DC BATTERY SYSTEMS

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1.0 SCOPE

This document provides design, operation, inspection, testing, and maintenance guidance for DC battery systems used for standby operations in stationary applications, including, but not limited to, power-generating stations, substations, telecommunications, data centers, switchgear protection systems, process control systems, emergency power supplies, and uninterruptable power supplies. In these applications, the operation of DC systems results in the batteries operating most of the time on a float charge with infrequent discharge (i.e., float service).

For lithium-ion batteries used for standby operations, refer to FM Property Loss Prevention Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*, for loss prevention recommendations related to fire and explosion hazards.

This data sheet does not cover energy storage batteries, diesel engine startup batteries, batteries in mobile equipment (such as lift trucks and cranes), or the storage of batteries.

1.1 Hazards

A stationary standby battery is a critical component of an electrical protection system and/or emergency power system used to protect connected equipment and systems from electrical faults or system disturbances that could result in equipment damage, arcing fault, fire, or unsafe shutdown of a critical process.

1.2 Changes

October 2025. Interim revision. Major changes include the following:

A. Clarified the scope with respect to lithium-ion batteries in emergencies, UPS and switchgear applications.

B. Revised Section 2.3.7 to further clarify when on-line continuous condition monitoring system for lead-acid/nickel-cadmium batteries is needed.

C. Revised li-ion battery ITM guidance in Section 2.5.4:

1. Added recommendation to perform annual BMS monitoring data review to identify any potential early deficiencies.
2. Changed the battery capacity testing recommendation from every 5 years to every 3 years.

D. Added loss prevention guidance for sodium metal chloride (SMC) batteries for switchgear applications in Section 2.5.5

E. Added support material on capacity testing and sodium metal chloride batteries in Sections 3.3.6 and 3.4.3.

2.0 LOSS PREVENTION RECOMMENDATIONS

Equipment protection strategies and inspection, testing, and maintenance (ITM) methodologies will vary to ensure the ongoing integrity and reliability of distinct pieces of equipment and systems. These variations can be attributable to the operating and environmental conditions present and the size, criticality, and history of the equipment and systems. Furthermore, there can be more than one effective way to meet the intent of preventing or mitigating the risk presented by the equipment breakdown scenario. An engineering evaluation of the alternative strategies used to meet the intent of the recommendations presented in this data sheet may need to be performed. When performing the engineering evaluation, consider the following:

- Equipment breakdown scenarios and resulting impacts on production, utility, and support systems, including damage to interconnected or surrounding equipment and areas
- Equipment viability for the intended service
- Operating and ITM history/trends as well as current operating and environmental conditions
- Asset integrity program scope and implementation
- Operator competency
- Safety device adequacy

- Equipment contingency planning viability

2.1 FM Approved Equipment

2.1.1 Use FM Approved equipment, materials, and services whenever they are applicable and available. For a list of products and services that are FM Approved, see the *Approval Guide*, an online resource of FM Approvals.

2.2 Construction and Location

2.2.1 Locate batteries where they will not be exposed to mechanical damage, heat, dust accumulations, moisture, or hazardous processes.

2.2.2 If the facility is located in FM's 50-year through 500-year earthquake zones as defined in Data Sheet 1-2, *Earthquakes*, provide seismic bracing and support to the battery systems, including restraint of battery racks and batteries to the racks. Refer to Data Sheet 1-2 for more guidance.

2.2.3 Install battery systems above the predicted 0.2% annual exceedance (500-year) flood elevation. Include 1 to 2 ft (0.3 to 0.6 m) of freeboard. Refer to Data Sheet 1-40, *Flood*, for more details.

2.2.4 Locate lead-acid and nickel-cadmium batteries in a minimum one-hour fire-rated room.

2.2.5 When flooded batteries are located on upper floors, seal all floor penetrations within 10 ft (3 m) of the battery rack.

2.3 Equipment and Processes

2.3.1 General

For emergency applications where high availability is needed, such as switchgear or emergency lube oil pump applications, use battery technologies with fewer thermal runaway, fire and explosion hazard concerns, such as lead-acid and nickel-cadmium batteries.

2.3.2 Thermal Management and Ventilation

2.3.2.1 To optimize the performance and aging rate of the batteries, maintain the battery room or area as close to 77°F (25°C), or temperature range specified by manufacturer, as possible.

To reduce the likelihood of thermal runaway, do not place lithium-ion batteries in locations where temperatures higher than 158°F (70°C) are expected to occur.

2.3.2.1.1 For critical battery systems, such as data centers UPS battery rooms, or telecommunication battery rooms, do the following:

A. Provide HVAC systems separate from the equipment areas for thermal management and protection of other equipment from contamination damage due to battery thermal runaway.

B. Install a room temperature monitor that will alarm remotely to a constantly attended location.

2.3.2.2 For cabinets or closets housing valve regulated lead-acid (VRLA) batteries, provide a forced air ventilation system, or one with enough vent openings to allow natural ventilation to limit the rise of the temperature.

2.3.2.3 For lead-acid and nickel-cadmium batteries, design ventilation systems to the battery room and cabinet in accordance with the following guidance to limit an explosive accumulation of hydrogen gas below 1% of the total volume of the room during the worst-case event of simultaneous "boost" charging of all the batteries.

A. Provide continuous ventilation at a rate of not less than 1 cfm/ft^2 (5.1 LPS/m^2) of floor area of the room with suction points located at the roof level, or

B. Provide ventilation and thermal management in accordance with IEEE 1635.

2.3.2.4 For lead-acid and nickel-cadmium batteries, provide a hydrogen detection system at roof level or ventilation failure monitoring device to alarm remotely at a constantly attended location. Set the alarm level of the hydrogen detection system below 1%.

2.3.2.5 For lithium-ion batteries, provide a gas detection system and ventilation system for fire and explosion hazards per Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*.

2.3.3 Battery Acid Spill Control

2.3.3.1 Do not use absorbent battery acid pillows for permanent acid spill protection unless required by the local authorities.

2.3.3.2 When battery acid spill control is provided, do the following:

A. Use only FM Approved (Class 4955) battery acid absorbent pillows.

B. Remove or replace pillows (where required) whenever indications of acid exposure are exhibited (e.g., pillow fabric shows distinct color change).

C. Promptly replace leaking batteries to eliminate the need for battery acid absorbent pillow protection.

2.3.4 System Design and Sizing Considerations

2.3.4.1 General

2.3.4.1.1 Design the battery size (capacity and duty cycle) with consideration of the following criteria, at a minimum (refer to IEEE 485 and IEEE 1115 for more sizing guidance):

- DC load profile, including number of loads, sequence in which the loads draw current, and current and duration of each load
- Minimum operating voltage for DC loads when the battery reaches its end of discharge (i.e., 80% of capacity)
- Lowest ambient temperature expected at battery

2.3.4.2 Power Generation Equipment

2.3.4.2.1 When rotating equipment requires lubrication during shutdown and a DC pump is used for emergency shutdown, provide two independent DC systems: one for emergency lube/seal oil pump system and the other for control and protection. Each system should be powered from separate and independent sections of the ac power systems.

2.3.5 Electrical Protection

2.3.5.1 Provide a DC disconnect switch device to facilitate the removal of a battery string from service for the purpose of offline maintenance and testing.

2.3.5.2 Provide an overcurrent protection device for the battery string against short-circuit faults only. Select the appropriately sized protection device (i.e., circuit breakers or fuses rated for DC applications based on a system study). These devices should be rated at the maximum operating voltage and available fault current.

