THE IMPLICATIONS OF USING ALTERNATIVE CHEMISTRIES IN TRADITIONAL STATIONARY BATTERY APPLICATIONS

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Abstract
This paper examines the implications of using alternative battery chemistries in stationary applications; specifically, those which traditionally use lead-acid or nickel-cadmium batteries. In it we examine safety, reliability, maintenance, and regulatory impacts involved as well as size, weight, and cost comparison factors. For comparative purposes we choose a 20-year design life 200-AH 60-cell VLA battery installed in a temperature-controlled environment as the standard, with an assigned factor of 1.0, and we compare the other chemistries to this standard. Alternative chemistries considered include lithium-ion, sodium-ion, and sodium metal chloride. We also consider compact/sealed versions of the traditional chemistries to highlight advances aimed at addressing some of their main drawbacks. By comparing old and new battery technologies we seek to answer the following questions. Do the new higher energy density chemistries offer meaningful benefits in stationary applications, and if so, do the benefits justify the costs?

Introduction
Lead-acid (LA) and nickel cadmium (NiCd) battery systems provide control and reserve power for modern life as we know it. These systems provide breaker tripping, closing and control power for switchgear, power for automated controls, power for field flashing of generators, power for emergency lube oil and seal oil pumps and other critical motors, reserve power for uninterruptible power systems (UPS), control power for many industrial processes, and operating power for critical communication systems. In short, these battery systems make modern life possible, and they surround us.

A LA or NiCd stationary/standby battery is a collection of cells connected in series that when properly designed, installed, and maintained will never fail to support the connected load. It is a highly reliable source of standby power. It is available when no other power source is available. It is always replaced while still capable of supporting the connected load, because the cost of a stationary battery failing to support its connected load under worst case conditions can easily reach into millions of dollars.

A typical stationary/standby DC system consists of a battery, rectifier/charger, and load connected in parallel. In this arrangement the battery is maintained at a constant voltage (float voltage) and only discharges during an input power failure to the rectifier/charger, a failure of the rectifier/charger, or when the load exceeds the capability of the rectifier/charger such as when tripping or closing circuit breakers in switchgear.
The battery is held at or very near 100% State-Of-Charge (SOC) in an on-line standby mode waiting for an unplanned discharge. See figure 1.

[1] *The authors' views and opinions expressed in this article are his own and do not represent or reflect Honeywell's views and opinions.*

Depending upon system design, there may or may not be an overcurrent protection device between the battery and DC bus, but there are normally no contactors or semiconductors between the battery and the load.

