SECTION 6: BATTERY BANK SIZING PROCEDURES

ESE 471 – Energy Storage Systems

Batteries for Stationary Applications

- Battery energy storage systems are used in a variety of *stationary* applications
  - Telecom., remote communication systems
  - Bridging supply for UPS applications
    - Data centers
    - Hospitals
    - Wafer fabs, etc.
  - Utilities – switch gear – black start
    - Power plant
    - Substation
  - Off-grid PV systems
    - Residential
    - Commercial
    - Remote monitoring
- Lead-acid batteries still commonly used in these applications

Autonomy

- ***Autonomy***
  - Length of time that a battery storage system must provide energy to the load without input from the grid or PV source
- Two general categories:
  - Short duration, high discharge rate
    - Power plants
    - Substations
    - Grid-powered
  - Longer duration, lower discharge rate
    - Off-grid residence, business
    - Remote monitoring/communication systems
    - PV-powered

Battery Bank Sizing Standards

- Two IEEE standards for sizing lead-acid battery banks for stationary applications
  - **IEEE Std 485**
    - *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications*
    - Short duration, high discharge rate
  - **IEEE Std 1013**
    - *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic Systems*
    - Longer duration, lower discharge rate
- We'll look first at the common considerations for both standards before

Basic Battery Sizing Approach

- Determine the ***load profile*** over the autonomy period
- Size a battery bank to have sufficient capacity to provide the required energy over the autonomy period, accounting for:
  - ***System voltage***
  - ***Temperature***
  - ***Aging***
  - ***Maximum depth of discharge***
  - ***Rate of discharge***

Common Battery-Sizing Considerations

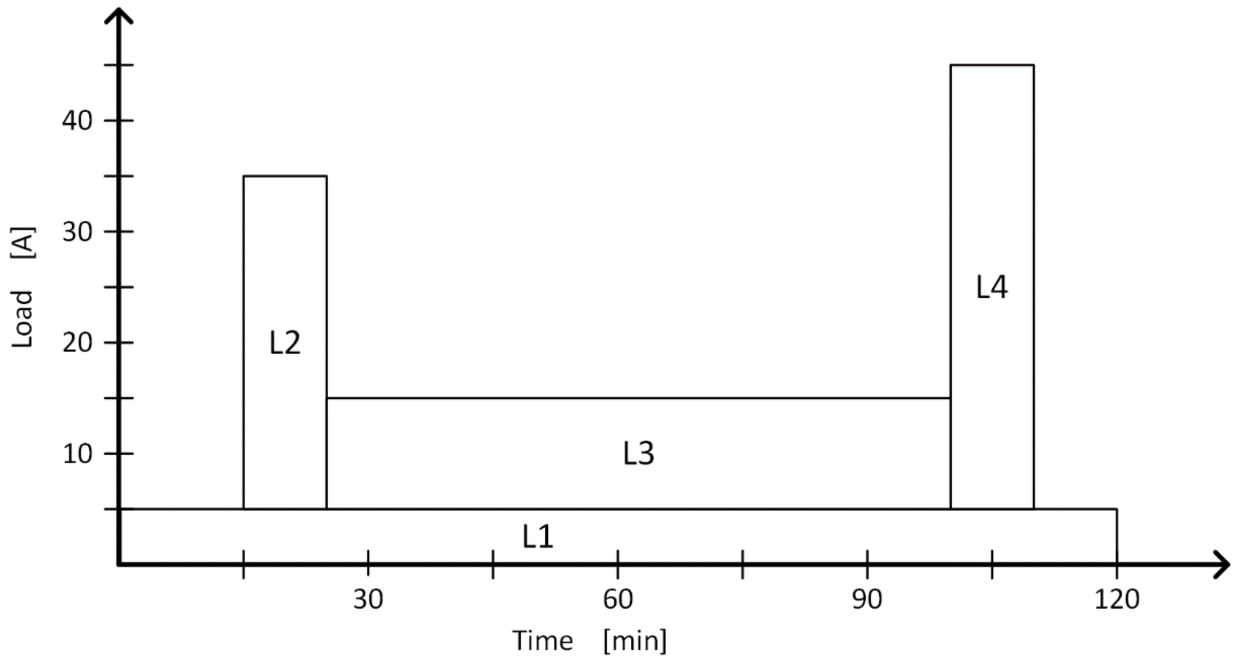
Duty Cycle

- Tabulate and, possibly, plot system loads over the autonomy period
  - Duty-cycle diagram (plot) often more useful for shorter duration, higher current applications

- For example, consider a 2-hr autonomy period with the following loads:

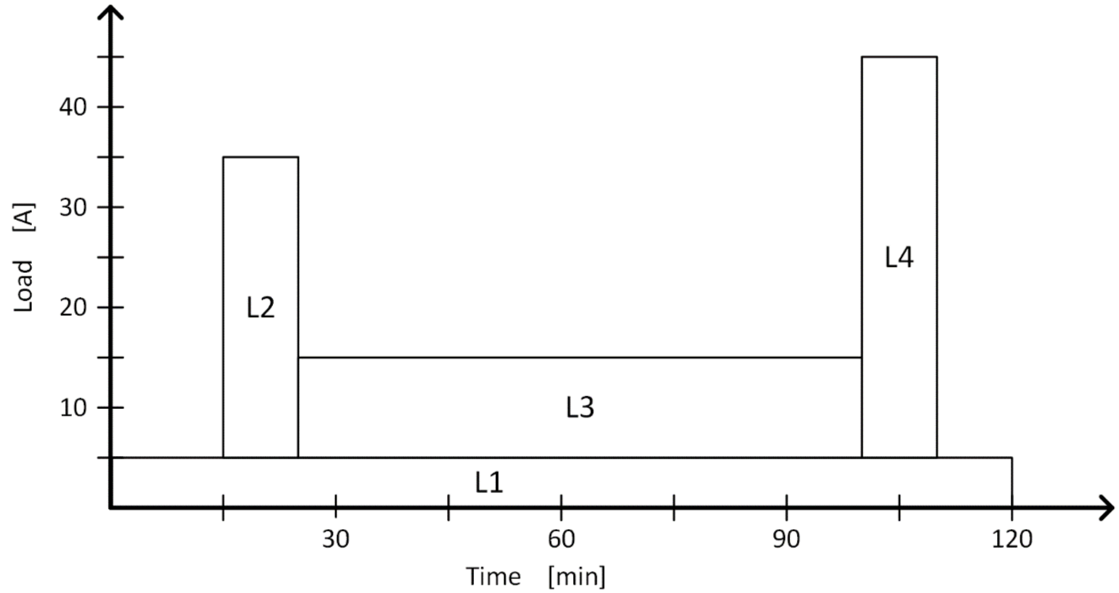
Load #	Current (A)	t_{start} (min)	T (min)
1	5	0	120
2	30	15	10
3	10	25	75
4	40	100	10