2.3.5.3 Provide battery chargers with DC high-voltage protection against overcharge of the connected battery systems.

2.3.5.4 Provide ground fault detection systems for ungrounded DC systems.

2.3.6 Instrumentation, Control, and Alarm

2.3.6.1 Provide DC systems with the following alarms remotely, at a minimum. Have all the alarms individually report to a constantly attended location.

- DC bus undervoltage alarm
- Battery charger output breaker open alarm
- Battery charger DC output failure alarm
- Battery charger AC power input failure alarm
- Charger low-DC voltage alarm

- Battery string disconnector open alarm
- BMS failure alarms (per Section 2.3.7)
- Battery high/low temperature alarm (Lithium-ion and sodium metal chloride batteries)

Note: The function of the DC bus undervoltage alarm is to alert the operator that the battery is being discharged. The DC bus undervoltage relay should be adjustable and set to alarm at a voltage slightly less than that of the open circuit voltage of the battery (e.g., approximately 119 V for a 58-cell, 125 V battery) rather than at the minimum allowable system voltage (typically 105 V for a 125 V system). This higher setting will alert the operator whenever the battery is supplying energy to the DC bus load (e.g., more load than the charger can handle) sufficiently early to take appropriate corrective action.

2.3.7 Online Condition Monitoring

2.3.7.1 Provide online condition monitoring systems for the following types of batteries:

A. Critical batteries the loss of which will have a significant business impact (e.g., data center UPS systems).

B. Batteries for which the inspection, testing, and maintenance intervals in Section 2.5 must be significantly extended

C. Any type of lithium-ion batteries

2.3.7.2 Provide online condition monitoring systems to monitor the following parameters, when applicable:

- Battery cell temperature
- Battery cell voltage
- Battery charge current at string level
- Battery discharge current at string level
- Battery string voltage
- Battery cell internal resistance (lead-acid only)
- Battery cell connection resistance (lead-acid and nickel-cadmium only)
- Battery electrolyte level (flooded battery only)
- State of heath (SOH) and state of charge (SOC) (for lithium-ion or sodium metal chloride batteries only)

For lithium-ion and sodium metal chloride batteries, the battery management system (BMS) acts as a built-in monitoring system in addition to its control functions, and thus an external monitoring system is not required. The user needs to work with the battery manufacturer to ensure the interface provided works for them and provide the data regarding critical parameters such as state of health and cell temperature to external display.

Refer to Sections 3.5 and 3.6 for more details on online condition monitoring systems.

2.3.7.3 Provide automatic controls to accomplish at least one of the following for lithium-ion batteries when there are indications leading to a thermal runaway, such as cell high temperature, excessive charging/ overcharging current, cell over voltage or under voltage, or BMS system key components failure:

A. Disconnect battery from charger or rectifiers.

B. Turn off the rectifiers or chargers.

When the design of BMS allows alarm only due to the failure of its key components (e.g., voltage sensor, current sensor, temperature sensor, and communication channel), develop a formal emergency operating procedure to shut down the process and the battery system manually until the problem is corrected.

2.3.7.3.1 If continuity of operation is so critical that the battery system cannot shut down under any of the circumstances listed in Section 2.3.7.3, provide N+1 redundancy into battery systems in isolated areas, with each location and system configured as outlined in this data sheet.

2.4 Fire Protection

2.4.1 For battery systems that use lithium-ion technologies, provide fire protection in accordance with Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*.

2.4.2 For battery systems that don’t use lithium-ion technologies, provide an automatic sprinkler system designed in accordance with Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*. Design the automatic sprinkler system for an HC-2 occupancy and use quick-response sprinklers.

Clean agent fire extinguishing systems can be provided as supplementary protection when there is a need to limit equipment and nonthermal damage. Provide the clean agent system in accordance with Data Sheet 4-9, *Halocarbon and Inert Gas (Clean Agent) Fire Extinguishing Systems*, for the electrical and battery electrolyte hazard.

2.5 Operation and Maintenance

2.5.1 General

2.5.1.1 Operate the battery and its support systems in accordance with approved operating instructions and within prescribed battery thermal and electrical limits (i.e., float/equalizing voltage limit).

2.5.2 Inspection, Testing, and Maintenance

2.5.2.1 Implement a battery system inspection, testing, and maintenance program. See Data Sheet 9-0, *Asset Integrity*, for guidance on developing an asset integrity program.

2.5.2.2 Perform minimum weekly visual inspection of the battery room and battery system components for identification of any abnormal condition (e.g., room ventilation failure, excessive room temperature).

2.5.2.3 Perform the inspection, testing, and maintenance practices listed in Table 2.5.2.3-1. The acceptance criteria for the battery tests are listed in Table 2.5.2.3-2.

Table 2.5.2.3-1. Inspection, Testing, and Maintenance

Frequency	*Flooded Lead-Acid*	*Flooded Nickel-Cadmium*	*Sealed Lead-Acid (VRLA)*	*Lithium-ion*
Monthly	• Check the float voltage & float current at battery terminal. • Check the charger outpower voltage and current. • Check ambient temperature and condition of ventilation. • Perform visual inspection of cells to check electrolyte level, and look for evidence of corrosion, leakage, cracks, excessive sediment, etc. • Check pilot cell voltage and temperature. • Check battery monitoring systems to ensure they are operational.	• Check the float voltage at the battery terminal. • Check the charger output voltage and current. • Check electrolyte levels and look for evidence of corrosion, leakage, cracks, etc. • Check battery monitoring systems to ensure they are operational.	• Check the float voltage and current at the terminals. • Check charger voltage and current. • Check ambient temperature and ventilation condition. • Perform visual inspection of cells for evidence of corrosion, leaks, overheating, and distorted cases. • Check battery monitoring systems to ensure they are operational.	See Section 2.5.4 for guidance.
Quarterly[1]	In addition to monthly inspection: • Check the temperature of 10% of the cells. • Check the individual cell voltages of all cells.	In addition to monthly inspection: • Check the pilot cell electrolyte and temperature.	In addition to monthly inspection: • Check the internal ohmic values for each cell. • Check the negative terminal temperature of 10% of the cells. • Check the individual cell voltage of all cells.	
Annually	In addition to quarterly inspection: • Check inter-cell resistances. • Check the internal ohmic values (optional).	In addition to quarterly inspection: • Check all inter-cell resistances.	In addition to quarterly inspection: • Check inter-cell resistances. • Check the string AC ripple current.	

Note 1. For less critical batteries, bi-annually is acceptable

Table 2.5.2.3-2. Acceptance Criteria for Battery Tests

Test	*Acceptance Criteria*
Electrolyte levels	Electrolyte levels in flooded cells must fall between the min and max lines. Cells must not be overfilled. Electrolyte leaks can cause a battery short circuit.
Cell voltages	Cell voltages must compare well with the rated voltage and be within 0.05 volts of each other.
Ripple	Ripple in the charger waveform must be within the manufacturer’s tolerance for sealed lead-acid batteries. (Usually, maximum ripple voltage of about 0.5% of float voltage, and maximum ripple current of 5 A rms for every 100 A-h of battery capacity. Excessive ripple will lead to overheating and loss of battery life.)
Float current	Float current must remain constant. Increase in float current of about 300% indicates the possibility of thermal runway in VRLA batteries (vented batteries will not experience thermal runaway because of the large volume of electrolyte acting as a heat sink).
Internal ohmic	Internal cell resistances must not vary by more than approximately 50% compared with baseline values.
Inter-cell connections	Inter-cell connection resistance must not increase more than 20% from the baseline value. Note the baseline values are specific to each connection and can be established during commission testing or when the connection is known in good condition.

