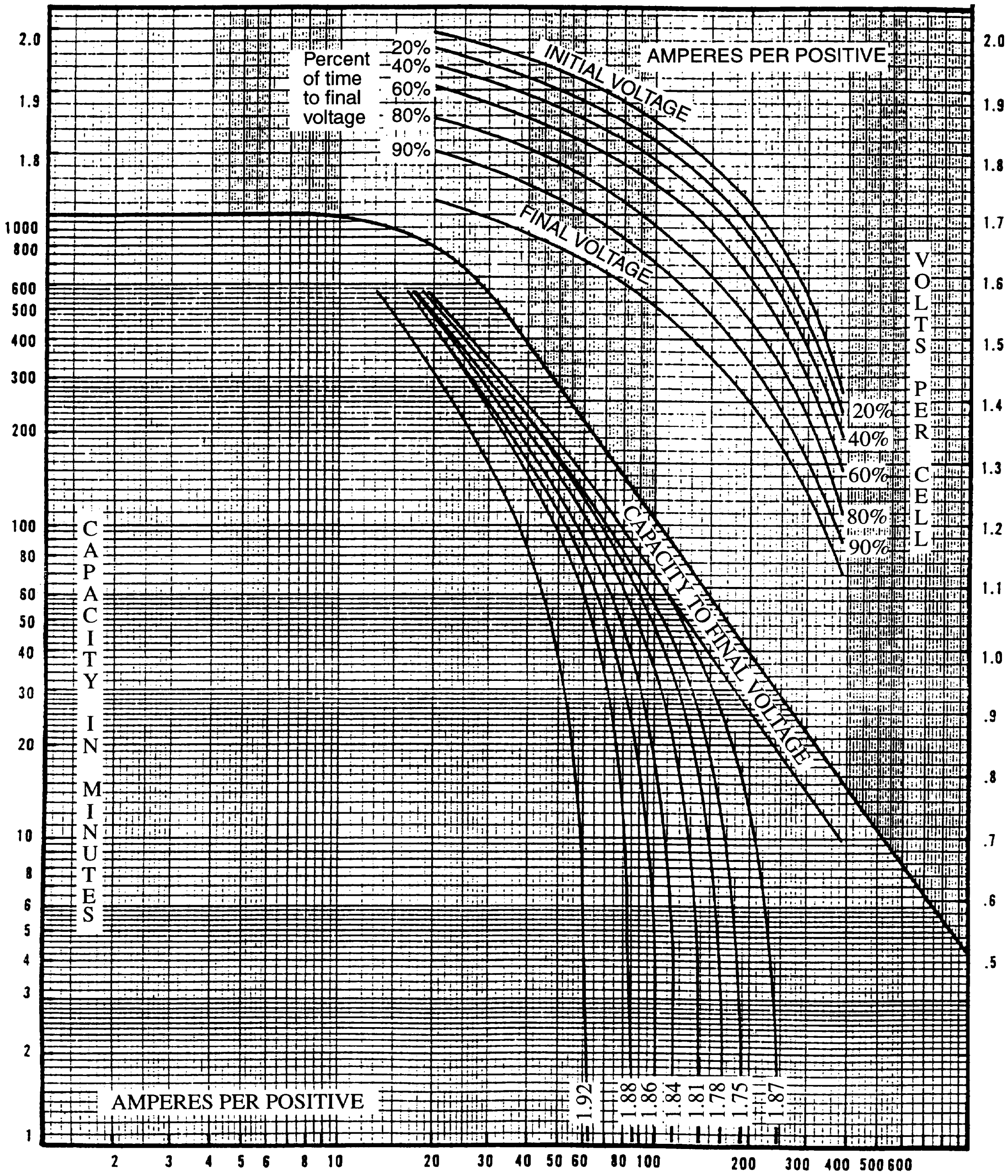


Figure C.2—Discharge characteristics of DEF-type cell

C.2 Sample calculations

C.2.1 Example no. 1 (using “fan” curves)

A sample voltage calculation for an assumed cell type, duty cycle, and conditions follows:

Cell type:	ABC, 10 positive plates
Duty cycle:	700 A for 1 min, then 500 A for 59 min, then 150 A for 180 min
Conditions:	Electrolyte temperature: 25 °C (77 °F) Cell capacity:100% of rated capacity

The average cell voltage at the time where the voltage is to be determined is found on the “fan” curve at the intersection of (a) the cumulative total ampere-hours per positive plate and (b) the ampere-hours per positive plate. When necessary, interpolate between adjacent “final volt” lines.

Step 1

Using the ABC discharge characteristic curves (Figure C.1), determine cell volts during the first 1 min load: 700 A for 1 min = 11.67 Ah increment

$$11.67 \text{ Ah cumulative, or } \quad \frac{11.67}{10} = 1.17 \text{ Ah/positive cumulative}$$

$$\frac{700 \text{ A}}{10 \text{ positive plates}} = 70 \text{ A/positive plate}$$

From the curve, 70 A/positive plate intersects 1.17 Ah/positive plate (at the abscissa line) at approximately 1.86 V/cell.