Duty-Cycle Diagram



Load #	Current (A)	t_{start} (min)	T (min)
L1	5	0	120
L2	30	15	10
L3	10	25	75
L4	40	100	10

Duty-Cycle Diagram



- Total energy (actually, charge) required by the load over the autonomy period is the area under the curve
  - Sizing procedures map the load profile to a battery capacity capable of supplying the load

Constant-Current vs. Constant-Power Loads

- Typically easiest to deal with constant-current loads
- Convert constant-power loads to constant current
  - Approximate, because battery voltage decreases during discharge
  - Use a minimum voltage to provide a conservative estimate

$$I = \frac{P}{V_{min}}$$

  - V_{min} can be either the manufacturer's recommended minimum voltage or 95% of the nominal voltage

System Voltage

- Batteries are comprised of multiple series-connected cells
  - For lead-acid batteries at 100% SoC, nominal voltage is 2.1 V/cell
- Common battery configurations:
  - 1 cell: 2 V
  - 3 cells: 6 V
  - 6 cells: 12 V
- Multiple batteries can be connected in series for higher system voltage
  - Efficiency
  - Capacity optimization
  - Other system-specific considerations

Operating Temperature

- Standard temperature for battery capacity rating is 25 °C
- Capacity decreases at lower temperatures
- For minimum electrolyte temperatures below 25 °C, ***multiply determined capacity by a correction factor***
  - For example, from IEEE 485, Table 1:

Electrolyte Temp. [°F]	Electrolyte Temp. [°C]	Correction Factor
40	4.4	1.30
50	10	1.19
60	15.6	1.11
70	21.1	1.04
77	25	1.00

- ~0.5%/°F (0.9%/°C) reduction in capacity below 77 °F (25 °C)
- Capacity is typically not corrected for electrolyte temperatures above 25 °C

Aging

- Battery capacity degrades with age
- IEEE standards recommend replacing batteries when capacity has degraded to 80% of initial value
- Adjust battery capacity for aging to ensure adequate capacity at end of lifetime

$$C_{age} = \frac{C_0}{0.8}$$

- For example, if 100 Ah of capacity is required, initial aging-adjusted capacity is

$$C_{age} = \frac{100\ Ah}{0.8} = 125\ Ah$$

Maximum Depth of Discharge

- For many battery types (e.g. lead acid), lifetime is affected by ***maximum depth of discharge*** (DoD)
  - Higher DoD shortens lifespan
  - Tradeoff between lifespan and unutilized capacity

- Calculated capacity must be adjusted to account for maximum DoD
  - Divide required capacity by maximum DoD

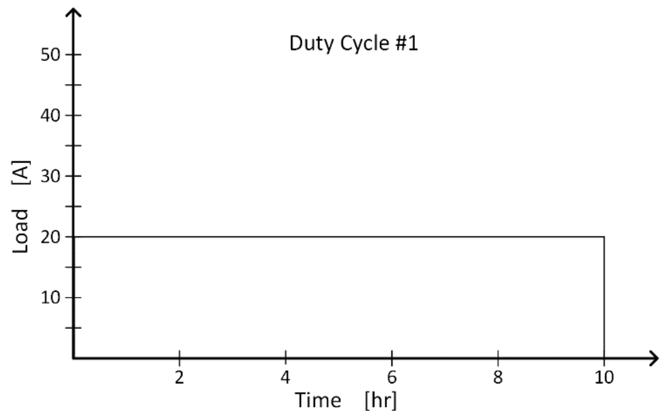
$$C_{DoD} = \frac{C_0}{DoD}$$

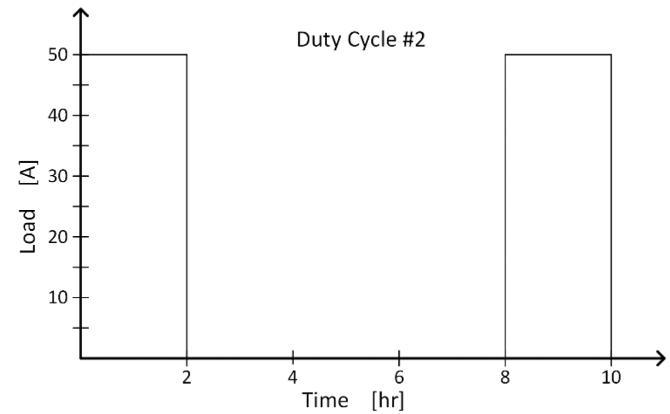
- For example, if 100 Ah is required, but DoD is limited to 60%, the required capacity is

$$C_{DoD} = \frac{100\ Ah}{0.6} = 167\ Ah$$

Battery Capacity vs. Rate of Discharge

- Consider two different 10-hour duty cycle diagrams:





- Equal energy requirements:

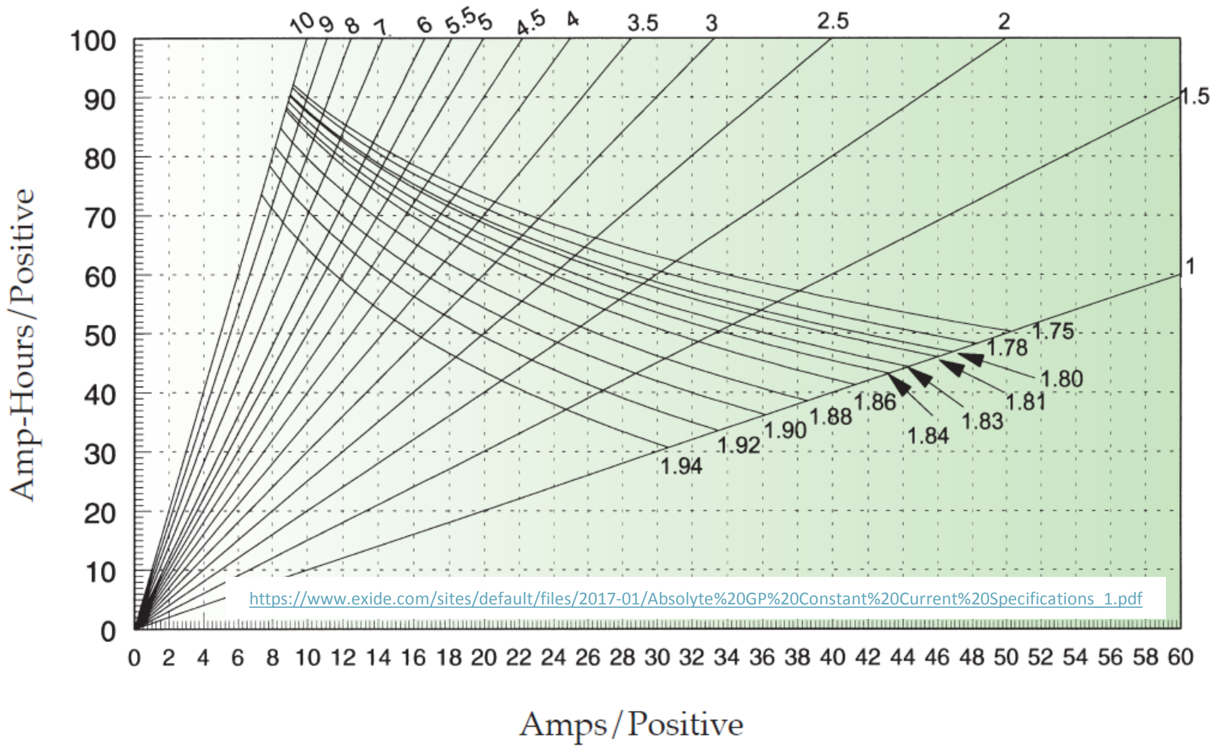
$$E_1 = 20\ A \cdot 10\ h = 200\ Ah$$

$$E_2 = 50\ A \cdot 2\ h + 50\ A \cdot 2\ h = 200\ Ah$$

- But, different required battery capacities:
  - Battery capacity is a function of discharge rate
  - As discharge rate increases
    - Losses increase
    - Capacity decreases

Battery Performance Curves

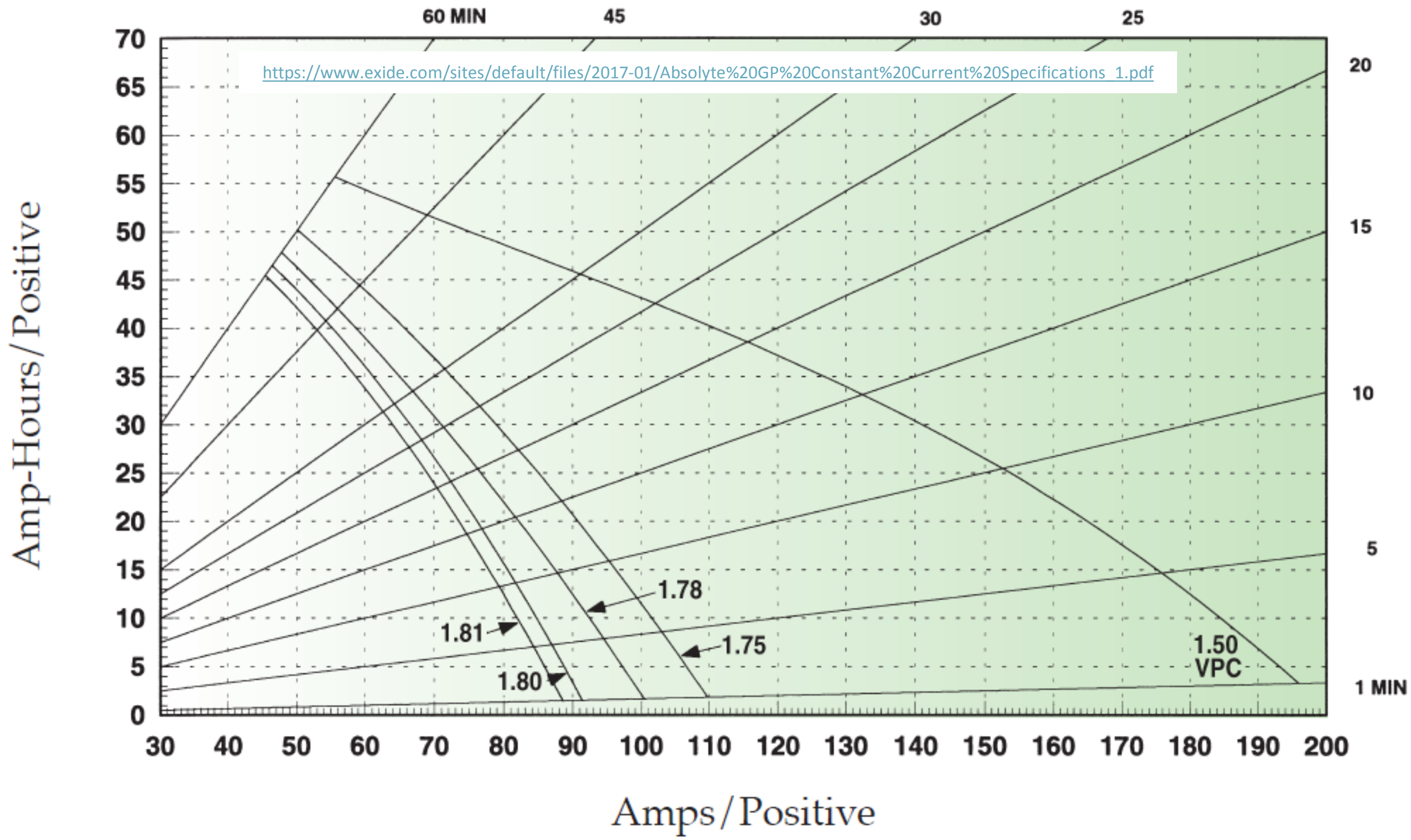
- Capacity vs. discharge current
  - Different curves for different minimum cell voltages



- Straight lines are lines of constant discharge time
  - Here, 1 to 10 hours

Battery Performance Curves

- Same cells, 1-60 minute discharge time:



- Capacity decreases at higher discharge rates

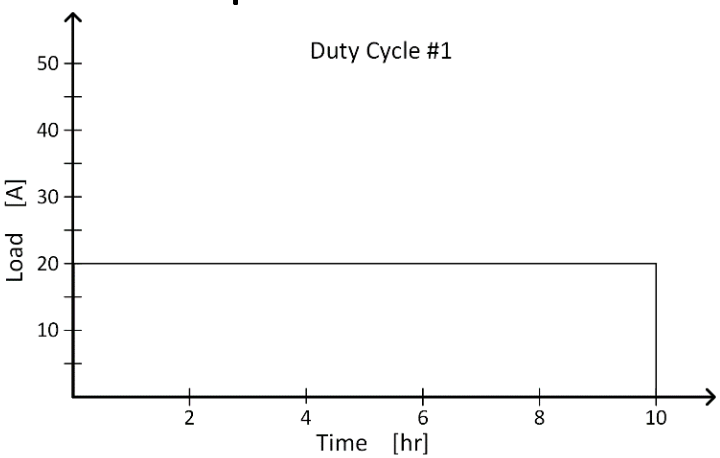
Battery Capacity vs. Rate of Discharge

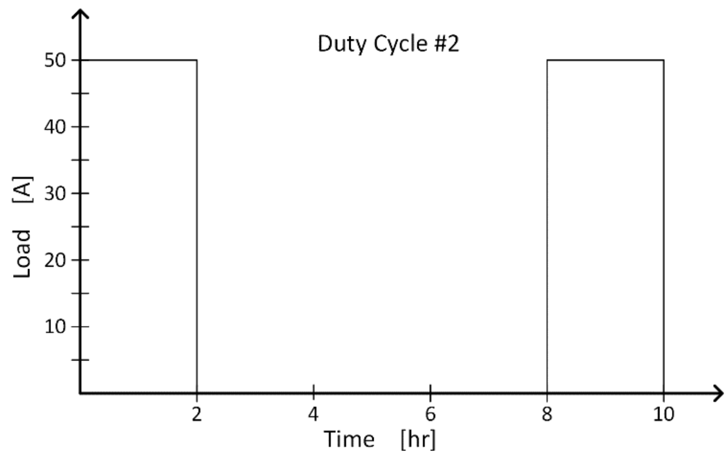
- When sizing a battery, we must account for discharge rates in addition to total energy
  - Larger nominal capacity required for higher discharge rates
- For example, consider a cell with the following constant-current discharge data for a minimum cell voltage of 1.8 V

Discharge Time [hr]	24	12	10	8	7	6	5	4	3	2	1
Discharge Current [A]	12	23	27	32	35	40	45	53	66	88	141
Capacity [Ah]	288	276	270	256	245	240	225	212	198	176	141

Battery Capacity vs. Rate of Discharge

- Choose sizing procedure based on maximum load current
  - Relative to discharge rates for the selected/proposed batteries
    - Greater than or less than the 20-hr rate?
  - Relative to average load
    - Significantly greater than average load?
- For example:





- Max current for #2, 50 A, significantly exceeds average current, 20 A
  - IEEE std 485 is the appropriate procedure
  - IEEE std 1103 may yield an overly-conservatively-sized battery

Battery Capacity vs. Rate of Discharge

- Two methods for accounting for reduced capacity at higher discharge rates:
  - ***Capacity factor***, k_t
    - Used in IEEE std 485
  - ***Functional hour rate***
    - Used in IEEE std 1013
- Next, we'll look at each of these procedures in depth

IEEE Std 485

IEEE Std 485

- IEEE std 485 battery sizing procedure
  - Shorter-duration, higher-current applications
  - Max current greater than 20-hr rate
  - Max current much greater than average current
- Common applications:
  - Bridging supply for UPS applications
    - Data centers
    - Hospitals
    - Wafer fabs, etc.
  - Utilities – switch gear – black start
    - Power plant
    - Substation

IEEE Std 485 – Tabulate Loads

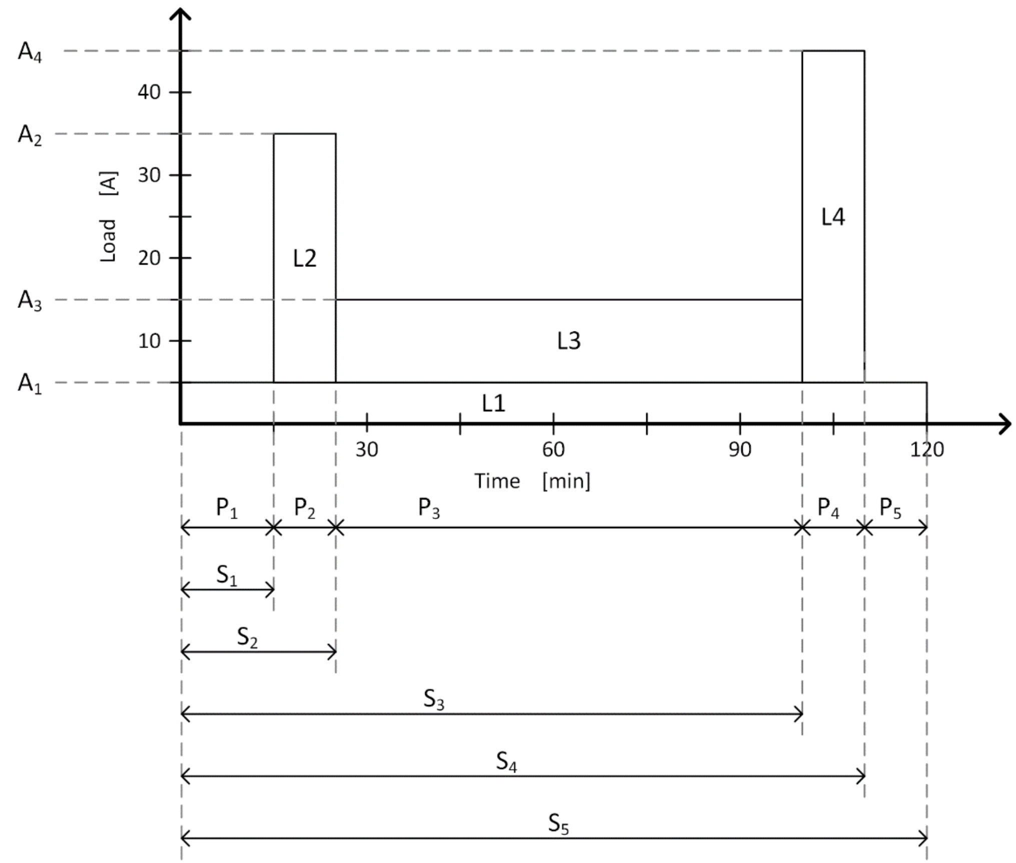
- First, tabulate loads over during the autonomy period
  - For example:

Load #	Current (A)	t_{start} (min)	T (min)
1	5	0	120
2	30	15	10
3	10	25	75
4	40	100	10

- Next, generate the duty cycle diagram

IEEE Std 485 – Duty Cycle Diagram

- Duty cycle diagram is divided into ***periods*** and ***sections***
  - ***Period*** – a portion of the duty cycle with a constant load, P_i
  - ***Section*** – portion of the duty cycle from the beginning of the cycle to the end of each period, S_j