2.5.2.3.1 Where an online battery monitoring system is installed, perform monthly visual inspections and test the parameters listed in Table 2.5.2.3-1 that are not specifically monitored by an online system and reviewed by site personnel. Perform capacity tests at the frequency specified in Section 2.5.2.4.

2.5.2.4 Perform a capacity test (also called "performance test" or "discharge test") every five years for flooded lead-acid, flooded nickel-cadmium batteries, and every two years for sealed lead-acid (VRLA) batteries. When deterioration in capacity is noticed, increase the frequency of testing to once every year.

Excessive capacity deterioration is indicated when the capacity drops below 90% of rated value for lead-acid batteries, and when the capacity drops more than an average 1.5% per year of rated capacity from its capacity on the previous testing for nickel-cadmium batteries. During capacity testing, perform the following activities:

A. If the battery under test is the only one installed, connect a spare battery bank to the system to allow the battery bank to be isolated for testing without jeopardizing the electrical system in the event a fault incident occurs during the capacity test. Alternatively, perform the test during the planned outage.

B. Perform infrared scanning on battery system components whenever applicable to detect any overheating-related deficiency.

Batteries are designed with a certain amount of cycling life (>100 cycles). By following the recommended testing frequency in this data sheet, a battery will be capacity tested up to about 10 times in its life. Therefore, the recommended capacity testing will have a negligible impact on battery life.

2.5.2.5 For lead-acid type, replace the battery system when its measured capacity approaches 80% of its rated capacity. For nickel-cadmium batteries, replace at 70%.

When lead-acid and nickel-cadmium batteries are replaced with lithium-ion batteries, consult with battery and equipment OEM to ensure matching performance, such as voltage between the existing charger and the level required by the li-ion battery systems, and their battery management systems.

2.5.3 Lead-Acid and Nickel-Cadmium Battery Charger Maintenance

2.5.3.1 Perform monthly visual inspections to verify the charger is set for float charge, check meters, and address any alarms.

2.5.3.2 Perform the following maintenance annually:

A. Confirm the battery charger output voltage and current are within specifications for the battery.

B. Verify the charger is set for float charge.

C. Clean out rectifier/inverter if needed (low-pressure clean air may be used).

D. Inspect all internal components.

E. Make sure all connections are tight.

F. Check meters and alarms for accuracy.

2.5.4 Maintenance of Lithium-Ion Batteries

2.5.4.1 Perform minimum weekly visual inspection of the battery room and battery system components for identification of any abnormal conditions such as room ventilation failure, water leaks, malfunction of battery room environmental control devices, connection related issues or abnormal indications from battery management system.

Immediately take corrective action when any of the following situations occur:

- Battery room temperature is outside of the temperature range specified by OEM.
- Battery string voltage is outside of the voltage range specified by OEM
- Battery management system is not functional.
- Battery modules in operation change shape or appear abnormal in any other way.
- Environmental contamination such as water leaks within the battery room

2.5.4.2 Perform the following BMS maintenance activities annually:

- Evaluate monitoring cell voltages to ensure maximum allowable voltage spread between cells is maintained in accordance with manufacturer's recommendations.

- Evaluate all monitored temperatures to ensure the maximum allowable temperature spread is maintained in accordance with manufacturer's recommendations
- Verify that all safety mechanisms within the BMS are operational. (If an automatic function is not performed by the BMS, safety mechanisms can be verified by testing contactor operation, using the BMS diagnostic mode. Consult with the manufacturer for needed guidance.)
- Review Trend alarm and warning history to help determine if a problem might be developing.
- Evaluate the difference between the BMS SOH value and the most recent measured capacity value, per capacity/load testing. Consult with the manufacturer for guidance regarding any discrepancy.

2.5.4.3 Perform battery discharge testing or battery capacity testing every three years or with a frequency of every 25% of battery service life. Select the testing discharge current in accordance with OEM guidance to avoid thermal runaway event during testing. In addition, monitor the discharge testing with respect to parameters such as discharge current, cell voltage and module temperatures, which are generally monitored by battery management system.

Periodically perform infrared scanning of the battery systems under test to evaluate any potential adverse conditions within the battery and/or system connection.

If the capacity test fails early due to BMS disconnection, review all the recorded voltages, temperatures, alarm logs and thermal scans performed during the test. Consult the manufacturer for corrective actions. If early termination of the testing is due to deteriorated battery module(s), manufacturer repair or replacement is a typical corrective action.

According to publications, most lithium-ion batteries such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (LNMC) and lithium manganese oxide (LMO) have about 10-13 years of floating life in a controlled environment. Lithium titanium oxide (LTO) batteries claim to have about 20 years' floating life.

For lithium-ion batteries in battery backup units (BBU) utilized in data center halls, the Open Compute Project (OCP) design specification indicates 8 years floating life. In addition, full capacity testing is automatically performed every 1.5 years for each module. The measured capacity value from the testing is reported as SOH (state of health) in the BMS. Hence, additional capacity testing is not required.

2.5.4.3.1 When deterioration in capacity is noticed, increase the frequency of testing to once every year.

2.5.4.4 Replace the battery when its measured capacity approaches 80% of its rated capacity or as needed, per indication by the BMS monitoring system.

Lithium-ion cells typically start to show an accelerated rate of degradation once their capacity falls to 70% of their rated value. However, battery sizing for floating applications traditionally uses a 125% margin by considering that the battery should support the load when its capacity drops to 80% of its rated value, but not below 80%. In addition, given the higher inherent risk of fire and explosion associated with lithium-ion batteries, best practice is to define end of-life at 80% capacity.

2.5.5 Maintenance of Sodium-Metal Chloride Batteries

2.5.5.1 Perform minimum weekly visual inspections of the battery room and battery system components for identification of any abnormal conditions such as water leaks, malfunction of battery room environmental control devices, connection-related issues or abnormal indication from the battery management system, or presence of combustible material in the battery room.

Immediately take corrective action when any of the following situations occurs:

- Battery string voltage is outside of the voltage range specified by the OEM
- Battery management systems are not functional.
- Battery modules in operation change shape or appear abnormal in any way.
- Environment contamination issues such as water leak or debris

The weekly inspection can be adjusted based on the criticality of the battery system.

2.5.5.2 Perform the following BMS maintenance activities annually:

Poll and record BMS log files to trend alarm and warning history to help determine if a problem might be developing. This activity should include:

- Evaluate monitoring module voltages to ensure the maximum allowable spread between modules is maintained in accordance with manufacturer's recommendations.
- Evaluate all monitored temperatures to ensure the maximum allowable temperature spread and minimum/maximum allowable value is maintained per manufacturer's recommendations

2.5.5.3 Perform battery capacity testing every five years or with a frequency of every 25% of battery service life to verify the entire battery system can perform as manufactured. In addition, monitor the discharge testing with respect to parameters such as discharge current, cell voltage and module temperatures, which are generally monitored by the battery management system. Periodically perform infrared scanning of the battery systems under test to evaluate any potential adverse conditions.

See Section 3.3.6 for additional details.