The initial (only) voltage can also be obtained by projecting 70 A/positive plate vertically to the “initial volts” line where 1.86 V is also read. Thus, the first load will drop the battery voltage to 1.86 V/cell for the entire minute.

Step 2

Because the second load is less than the first load, the cell terminal voltage will rise upon its initiation. To determine the recovery voltage: 500 A for 0 additional minutes is 0 Ah increment, 11.67 Ah cumulative, or 1.17 Ah/positive plate cumulative.

$$\frac{500 \text{ A}}{10 \text{ positive plates}} = 50 \text{ A/positive plate}$$

On the curve, 50 A/positive plate intersects 1.17 Ah/positive plate (at the abscissa line) at approximately 1.89 V/cell.

Step 3

To determine the voltage at the end of 30 total minutes: 500 A for 29 additional minutes is a 241.67 Ah increment, 253.34 Ah cumulative, or 25.34 Ah/positive plate cumulative.

$$\frac{500 \text{ A}}{10 \text{ positive plates}} = 50 \text{ A/positive plate}$$

On the curve, 50 A/positive plate intersects 25.33 Ah/positive plate at approximately 1.88 V/cell.

Step 4 through Final

The above process is repeated for each step to determine the cell voltage at each point in the duty cycle. The results for this example are tabulated in Table C.1 and the voltage/time profile is shown in Figure C.3.

Table C.1—Cell voltage over time table using "fan" curve

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Load (A)	**Time interval (min)**	**Cumulative discharge time (min)**	**Incremental Ah removed**	**Cumulative Ah removed**	**Cumulative Ah per positive plate (5)/10**	**Load amperes per positive plate (1)/10**	**Intersect at (6) and (7) V/cell**
700	0	0	0	0	0	70	1.86
700	1	1	11.67	11.67	1.17	70	1.86
500	0	1	0	11.67	1.17	50	1.89
500	29	30	241.67	253.34	25.33	50	1.88
500	30	60	250	503.34	50.33	50	1.86
150	0	60	0	503.34	50.33	15	1.94
150	30	90	75.0	578.34	57.83	15	1.94
150	30	120	75.0	653.34	65.33	15	1.93
150	30	150	75.0	728.34	72.83	15	1.93
150	30	180	75.0	803.34	80.33	15	1.92
150	30	210	75.0	878.34	87.83	15	1.92
150	30	240	75.0	953.34	95.33	15	1.90

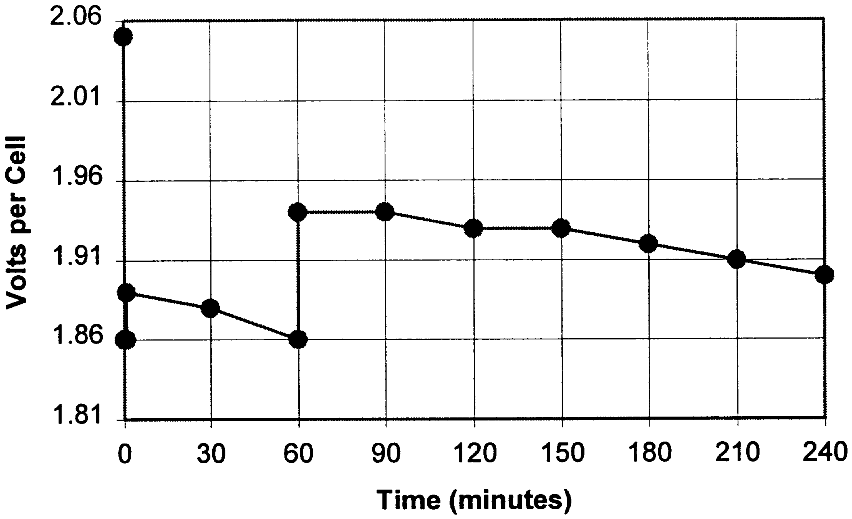


Figure C.3—Calculated voltage/time profile from “fan” curves

C.2.2 Example no. 2 (using “S” curves)

A sample voltage calculation for an assumed cell type, duty cycle, and conditions follows:

Cell type: DEF-21, 10 positive plates and characteristics as shown in Figure C.2
Duty cycle: 1000 A for 1 min, then, 700 A for 29 min, then 300 A for 180 min
Conditions: Electrolyte temperature: 25 °C (77 °F), TF = 1.00
80% capacity (1.25 aging factor, AF = 1.25)
Design margin, DM = 1.00
Cumulative correction factor = TF × AF × DM = 1.00 × 1.25 × 1.00 = 1.25

Calculations: Refer to Table C.2 and Figure C.2.

Col. A This is the time period in minutes. Example: 1–30 min (29 min of discharge).

Col. B This is the time interval for this part of the calculation. Example: The time interval is zero at the beginning of any period. The example only calculates the value at the beginning and end of each period. Intermediate values can be calculated.