IEEE Std 485 – General Procedure

- Determine the required capacity for each section
  - Rate of discharge is accounted for here
    - ***Discharge factor***, k_t
- Maximum section capacity identified
  - This is the ***uncorrected capacity***
- Uncorrected capacity is adjusted
  - Multiplied by ***temperature correction factor***
  - Multiplied by ***design margin***
  - Divided by ***aging factor***
- Result is the ***required capacity***

Section Capacity – Worksheet

Period	Load [A]		Change in Load [A]		Duration of Period [min]		Time to End of Section [min]		Discharge Factor, kt [Ah/A]	Required Section Size [Ah]
Section 1 - First period only										
1	A1 =	5	A1 - 0 =	5	P1 =	15	T = P1 =	15	0.78	3.9
									Section Total:	3.9
Section 2 - First two periods only										
1	A1 =	5	A1 - 0 =	5	P1 =	15	T = P1+P2 =	25	0.998	4.99
2	A2 =	35	A2 - A1 =	30	P2 =	10	T = P2 =	10	0.699	20.97
									Section Total:	25.96
Section 3 - First three periods only										
1	A1 =	5	A1 - 0 =	5	P1 =	15	T = P1+P2+P3 =	100	2.472	12.36
2	A2 =	35	A2 - A1 =	30	P2 =	10	T = P2+P3 =	85	2.217	66.51
3	A3 =	15	A3 - A2 =	-20	P3 =	75	T = P3 =	75	2.048	-40.96
									Section Total:	37.91

- Capacity determined for each section
  - Sum of capacities required for
    - *Change* in the load at the start of each period
    - Assuming that load persists until the end of the section
    - Scaled by the discharge factor, k_t, for the time from the start of the period to the end of the section

$$C_s = \sum_{p=1}^{s} \left[A_p - A_{p-1}\right] \cdot k_t$$

Discharge Factor

Period	Load [A]	Change in Load [A]	Duration of Period [min]	Time to End of Section [min]	Discharge Factor, kt [Ah/A]	Required Section Size [Ah]
Section 1 - First period only						
1	A1 = 5	A1 - 0 = 5	P1 = 15	T = P1 = 15	0.78	3.9
					Section Total:	3.9
Section 2 - First two periods only						
1	A1 = 5	A1 - 0 = 5	P1 = 15	T = P1+P2 = 25	0.998	4.99
2	A2 = 35	A2 - A1 = 30	P2 = 10	T = P2 = 10	0.699	20.97

- So, what is k_t?
  - Note different k_t values for different times-to-end-of-sections
- Manufacturers provide data for current available for different times
  - Time-current product gives capacity at that discharge rate
  - Data given for a range of final cell voltages
    - ***This is how max depth of discharge is accounted for***
  - For example, for final cell voltage of 1.8 V/cell:

CELL TYPE	HOURS										MINUTES		
	24	12	10	8	7	6	5	4	3	2	1	30	15	1
50G														
50G05	5.1	9.3	11	13	14	16	18	22	27	37	58	94	133	189
50G07	7.7	14	16	19	22	24	28	33	41	56	87	142	199	283

https://www.exide.com/sites/default/files/2017-01/Absolyte%20GP%20Constant%20Current%20Specifications_1.pdf

Discharge Factor

- ***Discharge factor***, k_t, for time-to-end-of-section, T:

$$k_t = \frac{C_{nom}\ \ [Ah]}{A_T\ \ [A]}$$

- C_{nom}: nominal capacity
  - Typ. 8 or 20 hr capacity
  - From manufacturer's data
  - Arbitrary – used as reference capacity for final sizing
  - For example:
    - $C_{nom} = 50\ Ah$ (8 hr)
    - Calculated capacity requirement: 150 Ah
    - Required number of cells: 3
- A_T: current available for time-to-end-of-section, T
  - From manufacturer's data

Discharge Factor

- Consider the following battery data for discharge to 1.8 V/cell:

	Hours											Minutes		
Discharge time	24	12	10	8	7	6	5	4	3	2	1	30	15	1
Discharge current [A]	5.1	9.3	11	13	14	16	18	22	27	37	58	94	133	189
Capacity [Ah]	122	112	110	104	98	96	90	88	81	74	58	47	33.3	3.15

  - Let $C_{nom} = 104\ Ah$ (8 hr capacity)
  - Discharge factor for 1 hr:

$$k_t = \frac{C_{nom}}{A_T} = \frac{104\ Ah}{58\ A} = 1.79\ hr$$

    - That is, for 1-hr discharge, size for 1.79 hr using the 8 hr capacity as a reference
    - Accounts for capacity reduction at high current
  - Discharge factor for 15 min:

$$k_t = \frac{C_{nom}}{A_T} = \frac{104\ Ah}{133\ A} = 0.782\ hr$$

  - Linearly interpolate currents for intermediate discharge times

Discharge Factor - Example

	Hours											Minutes		
Discharge time	24	12	10	8	7	6	5	4	3	2	1	30	15	1
Discharge current [A]	5.1	9.3	11	13	14	16	18	22	27	37	58	94	133	189
Capacity [Ah]	122	112	110	104	98	96	90	88	81	74	58	47	33.3	3.15

- Again, let $C_{nom} = 104\ Ah$ (8 hr capacity)
  - Each battery can provide 13 A for 8 hr
- Determine the # of batteries required to supply 100 A for 2 hr (200 Ah)
  - Discharge factor:

$$k_t = \frac{C_{nom}}{A_T} = \frac{104\ Ah}{37\ A} = 2.81\ hr$$

  - Required capacity:

$$C = A \cdot k_t = (100\ A) \cdot (2.81\ hr) = 281\ Ah$$

  - Required number of batteries:

$$N = \frac{C}{C_{nom}} = \frac{281\ Ah}{104\ Ah} = 2.7\ \rightarrow 3$$

- Note that failure to account for discharge rate would yield N = 2

Section Capacity

- Section capacity given by:

$$C_s = \sum_{p=1}^{s} \left[A_p - A_{p-1}\right] \cdot k_t$$

- $[A_p - A_{p-1}]$ is the change in current at the start of each period
  - Assumed to last until the end of the section, duration T
  - Adjusted by the change in current at the next period
  - May be positive or negative

- Each current scaled by the discharge factor for time T:

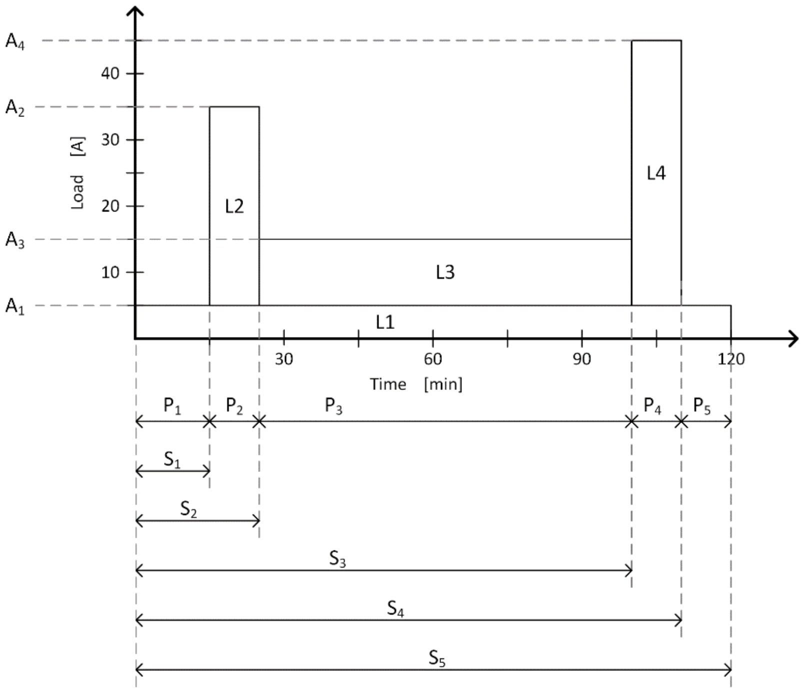
$$\left[A_p - A_{p-1}\right] \cdot k_t = current\ req.for\ T \cdot \left(\frac{C_{nom}}{current\ avail.for\ T}\right)$$

or

$$\left[A_p - A_{p-1}\right] \cdot k_t = \left(\frac{current\ req.for\ T}{current\ avail.for\ T}\right) \cdot C_{nom}$$

Section Capacity – Worksheet

- Consider the third section:
  - k_t determined for each T
  - Change in load scaled by k_t to give required capacity for each period within the section
  - Section capacity is the sum of the period capacities



Period	Load [A]	Change in Load [A]	Duration of Period [min]	Time to End of Section [min]	Discharge Factor, kt [Ah/A]	Required Section Size [Ah]
Section 3 - First three periods only						
1	A1 = 5	A1 - 0 = 5	P1 = 15	T = P1+P2+P3 = 100	2.472	12.36
2	A2 = 35	A2 - A1 = 30	P2 = 10	T = P2+P3 = 85	2.217	66.51
3	A3 = 15	A3 - A2 = -20	P3 = 75	T = P3 = 75	2.048	-40.96
					Section Total:	37.91

Uncorrected Capacity

- ***Uncorrected capacity*** is the largest total section capacity
  - Plus capacity for any random loads
- Capacity then adjusted for
  - Temperature
  - Design margin
  - Aging

Maximum Section Size +	Random Section Size =	Uncorrected Size
61.445	0	61.445

Uncorrected Size x	Temperature Correction Factor x	Design Margin /	Aging Factor =	Required Capacity [Ah]
61.445	1.19	1.15	0.8	105.11

- Result is the ***required capacity***
  - ***Number of cells*** required is determined from the required capacity and the reference capacity

$$N = \frac{C}{C_{nom}}$$

- Note that DoD was accounted for by selecting capacity data for the appropriate final cell voltage

IEEE Std 1013

IEEE Std 1013

- IEEE std 1013 battery sizing procedure
  - Longer-duration, lower-current applications
  - Max current less than 20-hr rate
  - Max current not significantly greater than average
- Typically for off-grid PV systems
  - Residential
  - Commercial
  - Remote monitoring

IEEE Std 1013 – General Procedure

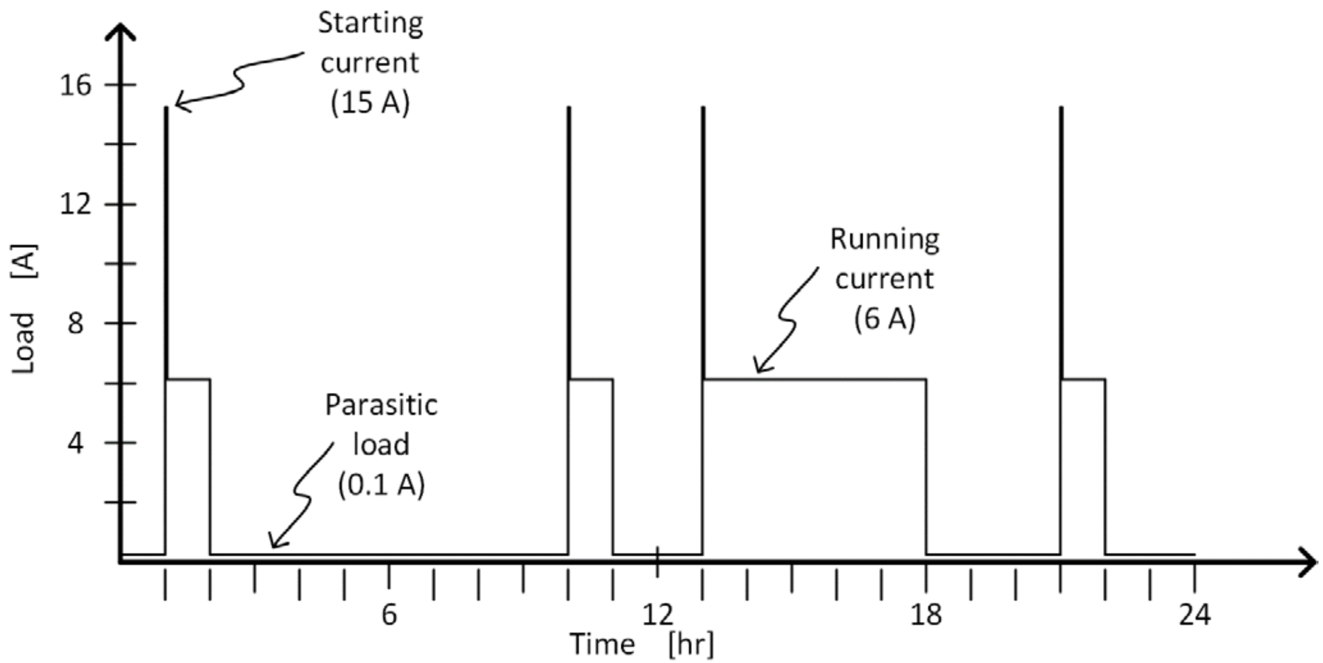
- Determine the required ***autonomy period***
- ***Load determination***
  - System voltage and allowable range
  - Tabulate loads – daily or over the autonomy period
  - Load profile (duty cycle) diagram
- Calculate ***energy requirement*** (Ah) over the autonomy period
  - Unadjusted capacity
- ***Adjust capacity*** for
  - Depth of discharge
  - Aging
  - Temperature
  - Design margin
  - Discharge rate

Load Determination

- ***Tabulate loads*** over autonomy period
  - Current
  - Start time and duration
  - Momentary (e.g. motor starting) and running loads
- Plot ***load profile*** where appropriate
  - Are timing, duration, and coincidence of loads known?
  - If not, determine worst-case scenarios
- Determine:
  - Maximum momentary current
  - Maximum running current
  - Total daily load (Ah/day)
  - Maximum and minimum allowable system voltages

Load Determination – Example

- Consider, for example, a remote refrigerator/freezer unit for medical storage and ice making
  - Solar charging
  - Six-day autonomy period
- Daily load profile:



Load Determination – Example

- Tabulate the load data, accounting for
  - Running current
  - Starting current
  - Parasitic load current (e.g. control electronics, etc.)