2.5.5.4 Replace the battery when its capacity (i.e., state of charge as reported by the BMS) approaches 80% of its rated capacity or as needed, per indication by the BMS monitoring system.

2.6 Training

2.6.1 Develop emergency operating procedures for the following scenarios:

- Loss of DC power
- DC bus undervoltage alarm
- Excessive H2 alarm for lead-acid and nickel-cadmium battery systems
- Emergency DC system in service alarm (i.e., loss of primary AC power)
- Charger output failure alarm
- Battery condition monitoring system alarm

2.6.2 For installations with lithium-ion batteries, provide the operators and key site personnel who interact with the batteries with training and awareness of lithium-ion battery thermal runaway, fire, and explosion hazards. Develop an emergency response plan for fire and thermal runaway incidents.

2.6.3 Develop a standard operating procedure for the following activity, at a minimum:

- Operating when the N+1 redundancy in the DC battery system is lost due to a planned outage

2.6.4 Develop, maintain, and train operators on the standard and emergency operating procedures. See Data Sheet 10-8, *Operators*, for guidance on developing operator programs.

2.7 Contingency Planning

2.7.1 Equipment Contingency Planning

When a battery string breakdown would result in an unplanned outage to site processes and systems considered key to the continuity of operations, develop and maintain a documented, viable battery equipment contingency plan per Data Sheet 9-0, *Asset Integrity*. See Appendix C of that data sheet for guidance on the process of developing and maintaining a viable equipment contingency plan. Also refer to sparing, rental, and redundant equipment mitigation strategy guidance in that data sheet.

2.7.2 Sparing

Sparing can be a mitigation strategy to reduce the downtime caused by a battery breakdown, depending on the type, compatibility, availability, fitness for the intended service, and viability of the sparing. For general sparing guidance, see Data Sheet 9-0, *Asset Integrity*.

2.7.2.1 Routine Spares

Routine battery string spares are spares that are considered to be consumables. These spares are expected to be put into service under normal operating conditions over the course of the life of the battery string, but not reduce equipment downtime in the event of a breakdown. This can include sparing recommended by the original equipment manufacturer. See Section 3.6 for guidance on routine spares.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Battery Types

The most common stationary standby batteries are lead-acid, nickel-cadmium, and lithium-ion batteries.

3.1.1 Lead-Acid Batteries

Lead-acid batteries can be flooded or valve regulated type (VRLA). Flooded lead-acid cells are constructed with the liquid electrolyte completely covering (flooding) the closely spaced plates in a clear container. The clear container allows for visual inspection of the plates and internal components. Normal charging results in gassing and water consumption. While this will necessitate electrolyte maintenance, the ability to replenish lost water makes flooded cells more tolerant of overcharging and operation at elevated temperature than VRLA cells. Therefore, flooded lead-acid batteries can achieve an average service life of from 15 to 20 years when they are maintained well.

Valve-regulated lead-acid (VRLA) cells are sealed except for a valve that opens as required to relieve excess internal pressure. These cells provide a means for recombination of gases to limit water consumption. The valve regulates the internal pressure to optimize recombination efficiency; hence, the term “valve regulated.” Depending on the constructer, VRLA can be absorbed glass mat (AGM) type or gelled electrical type cells. VRLA batteries are often called maintenance free because of no need of water top up. Under normal recombination operation, valve-regulated cells periodically vent very small amounts of hydrogen, and some hydrogen may also diffuse through the plastic case. When charging above the recommended manufacturer’s voltage values or operating at elevated temperatures, VRLA battery may result in excessive venting of hydrogen and oxygen from the cell and/or can result in premature dry out potentially leading to thermal runaway. The average service life to VRLA battery is less than 10 years per industrial experience when they are maintained well. It is not uncommon to replace VRLA batteries after a service life of less than 5 years. In extreme cases, VRLA batteries must be replaced at 2-year intervals.

3.1.2 Nickel-Cadmium Batteries

Nickel-cadmium batteries use an alkaline electrolyte (potassium hydroxide). The active materials are nickel oxyhydroxide in the positive plate, and cadmium metal in the negative plate. The batteries are resistant to mechanical and electrical stresses, operate well over a wide temperature range, and can tolerate frequent shallow or deep discharging. Thus, stationary standby nickel-cadmium batteries have an expected life of 20-25 years in a controlled environment, which is equivalent or better than flooded lead-acid designs, and better than VRLA.

3.1.3 Lithium-Ion (Li-Ion) Batteries

The term “lithium-ion battery” covers a broad category of chemistries. The product should be considered as a system of integrated components and not just a set of separate cells. The components in a conventional lithium-ion battery system are the lithium-ion cells, integral parts, and the auxiliary systems, including the battery management system (BMS). Manufacturers package these components in configurations known as packs, modules, or units. The charger may be integrated into the battery system, or it may be a separate component.

Due to their higher specific energy density and a greater sensitivity to electrical and environmental abuse, lithium-ion batteries need to be properly managed through BMS. The level of management depends on the specific chemistry chosen. When improperly managed, a lithium-ion battery will reach a “thermal runaway” state easily because it has a low cell resistance and high energy storage capacity. Therefore, a key determination in evaluating lithium-based battery reliability is the ability of its BMS to monitor and control the parameters of operation reliably and safely. Lithium-ion batteries have an average service life of up to 15 years when they operate in a controlled environment.

3.2 Typical Stationary Battery Standby Application

Battery designs are available for the following standby applications:

A. Long-duration (e.g., telecommunications) batteries are designed for applications in which the standby loads are a relatively constant low current. These batteries generally are required to run from 4 to 12 hours of constant discharge current load during emergencies.

B. Short-duration (e.g., high rate or uninterruptible power supply [UPS]) batteries are designed to supply large amounts of power for a relatively short period of time. In practice, 5-15 minutes is the most common backup time for large stationary UPS systems. Five minutes is enough time to start up and switch to generator power.

C. General purpose (e.g., switchgear and control) batteries are similar to long-duration batteries, but have additional design features to accommodate various load requirements within a duty cycle, including both short-duration, high-rate discharges and low current loads for long-duration (typically several hours).

3.3 Failure Modes and Battery Testing

3.3.1 General

Normal wear-out or aging mechanisms are part of normal operation. The aging of batteries can be split into two categories: calendar aging and cycling aging. The aging mechanisms in each category are fundamentally different. The overall aging of a battery in an application will be a combination of the two categories and will depend on duty cycle and other operating conditions. Aging eventually involves the reduction of available capacity. For lead-acid batteries, aging proceeds linearly to 80% of rated capacity and then accelerates. Thus, an 80% value is often called the “knee point” of its aging curve. Operating beyond the knee point significantly increases the risk of a battery failing to power critical load during an emergency. For nickel-cadmium battery, the knee point is typically 70% of rated capacity. Lithium-ion batteries typically have 60%-70% of rated capacity as knee points.

Calendar aging is mainly influenced by the design, and driven by temperature, operating voltage, and floating charging conditions.

Cycling aging is mainly influenced by the design, and driven by frequency, depth of discharge, and the charging rate. Since stationary batteries are typically in float applications, cycle aging data is not often provided. A battery with a good design can handle a certain amount of cycles and that is dependent on the depth of discharge (DOD). The deeper the discharge, the fewer cycles a battery can handle. For example, a VRLA battery for stationary standby applications from a reputable OEM can handle 100 cycles at 80% DOD, 190 cycles at 50% DOD, and 500 cycles at 20% DOD.