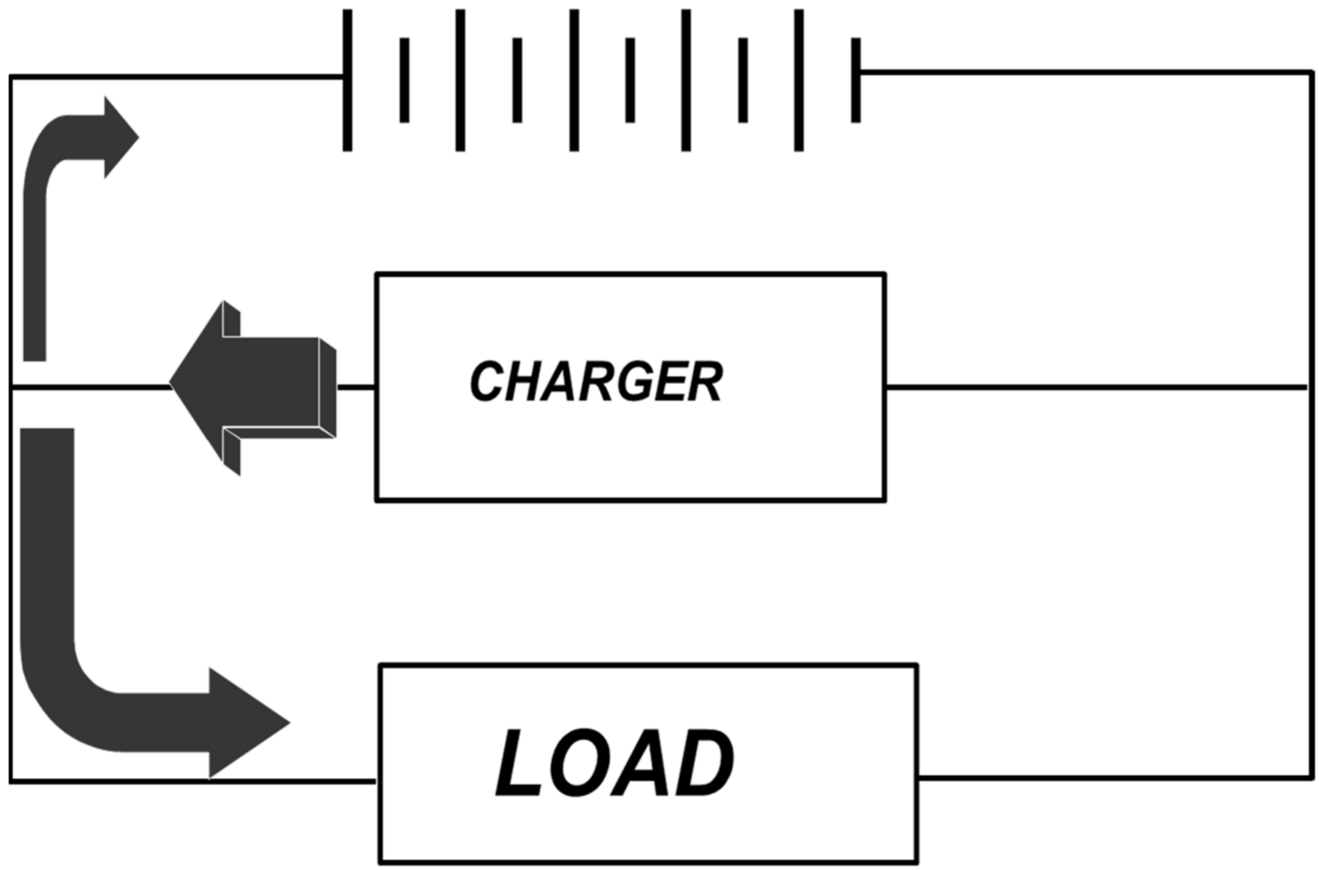

Figure 1 Simplified DC System

Due to the straightforward design of stationary/standby DC systems it may seem that substituting an alternative chemistry battery in these applications is similarly straightforward, but is it? The remainder of this paper will help answer that question, but here's a quick spoiler. It's not as simple as it seems, and the details always matter.

General Safety

LA and NiCd stationary/standby batteries are mature technologies that have been in commercial use for well over a hundred years. The safety hazards and mitigation requirements are well known and documented within the industry. A review of these hazards and mitigation strategies can be found in the 2021 Battcon paper entitled Reducing the Hazards of Stationary Battery Systems Through Intelligent Design.

Fire Safety

Thermal runaway is a hazard that most everyone has seen on the news thanks to fires caused by lithium-ion batteries (LIBs) in portable electronic devices and electric vehicles (EV), as well as in stationary battery energy storage systems (BESS). Thermal runaway is defined by National Fire Prevention Association (NFPA) standard 855-2023 as self-heating of an electrochemical system in an uncontrollable fashion. This hazard has been misapplied to LA and NiCd batteries. LA and NiCd are aqueous based chemistries and do not contain enough energy, of themselves, to support thermal runaway. That's not to say that LA and NiCd chemistries can't have a thermal event, because they can, but it's a slow and stoppable process, and the energy is supplied by the battery charger, not the battery. Additionally, a thermal event in an LA or NiCd battery usually doesn't result in a fire. Thermal Walkaway is the term used to differentiate the thermal hazard of LA and NiCd batteries from LIBs.

Thermal walkaway is a slow heating process driven by an external current source (charger) and caused by abuse, neglect or internal cell failures that result in overheating and increased gas production in a LA, NiCd, or other aqueous chemistry battery which can be controlled by removal of the charging source or reduction of the charging current.

Thermal walkaway and thermal runaway are vastly different thermal events. Thermal walkaway is a slow process that can be easily prevented by use of a temperature compensating charger with a remote temperature probe placed on the battery. It can also be easily detected by either automatic monitoring or maintenance personnel and once detected it can be easily arrested or stopped by reducing charging current or removing the charging source. Valve Regulated Lead Acid (VRLA) batteries ≥20kWh require a method of preventing thermal walkaway. Vented Lead Acid (VLA) and NiCd batteries do not have this requirement.