DC load device	Voltage window		Momemtary currents	Running currents	Occurances	Duration	Run Time	Daily Load
	Vmax [V]	Vmin [V]	[A]	[A]	[#/day]	[hr/occurance]	[hr/day]	[Ah/day]
Compressor (chill)	15	10.5		6	3	1	3	18
Compressor (ice making)	15	10.5		6	1	5	5	30
Compressor (starting)	15	10.5	15		4	0.0167	0.0667	1
Parasitic load (controls, etc.)				0.1	1	24	24	2.4

Total Daily Load [Ah/day]	51.4

- Motor starting currents conservatively assigned durations of one-minute (0.0167 hr)

Load Determination

5)	**Load Data Summary**				
a)	Maximum momentary current	15.1	A		
b)	Maximum running current	6.1	A		
c)	Maximum current	15.1	A	Max lines 5a and 5b	
d)	Total daily load	51.4	Ah/day		
e)	Maximum system voltage	15	V		
f)	Minimum system voltage	10.5	V		

- ***Maximum momentary current*** (line 5a)
  - Motor starting current may be much larger than running current
  - Assumed duration is 1 min
  - Used for total daily load calculation and max current
- ***Maximum running current*** (line 5b)
  - If load coincidence is unknown, determine worst case
  - Used for total daily load calculation and max current
- ***Maximum current*** (line 5c)
  - Used when determining minimum system voltage when accounting for voltage drops

Load Determination

5)	**Load Data Summary**			
a)	Maximum momentary current	15.1	A	
b)	Maximum running current	6.1	A	
c)	Maximum current	15.1	A	Max lines 5a and 5b
d)	Total daily load	51.4	Ah/day	
e)	Maximum system voltage	15	V	
f)	Minimum system voltage	10.5	V	

- ***Total daily load*** (line 5d)
  - Daily energy (charge, really) requirement in Ah/day
  - Sum of products of currents and durations
  - Used for determining required capacity
- ***Maximum system voltage*** (line 5e)
  - Lowest max. allowable voltage for all system components
  - Used for determining number of series-connected cells
- ***Minimum system voltage***(line 5f)
  - Highest min. allowable voltage for all system components
  - Used for determining number of series-connected cells

Battery Capacity

- First, calculate the ***unadjusted capacity***
  - Product of total daily load and number of days of autonomy
- Next, ***adjust capacity*** for:
  - Maximum depth of discharge
  - Maximum daily depth of discharge
  - Minimum operating temperature
  - Design margin

Battery Capacity

6)	**Battery Capacity**				
	a)	Unadjusted capacity	308	Ah	line 5d * line 3
	b)	Max DoD	80	%	
	c)	Capacity adjusted for MDoD	386	Ah	line 6a/line 6b
	d)	Max daily DoD	20	%	
	e)	Capacity adjusted for MDDoD	257	Ah	line 5d/line 6d
	f)	…			

- ***Unadjusted capacity*** (line 6a)
  - Product of total daily load and number of days of autonomy
  - Daily energy (charge, really) requirement in Ah/day
- ***Maximum depth of discharge*** (MDoD, line 6b)
  - From manufacturer’s data/recommendation
  - Tradeoff between capacity and lifetime
- ***Capacity adjusted for MDoD*** (line 6c)
  - Unadjusted capacity divided by MDoD

Battery Capacity

6)	**Battery Capacity**				
	c)	...			
	d)	Max daily DoD	20	%	
	e)	Capacity adjusted for MDDoD	257	Ah	line 5d/line 6d
	f)	End-of-life capacity	80	%	
	g)	Capacity adjusted for EoL	386	Ah	line 6a/line 5f
	h)	...			

- ***Maximum daily DoD*** (MDDoD, line 6d)
  - From manufacturer's data/recommendation
- ***Capacity adjusted for MDDoD*** (line 6e)
  - Total daily load divided by MDDoD
- ***End of life (EoL) capacity*** (line 6f)
  - Battery to be replace when capacity degrades to this percentage of rated capacity
  - Typically 80% for lead-acid batteries
- ***Capacity adjusted for EoL*** (line 6g)
  - Unadjusted capacity divided by EoL capacity

Battery Capacity

6)	**Battery Capacity**				
g)	…				
h)	Capacity adjusted for DoD or EoL	386	Ah		Max of lines 6c, 6e, and 6g
i)	Min. operating temperature	25	degC		
j)	Temperature correction factor	1			
k)	Capacity adjusted for temperature	386	Ah		line 6h *line 6j
l)	…				

- ***Capacity adjusted for MDoD, MDDoD, or EoL*** (line 6h)
  - Largest of the three adjusted capacities
  - Satisfies all three requirements
- ***Temperature correction factor*** (line 6j)
  - Correction factor for minimum electrolyte temperatures below 25 °C
  - Don't compensate for temperature above 25 °C
  - From manufacturer's data (or IEEE std 485, Table 1)
  - ~0.5%/°F (0.9%/°C) reduction in capacity below 77 °F (25 °C)
- ***Capacity adjusted for temperature*** (line 6k)
  - DoD/EoL-adjusted capacity multiplied by temperature correction factor

Battery Capacity

6)	**Battery Capacity**				
	k)	...			
	l)	Design margin factor	1.1		
	m)	Capacity adjusted for design margin	424	Ah	line 6k * line 6l
7)	**Functional Hour Rate**		70	hr	line 6m/line 5b

- ***Design margin factor*** (line 6l)
  - Allows for load uncertainty and growth
  - Typically 10% – 25% (i.e. 1.1 – 1.25)
- ***Capacity adjusted for design margin*** (line 6m)
  - Temperature-corrected capacity multiplied by design margin
- ***Functional hour rate*** (line 7)
  - Used to account for discharge rate in final capacity determination
  - A conservative '*average*' discharge rate for the duty cycle
  - Adjusted capacity divided by the maximum running current