3.3.2 Battery Aging Due to Excessive Temperature

The design life of a battery is typically based on the electrolyte temperature of 77°F (25°C) in North America and 68°F (20°C) in other parts of the world. Continuous operation of lead-acid batteries at elevated temperature will reduce the life of a lead-acid battery by approximately 50% for every increase of 15°F (8.3°C). For nickel-cadmium batteries, life is reduced by 50% for every increase of 54°F (34°C) above 77°F (25°C). Like lead-acid batteries, lithium-ion batteries lose significant life if operated at high temperatures for prolonged periods (a half-life for every 15°F (8.3°C) as a common rule of thumb for most lithium-ion chemistries.

In addition, when battery cells/units experience large differential temperature between them (such as more than 3°C for lead-acid and 5°C for nickel-cadmium batteries) due to limited spacing between battery units/cells, uneven aging rate between cells/units can occur which potentially can cause some cells operate in overvoltage float charging leading to accelerated aging rate.

3.3.3 Flooded Lead-Acid Batteries: Major Failure Modes

3.3.3.1 Sulfating

Sulfating on the plates of the cell occurs due to undercharging. Undercharging occurs whenever the current passing through the cell is insufficient to offset self-discharge. For batteries in float service, this corresponds to low float voltage. This also can happen to spare cells stored for extended periods with no or insufficient charge.

Sulfated batteries are basically partially discharged/recharged batteries and therefore have reduced capability or performance. If allowed to remain in a partially recharged condition for an extended period, sulfated batteries may suffer irreversible damage, requiring replacement. If recognized in its early stages, sulfate can be removed by boosting or equalizing the affected cells.

(a) Early stage (b) Middle stage (C) Late stage

Fig. 3.3.3.1. Sulfation growth at different stages observed through visual inspection

3.3.3.2 Sediment (Shedding)

It is natural to see sediment in a flooded lead-acid cell. On a new cell this sediment is normally no more than a fine dusting across the bottom. The primary causes of excessive sediment accumulation are undercharging, overcharging, cycling, and high cell temperatures.

The battery manufacturer designs the cell to allow space at the bottom of the jar for the accumulation of material. If the sediment accumulation becomes so high that the sediment space is entirely filled, then the sediment may reach a point where it touches the bottom of the plates in the cell and causes a cell short. Once shorting between positive and negative plates is verified by voltage measurements, the cell should be replaced.

(a) Normal (b) Excessive

Fig. 3.3.3.2. Normal and excessive sediment observed at visual inspection

3.3.3.3 Positive Plate Growth

Positive plate growth is a normal process occurring during the service life of a flooded lead-acid battery. The rate of positive plate growth can be accelerated by excessive cycling, overcharging, undercharging, or high temperature operation. Examine the positive plates for signs of excessive growth, warping, cracking, or other abnormalities, and consider replacement, as necessary.

3.3.3.4 Electrolyte Level

The electrolyte should always be maintained between the maximum and minimum level lines. The electrolyte level should never be allowed to drop to a point that can expose the plate material to air. Only water that meets manufacturer specifications (e.g., de-ionized or distilled) should be added to the electrolyte.

Fig. 3.3.3.4. Severely low electrolyte observed at visual inspection

Table 3.3.3.4. Visual Indications and Likely Causes for Flooded Lead-Acid Batteries

Test	*Visual Indication*	*Failure Mode*
Jar Internal	An excessive amount of shiny crystals on the plates, which indicates sulphation	Undercharging
	Excessive gassing	Overcharging (check the float voltage)
	An accumulation of spongy lead material on the top and sides of negative plates	Overcharging
	Grid cracking or plate expansion	Aging
	Excessive sediment or shedding at the bottom of jar	Aging
Jar External	Split or bent post seals	Internal corrosion
	Post corrosion	Indicates the electrolyte is reacting with the lead to corrode the post, which is generally due to poor design and/assembly
	Damaged or missing flame arrestor caps	Flame arrestor caps are in place to prevent the hydrogen inside the batteries from igniting. Damaged flame arrestor needs to be repaired or replaced by following proper procedure.

3.3.4 VRLA Batteries: Major Failure Modes

3.3.4.1 Dry-Out

The recombination process in a VRLA battery is self-regulating and can result in minimal loss of water from the electrolyte. Other processes also can contribute to water loss:

- Normal corrosion of the battery plate
- Periodic venting of gases due to battery overcharging
- Evaporation of water vapor through the seals, pressure-relief valve, and battery case

If the electrolyte loses too much water, battery capacity is reduced. Excessive water loss also can create large voids in the electrolyte, increasing the battery's internal resistance and possibly leading to thermal runaway. Thermal runaway can generate enough heat to rupture the battery case and, in extreme cases, result in an explosion.

3.3.4.2 Float-Voltage Variation and High AC Ripple Current in the DC Circuit

VRLA batteries are sensitive to float-voltage variations and excessive ripple current. If the float voltage is too high, the rate of internal gas generation will exceed the cell's recombination ability. Excess gases are vented through the pressure-relief valve and will lead to dry-out.

3.3.4.3 High Temperature and Thermal Runaway

High battery temperatures require more current to maintain float voltage. High currents increase heat generation, which in turn results in even higher currents. This cycle, often called VRLA thermal runway, can lead to excessive hydrogen gas release creating explosion hazards potential.

3.3.5 Lithium-Ion Batteries: Major Failure Modes

3.3.5.1 Over-Discharge

Over-discharge of a lithium-ion battery occurs when a cell voltage falls below a critical minimum, which then allows copper from the negative foil to dissolve into the electrolyte. Upon recharge, the copper comes out of solution to form micro-shorts, rending the cell inoperable.

3.3.5.2 Overcharge

Charge current is generally controlled by the battery management system, but control failures or improper system setup can result in excessive charging current and cell damage (i.e., overcharging). Moderate level of overcharging typically results in more rapid aging while prolonged overcharging can cause lithium-ion battery cell to accumulate in the form of dendrites at the surface of an intercalation negative electrode leading to internal cell short circuits.

3.3.5.3 Overvoltage

Overvoltage means charging the battery at the voltage level above the design limit. Overvoltage charging, while is normally controlled and prevented by the BMS, can lead to oxygen evolution from the positive, decomposition of the electrolyte and catastrophic failure including thermal runaway. Overvoltage charging is generally caused by BMS control failure or improper system setup.

3.3.5.4 Electronic Failures

Lithium-ion batteries are normally equipped with BMS, including electronic components at cell/module/pack level and string level. Electronic failure is a common failure mechanism for BMS. Failure of an electronic component generally results in battery string being taken offline until problems are solved in order to prevent potential catastrophic thermal runaway event, so it is no longer available to support the load. For critical load that needs high availability of battery system such as UPS batteries for critical data centers, use N+1 battery string system is a common practice.

3.3.5.5 Thermal Runaway

When a lithium-ion cell is exposed to serious amount of heat from external source or from internal short circuits, it can become unstable and its internal material can react uncontrollably initiating a process of thermal runaway. The onset temperature of this process varies by design but is generally in excessive of 100°C. This process often leads to expulsion of hot gasses and fire in a cell. The situation is made catastrophically worse if cell-to-cell propagation of an individual cell thermal runaway is not controlled in the module and battery system design. Refer to Data Sheet 5-33, *Lithium-Ion Battery Energy Storage System*s, for more information on lithium-ion battery thermal runaway.