Thermal runaway occurs rapidly and once initiated, it cannot be stopped. The self-heating reaction cycle begins when the internal temperature exceeds the threshold temperature for the specific chemistry and cell design. The resulting reactions produce significant heat and copious quantities of toxic, flammable, and potentially explosive gases in a short amount of time. The internal threshold temperature for the series of reactions leading up to thermal runaway in LIBs is typically between 100° and 120°C.

Thermal runaway can be initiated by an external heat source, internal cell fault/short circuit, overcharging, charging after an overdischarge, charging outside the allowable temperature range, external short circuit, or physical damage. The BMS should protect the battery from all these conditions except an external heat source, intercell cell fault/short circuit, and physical damage. Additionally, the electrolytes used in LIBs available at this time are flammable with low autoignition temperatures and may ignite upon rupture of the cell. The overarching safety issues with LIBs are fire and copious quantities of flammable/explosive/toxic gases resulting from thermal runaway.

Thermal runaway is a major safety consideration with LIBs and sodium-ion batteries. Once the size of a stationary LIB or sodium-ion battery reaches 20kWh, the safety requirements of NFPA 855 and the International Fire Code (IFC) essentially require the batteries to be placed outside in a container that meets the deflagration and explosion-resistant requirements specified in NFPA 68 and 69. The safety requirements for LIBs and sodium-ion batteries make them unattractive and costly for many stationary battery applications. The paper PCIC 2024-59, Replacing Lead-Acid and Nickel-Cadmium Stationary Batteries With Lithium-Ion – It's Not A Simple Swap, presented at the 2024 IEEE PCIC conference contains a detailed listing of the safety requirements for LIBs. The paper Storing Lithium Batteries – The Safety Needs and Regulatory Requirements presented at the 2023 Battcon discusses the storage requirements for LIBs.

While often regarded as safer than LIBs, sodium-ion batteries can also go into thermal runaway, and this can be a limiting factor in many stationary applications. Additionally, at the time of this writing, there are no manufacturers offering sodium-ion products compatible with 125VDC systems for the stationary battery market.

Sodium Metal Chloride (SMC) batteries operate at approximately 250°-350°C but pose no thermal runaway or thermal walkaway hazard. SMC cells are mounted in insulated stainless-steel modules and although the internal temperature is quite high the external module temperature is only a few degrees above ambient.

Transportation Safety

LA and NiCd batteries can be shipped as Hazard Class 8 hazmat shipment or when shipped by truck or rail as exempt (non-hazmat shipment) when in compliance with 49 CFR part 173.159, paragraph E.

LIB and sodium-ion battery shipments are always Hazard Class 9 hazmat shipments. The SOC of these batteries should be ≤30% for shipment and storage. There are no regulatory requirements currently requiring LIBs to be at ≤30% SOC for ground shipment. An SOC of ≤30% is required for air cargo shipments.

SMC batteries shipments are always Hazard Class 4.3 hazmat shipments. Additionally, these batteries must be discharged (SOC ~0%) and cold for shipment. SMC batteries are shelf stable in this state and do not require periodic recharging to maintain State of Health (SOH), which is a benefit compared to all the other chemistries compared.

Reliability

VLA and NiCd batteries are extremely reliable when properly designed, installed, and maintained. VRLA batteries have more failure mechanisms than VLA or NiCd and thus are not as reliable. LA and NiCd batteries do not require any sort of management system for safe and reliable operation. Typically, the only thing between a LA or NiCd battery and the load is the conductor and overcurrent protection device.

The reliability of VLA batteries is high enough that they are used in the Class 1E safety system of nuclear power plants. The IEEE 308 definition of Class 1E is: The safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal or that are otherwise essential in preventing significant release of radioactive material to the environment.