Functional Hour Rate

- ***Functional hour rate***
  - Adjusted capacity divided by the max running current
  - The discharge time at the max running current
  - Used to account for capacity dependence on discharge rate
  - An alternative to the discharge factor used in IEEE std 485
- For example:
  - Adjusted capacity: 424 Ah
  - Maximum running current: 6.1 A

  Functional hour rate = $\frac{C_{adj}}{I_{max}} = \frac{424\ Ah}{6.1\ A} = 70\ hr$

- For final cell selection, ***use the capacity rating at the functional hour rate***

Voltage Window Adjustment

8)	**Voltage Window Adjustment**				
	a)	Controller low-voltage disconnect	10.8	V	
	b)	Adjusted minimum voltage	10.8	V	Max of lines 5f and 8a
	c)	Controller full-charge voltage set point	14.7	V	
	d)	Adjusted maximum voltage	14.7	V	Min of lines 5e and 8c

- ***Controller low-voltage disconnect*** (LVD, line 8a)
  - Voltage at which the charge controller is set to disconnect the battery from the load
  - Voltage at the maximum DoD
- ***Adjusted minimum voltage*** (line 8b)
  - Larger of the LVD set point and the minimum allowable system voltage
  - Used when determining number of series-connected cells
- ***Controller full-charge voltage set point*** (line 8c)
  - Voltage at which the charge controller stops charging the battery
  - Voltage at full SoC
- ***Adjusted maximum voltage*** (line 8d)
  - Smaller of the controller full-charge set point and the maximum allowable system voltage
  - Used when determining number of series-connected cells

Series-Connected Cells

9)	**Series-Connected Cells**			
a)	Recommended per-cell full-charge voltage	2.45	V/cell	
b)	Maximum number of cells in series	6		line 8d/line 9a rounded down
c)	Rec. per-cell end-of-discharge voltage	1.8	V/cell	
d)	Calculated per-cell EoD voltage	1.8	V/cell	line 8b/line 9b
	…			

- ***Recommended per-cell full-charge voltage*** (line 9a)
  - From manufacturer's data
- ***Maximum number of cells in series*** (line 9b)
  - Maximum allowable system voltage divided by the maximum volts/cell, rounded down
- ***Recommended per-cell end of discharge voltage*** (line 9c)
  - From manufacturer's data
- ***Calculated per-cell EoD voltage*** (line 9d)
  - Minimum system voltage divided by number of series cells

Series-Connected Cells

9)	**Series-Connected Cells**			
d)	…			
	If 9.d) > 9.c) proceed to 9.g), otherwise continue with 9.e)			
e)	Decremented # series-connected cells	-		line 9b - 1
f)	Adjusted maximum per-cell voltage	-	V	line 8d/line 9e
	Verify that 9.f) is within maximum allowable cell voltage. If not, adjust			
g)	Number of cells in series	6		line 9b or, if applicable, line 9e

- ***Calculated per-cell EoD voltage*** (line 9d)
  - Minimum system voltage divided by number of series cells
  - Minimum voltage seen by each cell at EoD
  - If less than recommended, decrement the number of series cells by one (line 9e)
- ***Adjusted maximum per-cell voltage*** (line 9f)
  - Maximum system voltage divided by the decremented number of series cells
  - Max per-cell voltage after reducing number of series cells
  - If greater than recommended maximum, adjustments are required

Series-Connected Cells

9) **Series-Connected Cells**

d)	…			
	If 9.d) > 9.c) proceed to 9.g), otherwise continue with 9.e)			
e)	Decremented # series-connected cells	-		line 9b - 1
f)	Adjusted maximum per-cell voltage	-	V	line 8d/line 9e
	Verify that 9.f) is within maximum allowable cell voltage. If not, adjust			
g)	Number of cells in series	6		line 9b or, if applicable, line 9e

- Minimum and maximum per-cell voltages must be within recommended range
  - If not, iteration is required
- Adjust some combination of the following:
  - Number of series-connected cells
  - Low-voltage disconnect set point
  - Controller full-charge voltage set point
- ***Number of cells in series*** (line 9g)
  - The selected number of series cells

Cell Selection and Capacity Determination

10)	**Cell Selection and Capacity Determination**			
a)	Smallest cell capacity available for selected cell type that satisfies capacity requirement, line 6m, when discharged to per-cell EoD voltage, line 9d or 9e, at functional hour rate, line 7. OR, if no single cell satisfies requirements, capacity of cell to be paralleled.	110	Ah	
b)	Number of parallel strings	4		line 6m/line 10a rounded up
c)	Final battery capacity	440	Ah	line 10a * line 10b

- Select a cell and enter the capacity (line 10a)
  - Really, a *battery* with the selected number of series-connected cells (line 9g)
- The smallest single cell, or smaller cells to be paralleled, to:
  - Satisfy adjusted capacity requirement (line 6m)
    - When discharged at the ***functional hour rate*** (line 7)
    - When discharged to the determined per-cell EoD voltage (section 9)
  - Minimize excess, unutilized capacity
- This is the ***capacity at the functional hour rate***
  - Not necessarily the battery's nominal capacity

Cell Selection and Capacity Determination

10)	**Cell Selection and Capacity Determination**			
a)	Smallest cell capacity available for selected cell type that satisfies capacity requirement, line 6m, when discharged to per-cell EoD voltage, line 9d or 9e, at functional hour rate, line 7. OR, if no single cell satisfies requirements, capacity of cell to be paralleled.	110	Ah	
b)	Number of parallel strings	4		line 6m/line 10a rounded up
c)	Final battery capacity	440	Ah	line 10a * line 10b

- ***Number of parallel strings*** (line 10b)
  - Number of parallel batteries needed to satisfy the adjusted capacity requirement (line 6m)
  - Adjusted capacity divided by the per-battery capacity, rounded up
- ***Final battery capacity*** (line 10c)
  - Capacity of the resulting battery bank
  - Per-battery capacity multiplied by the number of parallel strings
  - Battery bank capacity at the ***functional hour rate***

Battery Bank Summary

Summary

Battery manufacturer and model:	XYZ Batteries: 123-ABC	
Cells in series:	6	
Cells in parallel:	4	
Full-charge voltage:	14.7	V
End-of-discharge voltage:	10.8	V

- Battery sizing procedure is now complete
- Summarize key battery bank specifications at the end of the worksheet
- For our example:
  - Four of the specified batteries in parallel
    - Six cells per battery
  - Battery bank voltage range: 10.8 V – 14.7 V