3.3.5.6 Lithium-Ion Battery Aging

Lithium-ion batteries undergo irreversible capacity loss due to aging, which depends on temperature, average state of charge and cycling. For batteries that spend most of their time on float charge, the float voltage, operating temperature and aging of electronics will affect the calendar life. According to publications, most lithium-ion batteries such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (LNMC) and lithium manganese oxide (LMO) have about 10-13 years of floating life in a controlled environment. Lithium titanium oxide (LTO) batteries claim to have about 20 years' floating life.

3.3.6 Sodium Metal Chloride (SMC) Battery

The SMC battery pack is equipped with internal electric heaters, designed to achieve and maintain an internal working temperature between 509°F (265°C) and 662°F (350°C). The thermal insulation of the battery pack is such that with an internal temperature of 509°F (265°C), the surface temperature of the enclosure is just 50-59°F (10-15°C) above the environment.

One unique characteristic of SMC batteries is their behavior at full charge. Once fully charged, the internal DC/DC charging is switched off. In this condition, the battery float current is only used to power the BMS electronics and heating elements to maintain normal temperature. In other words, the battery behaves like a load. Hence, float current does not provide any meaningful indication of the battery system. In addition, SMC batteries do not provide filtering for the load, do not require a specific float voltage, and do not require equalization as long as the normal internal temperature is maintained.

3.3.6.1 Extended Power Outage

In the event of an external power loss, the battery is operative as long as the internal operational temperature is maintained. The heating elements utilize battery energy to maintain internal temperature. After several tens of hours, the temperature starts to decrease, eventually cooling to ambient temperature and causing the battery to solidify.

As soon as the battery is reconnected to a powered DC charger, the battery reheats to the minimum temperature before it recharges. This recovery process takes more than 12 hours to reach full capacity.

3.3.6.2 Failure Mechanisms

The major failure mechanisms of SMC batteries include:

1. Electrolyte cracking and dendrite formation:

Cracks in the beta-alumina solid electrolyte caused by aging or mechanical stress can promote the growth of metallic dendrites. These dendrites may penetrate separators and distort electric fields, potentially leading to an internal short circuit. A reaction between the anodic active material and the cathodic electrolyte will likely occur. This reaction converts liquid to chemically stable solids (table salt and aluminum). Aluminum is electrically conductive. Hence, this fault would cause the cell to have a similar impedance value of an operating cell but cause the battery pack to have an overall voltage of approximately 2.58V lower, per failed cell.

2. Operational failures such as overcharge/over-discharge and overheating:

Overcharge may result in electrolyte decomposition or generation of chlorine gas. These cells are engineered to withstand a certain degree of overcharge and are designed to fail safely before any chlorine gas is released. The Battery Management System (BMS) is installed to optimize charging voltage and current, thereby minimizing the risks of overcharge and over-discharge. It also helps prevent abuse-related risks and regulates the operational temperature to ensure reliable and optimum performance.

3. Cell seal leakage:

Laser welded hermetic seals are employed in cell manufacturing to ensure structural integrity and prevent leakage. Seal fatigue due to excessive thermal cycling and vibration is considered unlikely. In the rare event that the outer seam is compromised, a minimum amount of liquid sodium may escape and react with atmospheric oxygen, forming inert solid sodium oxide. If the inner seam fails, liquid sodium tetra-chloroaluminate may leak, potentially producing a small amount of white smoke (primarily hydrochloric acid vapor), with only limited impact on the battery's overall integrity.

4. Aging

SMC batteries age differently than traditional electrochemical batteries from thermal and cycle perspectives. Over time, a battery's available capacity can decrease due to cell failures; and 80% of rated capacity is considered end of life, because most specifications indicate 125% of needed capacity. Due to its unique construction features, the available capacity is proportional to the state of charge reported by the BMS. The open-circuit voltage of an aged battery has a nearly linear relationship with its available capacity, which is monitored in real time during standby.

Capacity testing ensures that the designed load could be supported by the battery system, including the BMS, modules and DC bus distribution. Hence, the recommended capacity testing is a functional test in principle.

3.4 Inspection, Testing, and Maintenance

The majority of failure modes mentioned above can be detected through inspection, testing, and maintenance activity or continuous online monitoring by recognizing detriment factors and deficiency indication. Table 3.4 lists the recommended battery tests and the failure mode each test is capable of detecting.

Table 3.4. Tests and Failure Modes for Lead-Acid and Nickel-Cadmium Batteries

Test	*Comment*	*Failure Mode*
Electrolyte levels	Exposure of battery plates above the electrolyte level can lead to rapid cell failure and destruction. Electrolyte leaks can cause a battery short circuit.	Dry-out, low level, or overfill. Rate of change in the electrolyte level can be used to identify potential need for replacement of a cell.
Individual Cell voltages	Operation of batteries outside the manufacturer's range may lead to loss of capacity, sulfation, accelerated grid corrosion, and reduction of life expectancy.	Low-voltage cells: A cell voltage consistently below normal float condition and not caused by elevated temperature of the cells indicates that may require cell replacement. High voltage cells: Individual cells may exhibit a high voltage shortly after installation and should come into line with the others as they lose excess water and approach fully recombinant state. Prolonged operation above the cell's high voltage limit can has a detriment effect such as thermal runaway.
Ripple	Ripple is the AC component of a system's charging voltage imposed on the DC bus. A high ripple component can cause battery to cycle at the ripple frequency and result in heating, reduced life expectancy, possible thermal runaway, and battery gassing, and dry-out or excessive water topping. Many UPS systems in the market today have eliminated capacitors as a standard feature to reduce cost and footprint. This essentially introduced excessive harmful A/C ripple currents and therefore shorter life span of batteries, particularly for VRLA batteries. Flooded batteries can tolerate more ripple content than VRLA batteries because higher electrolyte volume helps cooling and improving their capability to better withstand long term ripple	Poor charger design and/or failed filtering components of the charger.
Float voltage	The correct battery float voltage at the battery terminal is critical and must be within manufacturer's recommended limits. Overvoltage will cause excessive gassing and drying of the electrolyte and also will contribute to potential thermal runaway.	Wrong setting of charger output voltage
Float current	The float current of a fully charged battery will depend on design feature of the battery and its internal condition.	Zero float current: a battery or connection in the string is openExcessive float current: potentially shorted cells in battery. For lead-acid battery (vented or VRLA), a rising trend of the float current can also indicate potential thermal runaway resulting in potential excessive hydrogen emission and fire.
Internal ohmic	The measurement of internal ohmic when compared with an established baseline may provide information about battery internal condition at certain degree. It is used to identify cells that require further evaluation. Internal ohmic values are useful as a trending tool. The readings without the benefit of baseline data are of limited value.	Cell degradation, requiring further evaluation or replacement
Inter-cell connection resistance	To identify high-resistance connections leading to overheating.	High-resistance or loose connections. Without corrective action such as retorquing or cleaning the contact surface area, battery system can experience excessive voltage drop or heat damaged/melted terminal during discharge.

3.4.1 Battery Capacity Testing

Capacity testing is used to determine whether the performance of the battery is within acceptable limits, and to trend battery aging. **It is considered by the battery industry to be the only test that accurately determines the internal health of a battery.** A capacity test takes approximately one full day to run, then two to three days to fully recharge the batteries.