Col. C This is the duty cycle in amperes for the period. Example: 700 A for 1–30 min.

Col. D Corrected amperes to account for aging, temperature, and design margin. Example: 700 × 1.25 = 875.

Col. E Ampere-minutes in both incremental and cumulative values. Example: The incremental ampere-minutes for the 29 min interval is 875 × 29 = 25 375. The cumulative ampere-minutes is the previous cumulative total (1250) plus the incremental value (1250 + 25 375 = 26 625).

Col. F Ampere-minutes per positive plate in both incremental and cumulative values. Example: Take the values from Col. E and divide by the number of positive plates. 25 375/10 = 2537 incremental and 26 625/10 = 2662 cumulative.

Col. G Amperes per positive plate, which is Col. D divided by the number of positive plates. Example: 875/10 = 87.5.

Col. H Time to final voltage is determined from the “S” curves. Example: Time to final voltage is read at 87.5 A/positive plate on the X-axis up to the “capacity to final voltage” curve. The needed value is then read from the right Y-axis and is 85 min. The “capacity to final voltage” curve is at the extreme right hand side of the 1.67 V line.

Col. I This is ampere/positive plate times the time to final voltage. Example: Multiply Col. G by Col. H (87.5 × 85 = 7437.5).

Col. J Percent of discharge is the cumulative ampere-minutes/positive plate divided by ampere/positive plate times time to final voltage. Example: This is Col. F (lower value) divided by Col. I (2662/74 37.5 = 0.358 or 35.8%).

Col. K Volts per cell is the expected cell voltage at the calculated point in time for the conditions specified as determined from the “S” curves. Example: The value is determined by taking the discharge rate in ampere/positive plate on the X-axis and projecting up to the percent of discharge curve and then reading the cell voltage at the left Y-axis (87.5 A and 35.8% discharge—interpolate between the 20% and 40% curves and read the value at the right Y-axis of 1.82 V/cell).

The results for this example are tabulated in Table C.2 and the voltage/time profile is shown in Figure C.4.

Table C.2—Cell voltage over time table using “S” curve

A	B	C	D	E	F	G	H	I	J	K
Time period	**Time interval**	**Duty cycle (A)**	**Corrected A (Col. C × correction factors)**	**A/min increment cumulative (Col. D × Col. B cumulative value)**	**A/min/ positive plate incremental cumulative (Col. D × Col. B positive plate cumulative value)**	**A/ positive plate (Col. D positive plate)**	**Time to final voltage (from “S” curve)**	**A/ positive plate × Time to final voltage (Col. G × Col. H)**	**% Discharge (Col. F cumulative/ Col. I)**	**V/cell (from “S” curve)**
0–1 min	0	1000	1250	0 0	0 0	125	—	—	0	1.815
	1	1000	1250	1250 1250	125 125	125	50	6250	2	1.81
1–30 min	0	700	875	0 1250	0 125	87.5	85	7437.5	1.68	1.865
	29	700	875	25 375 26 625	2537 2662	87.5	85	7437.5	35.8	1.82
30–210 min	0	300	375	0 26 625	0 2662	37.5	270	10 125	26.3	1.91
	180	300	375	67 500 94 125	6750 9412	37.5	270	10 125	92.9	1.75

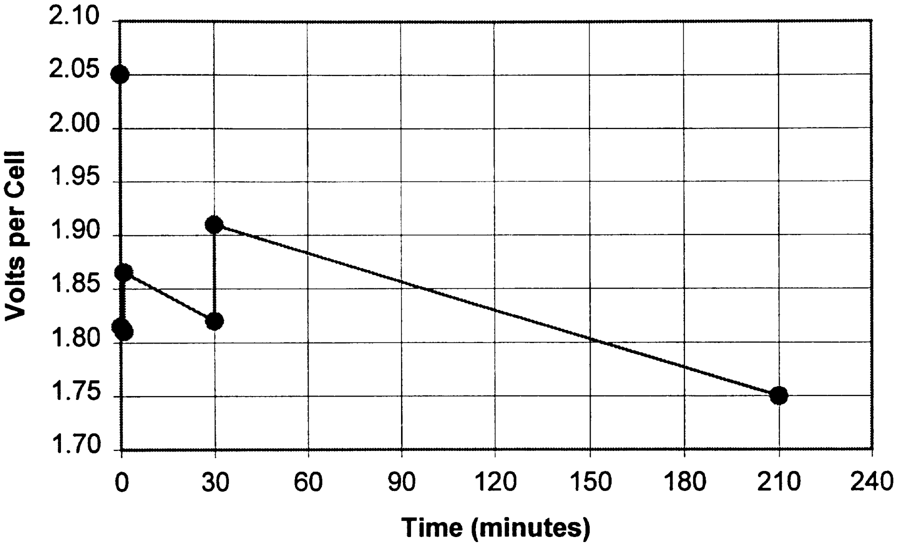


Figure C.4—Calculated voltage/time profile from “S” curves

Annex D

(informative)

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