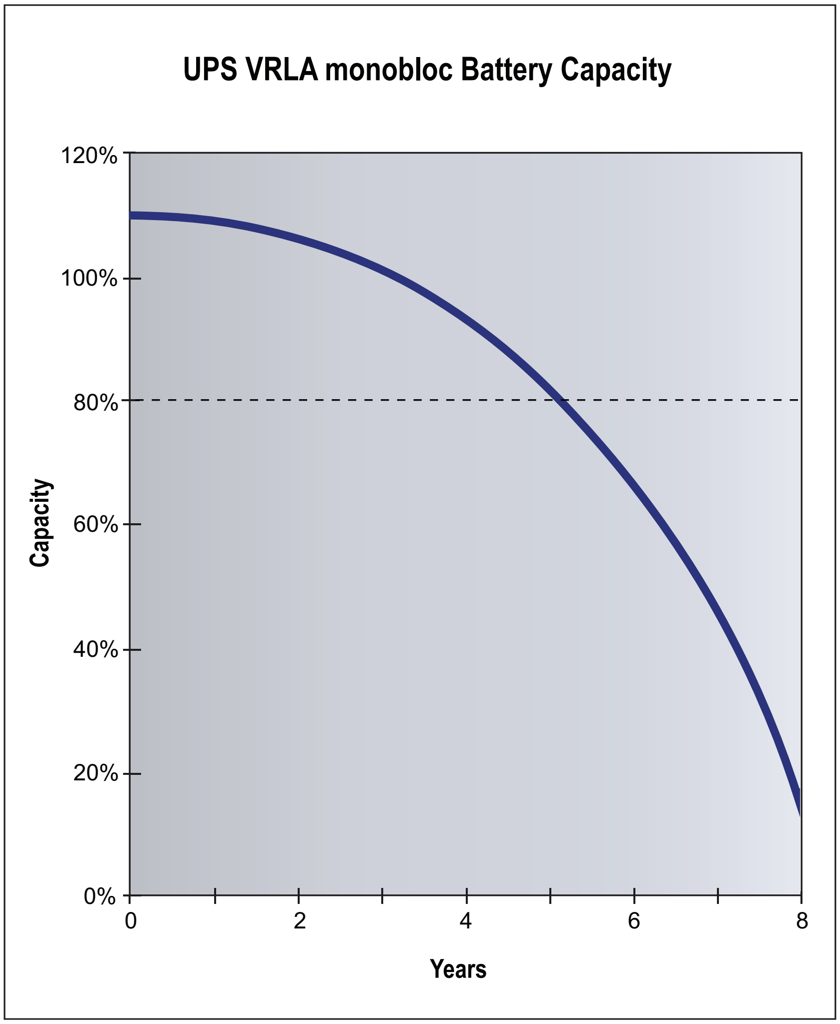

Fig. 3.4.1. An example of VRLA battery with design life of 5 years in a controlled temperature environment

It is desirable for comparison purposes that the capacity tests be similar in duration to the battery design duty cycle. Examples of typical designed run-times for different applications are as follows:

A. Data processing UPS batteries: 15 minutes

B. Industrial (process control) UPS batteries: from 30 minutes to several hours, depending on application

C. Telecommunication batteries: 4 to 12 hours

D. Switchgear batteries: more than 3 hours

When the capacity test is performed with a shorter duration, the discharge current should be determined based on the capacity table provided by the manufacturer (see Table 3.4.1 for an example) with the selected test duration.

Table 3.4.1. Example of a Battery Capacity Rating Table Provided by a Manufacturer

	Nominal Rates to 1.75 VPC Average						
Discharge time	1 Min	15 Min	30 Min	1 Hour	3 Hours	5 Hours	8 Hours
Current (amperes)	274	177	123	77	33	21	14

For example, in a substation, a battery bank is designed to operate for 8 hours as the duty cycle. A full-duration capacity test is performed with a duration of up to 8 hours. In the event a full-duration capacity test is not performed, some vendors using the actual capacity rate tables from the battery manufacturer will perform a 3-hour test at the 3-hour-rated discharge current per the manufacturer's rate table. This is acceptable only if the DC bus and intercell connectors, etc. can tolerate the higher current for 3 hours. See IEEE 1188, IEEE 450, and IEEE 1106 for more details on capacity testing.

3.4.2 Internal Ohmic Testing for Lead-Acid Batteries

Internal ohmic (resistance or conductance) measurements should not be treated as an alternative to capacity testing. Rather, they should be used as a means of prioritizing when capacity tests are needed for lead-acid batteries. Internal ohmic readings are useful as a trending tool. To use these readings effectively, accurate baseline readings should be taken after about three to six months of battery operation and be taken when the battery is at full state of charge. In addition, the following limitation of the internal ohmic readings should be understood and taken care as part of internal ohmic testing program to produce consistent and predictable trending results:

A. Each testing equipment make/model uses different techniques to measure different ohmic values. These values are difficult to correlate between types. Using the same testing equipment for baseline and future measurement should be followed to yield meaningful trending results.

B. Ohmic reading can be subject to wide variation due to many other factors such as small changes in equipment calibration, meter lead quality, temperature, placement of the meter probes on the batteries. Having a trained testing personnel are essential to consider any of these factors that might lead a trending to become invalid.

C. The effectiveness of internal ohmic measurement varies by the application. The measurements have good correlation with internal health of lead-acid batteries in short, fast discharge applications but no good correlation with long discharge applications.

3.4.3 Battery Capacity Test

Capacity testing should be carried out in accordance with industrial standards such as IEEE 1188 for full guidance, including pretesting requirements, information to record before and during testing, when to terminate the testing, and capacity calculations.

In general, two methods for capacity testing are available: rated adjusted and time adjusted.

A. Time-adjusted capacity testing

This method is used for batteries in applications with duration of one hour or more, such as switchgear/substation batteries and power generation emergency batteries. The test discharge current should be contact current or constant power load equal to the manufacturer's published rating for the selected test duration.

The system's capacity is calculated with the following method:

$$C = \frac{Ta}{Tc \times Kt} \times 100$$

EQUATION

C = % of rated capacity at 77°F (25°C)

Ta = the actual time of the test to the specified end voltage

Tc = the rated time of the test to the specified end voltage

Kt = the time-temperature correction factor due to a different temperature from 77°F (25°C) at the testing

Example: A VRLA battery is rated to deliver 105 Amps for 4 hours to 1.75Vdc as the end voltage per cell at 77°F (25°C), was discharged at 105 Amps and the system end voltage was reached at 3 hours.

$$C = \frac{3}{4} \times 100 = 75\%$$ **EQUATION**

B. Rate-adjusted capacity testing

This testing is recommended for batteries with a specification of one hour or less. Two variants of adjusting the discharge current are used for testing:

1. The test discharge current is the manufacturer's published rating multiplied by the derating factor of 80%.
2. The test discharge current is the manufacturer's published rating multiplied by the temperature correction factor, based on the initial battery temperature

The system's capacity is calculated with the following method:

$$C = \frac{Xt \times Kt}{Xc} \times 100$$ **EQUATION**

C = % of rated capacity at 77°F (25°C)

Xt = the actual discharge current for the test

Xc = the OEM published current rating for the actuarial time to the specified end voltage

Kt = the time-temperature correction factor due to different temperature from 77°F (25°C) at the testing

3.5 Online Monitoring

3.5.1 Lead-Acid and Nickel-Cadmium Batteries

Battery monitoring systems are primarily used for lead-acid batteries and are not very common for nickel-cadmium batteries. The following parameters can be monitored:

A. Voltage: cell, group of cells, partial string, and/or battery terminal voltage

B. Current: charge, and discharge current

C. AC ripple voltage and current: the AC components of the string voltage and current

D. Temperature: cell/battery and/or ambient temperatures

E. Intercell connection resistance: Intercell battery connection resistance

F. Internal ohmic: Ohmic values for each cell, or cell groups

G. Electrolyte levels for each cell (for flooded type)

H. Coup de fouet: Initial voltage drop and recovery of the battery under load

The advantage of battery monitoring systems is their ability to automatically collect, trend, analyze, and then report the results of continuously collected data. They allow automation of many maintenance activities that would otherwise have to be performed manually. These systems can provide warning for serious out-of-tolerance conditions in near real time. The limitations of battery monitoring systems include lack of information from visual inspection and capacity tests.

3.5.2 Lithium-Ion Batteries Battery Management System (BMS)

Since lithium-ion battery systems are extremely sensitive to charging regimes, all include BMS. The BMS of a lithium-ion battery acts as a built-in monitoring system in addition to its control functions of battery charging and discharging operation, and provides actions and alarms required. Lithium-ion battery modules/packs with individual BMS that are placed in parallel typically have a built-in method of establishing a primary BMS (which includes failover provisions to another BMS if that one fails) when the BMSs are wired together through a communications bus, or they may serially report up to a primary BMS or EMS (energy management system). Common monitoring parameters of the BMS include the following:

- Cell voltage
- Cell temperature
- Batter voltage at string/rack terminal
- String current
- Ambient temperature
- BMS system electronic/sensor and communication channel failure
- Status of ancillary systems such as the thermal management system safety devices (such as contactors, fuses, or circuit breakers) and the charger operation.

The following is a list of typical functions built into the BMS to automatically isolate a battery system to proactively protect it from failure when the operating limits of the battery system are exceeded:

- Cell overvoltage
- Cell undervoltage
- Rack overvoltage
- Rack undervoltage
- Excessive voltage imbalance between cells
- Overtemperature
- Under temperature
- Temperature imbalance between cells
- Charging overcurrent
- Discharge overcurrent

For standby applications, it is not uncommon to have battery BMS system alarm only at the presence of electronic or sensor failures for manual shutdown.

3.5.3 Sodium Metal Chloride Battery Management System

An integrated battery management system (BMS) is essential for the safe and reliable operation of SMC batteries. The BMS generally monitors key parameters such as temperature, voltage, current and insulation at either module or string level. The main functions of the BMS based on some manufacturers' inputs are:

- **Battery thermal management:** The battery needs to be warm before charging or discharging. The thermal management of the BMS automatically initiates the heating process as soon as the battery is powered.
- **Battery thermal protection:** Prevents overheating by disconnecting its discharge path and cutting power to the battery heaters if the internal temperature exceeds a critical threshold such as 350˚C
- **Battery charge regulation:** Regulates the charging parameters (voltage and current) to optimize charging performance.
- **Battery power/energy measurement:** The BMS continuously calculates the battery state of charge (SOC) to ensure a reliable and safe operation.
- **Battery operating condition monitoring:** Evaluates various conditions such as string voltage unbalance, under/overvoltage, overcurrent, under/over battery temperature, under/over ambient temperature, heater fuse and insulation levels. These checks ensure a reliable and safe operation for both battery and heating elements.
- **Self-diagnostics:** Performs internal health checks to identify failure in its components, including communication electronics, temperature/voltage/current sensors, and internal protection components.

3.6 Routine Spare Battery Cells

Ensure the viability of routine spares by storing and maintaining them in accordance with the original equipment manufacturer's instructions. Refer to Data Sheet 9-0, *Asset Integrity*, for additional guidance. The following are common routine spares for battery strings:

- Battery cells

Maintaining routine spare battery cells is a common practice, particularly in UPS industry which commonly spares ~10% of total battery cells. It is recommended to buy routine spare battery cells up front and keep them on float on a separate charger so that they are aging at approximately the same rate as the active batteries. The benefit of this practice is that the routine spare batteries will have similar internal impedance as the active batteries when it becomes necessary to replace an individual cell and they can float relatively well together, i.e. they will have similar floating voltage to avoid potential cell float undervoltage and overvoltage.

The routine spare battery cells should be maintained in the same way as the active batteries.

3.7 Loss History

Table 3.7 shows FM client losses involving batteries over a recent 20-year period. All loss amounts have been indexed to 2019 values.

The statistical analysis per losses with known negative contributing factors provided the following conclusions:

- 23% of losses due to inherited design issue in DC systems. Note: these losses are exclusively from power generation occupancy.
- 20% of losses due to lack of adequate maintenance.
- 17% of losses due to aging.
- 7% of losses due to excessive battery room temperature.
- 6% of losses due to loosen connections at battery system.
- 27% of losses due to miscellaneous issues such as manufacturing defects, human errors, external cable failures, inverter failure, etc.

Table 3.7. FM Battery-Related Losses by Peril, 2000-2019

Peril	*# of Losses*	*Total Gross, US$ millions*
Electrical Breakdown	7	35.29
Explosion	2	0.60
Fire	19	92.76
Pressure Equipment Breakdown	1	21.04
Service Interruption	3	6.60
Mechanical Breakdown	7	107.3

4.0 REFERENCES

4.1 FM

Data Sheet 1-2, *Earthquakes*
Data Sheet 1-40, *Flood*
Data Sheet 5-33, *Lithium-Ion Battery Energy Storage Systems*
Data Sheet 8-1, *Commodity Classification*

4.2 Other

Institute of Electrical and Electronic Engineers (IEEE):

- IEEE 450, *Recommended Practice for Maintenance, Testing and Replacement of Vented Lead-Acid Batteries for Stationary Applications*.
- IEEE 485, *Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications*.
- IEEE 1106, *Recommended Practice for Installation, Maintenance, Testing and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications*.
- IEEE 1115, *Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications*.

- IEEE 1188, *Recommended Practice for Maintenance, Testing and Replacement of Valve-Regulated Lead-Acid Batteries for Stationary Applications*.

APPENDIX A GLOSSARY OF TERMS

Battery cells: The basic electrochemical building block of a battery, characterized by a positive electrode, a negative electrode, and electrolyte. This terminology is used interchangeably with battery unit in this document.

Floating operation: Operation of a battery system in which the battery spends most of the time on float charge with infrequent discharge.

Rated capacity: The capacity assigned to a battery system by its manufacturer for a given discharge rate and time at a specified electrolyte temperature to a given end of discharge voltage.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

October 2025. Interim revision. Major changes include the following:

A. Clarified the scope with respect to lithium-ion batteries in emergencies, UPS and switchgear applications.

B. Revised Section 2.3.7 to further clarify when on-line continuous condition monitoring system for lead-acid/nickel-cadmium batteries is needed.

C. Revised li-ion battery ITM guidance in Section 2.5.4:

1. Added recommendation to perform annual BMS monitoring data review to identify any potential early deficiencies.

2. Changed the battery capacity testing recommendation from every 5 years to every 3 years.

D. Added loss prevention guidance for sodium metal chloride (SMC) batteries for switchgear applications in Section 2.5.5

E. Added support material on capacity testing and sodium metal chloride batteries in Sections 3.3.6 and 3.4.3.

April 2021. This is the first publication of this document.