The alternative chemistries considered in this paper, LIB, Sodium-ion, and SMC all require Battery Management System (BMS) for safe operation. The BMS must, at a minimum, prevent cell overcharge, cell over discharge, cell and battery overtemperature, and cell and battery under temperature operation, and protect the battery from damage due to an external short circuit. The BMS normally performs active cell SOC balancing. This is required since none of these chemistries can be overcharged without damage and potential thermal runaway, (SMC batteries can be damaged by overcharge but will not go into thermal runaway). VLA, VRLA, and NiCd batteries do not require active cell SOC balancing as this can be achieved by equalize charging the entire battery. The energy from any overcharge is consumed by the water via electrolysis. In SMC batteries the BMS also controls the heater circuits required to maintain proper operating temperature.

Protecting the alternative chemistries requires computer controlled disconnect devices to isolate a string of cells, modules, or the entire battery, and semiconductor switches for cell balancing. These disconnect devices will likely be a combination of semi-conductors, contactors, and fuses or circuit breakers. The presence of contactors and/or semiconductors in the power path reduces the reliability of the battery system. These devices are not present in LA and NiCd stationary/standby systems.

The decision-making process of keeping the alternative chemistries in a safe operating state typically requires a microprocessor or microcomputer. The alternative chemistry battery will become inoperable or unsafe should either the controller or isolation/interrupting device(s) fail. These devices are not present in LA and NiCd stationary/standby systems.

Additionally, the primary function of the BMS is the safety of the alternative chemistry battery while protection of the load is a secondary consideration, if considered at all. The paper Practical Results From Short Circuit

Testing Of Lithium Batteries In Telecom Circuits by Murray Wyma presented at the 2024 Battcon showed that some BMS's are so good at protecting the cells they manage that they would not allow the battery to provide enough current to trip a small distribution circuit breaker downstream in the DC system. This allowed a small fault to shut down the entire DC system.

The very devices needed to make alternative chemistries safe also reduce the reliability of the battery system. Adding parallel battery strings can increase the system reliability, but how many redundant batteries are necessary? This question has prompted much discussion in the various IEEE ESSB working groups. The general consensus is that at least one redundant battery is needed, (N+1 redundancy), but is that sufficient? That question has yet to be answered. For the purposes of this paper one redundant battery string is enough. This means that an additional parallel string in excess of the number of strings used to reach the comparison capacity (200Ah) is required for the alternative chemistries considered in this paper.

Battery Chargers/Rectifiers

The battery charger/rectifier commonly used with LA or NiCd batteries may not work well, or at all, with alternative chemistry batteries. Alternative chemistry batteries can tolerate undercharge but not overcharge, and their internal losses are significantly less than LA or NiCd batteries. This can make float charging very problematic. Some chargers are designed to always operate in parallel with a LA or NiCd battery and have poor regulation qualities and/or high output ripple voltage without a battery connected. The battery provides output filtering of the charger and supplies transient or short duration loads. Such chargers are incompatible with the alternative chemistries in this paper.

The charger/rectifier should be well filtered and very responsive to load changes. In the case of LIBs, it is desirable that the charger be controlled by the BMS, but the BMS will protect the battery from the charger without communications. Many newer microprocessor-controlled chargers can interface with a BMS.

SMC batteries can tolerate a wide range of input voltage as the BMS uses an internal DC-DC converter to charge the battery. SMC batteries do not require BMS control or interface with the charger/rectifier, but the charger must be well filtered and responsive to load changes. The charger/rectifier should be thoroughly evaluated and approved by the battery manufacturer to ensure compatibility with the selected alternative chemistry battery.

Maintenance & Testing

The alternative chemistry batteries are not maintenance free even though some manufacturers claim so. There is normally no cell level maintenance with any of the alternative chemistry batteries considered in this paper. However, the BMS requires maintenance or parts replacement. The alternative chemistry cells will typically outlast the BMS. IEEE P2962 Draft Recommended Practice for Installation, Operation, Maintenance, Testing, and Replacement of Lithium-ion Batteries for Stationary Applications has just finished balloting and will soon be in the comment resolution phase. The maintenance requirements in P2962 are essentially annual routines and downloading/analyzing BMS data. Currently there are no companion documents for sodium-ion or SMC batteries.

Capacity and/or functional discharge testing is required, and may be more important, for alternative chemistries than for lead-acid and NiCd batteries as the BMS may become uncoordinated with the actual condition of the battery due to the very infrequent discharges experienced in stationary applications. In stationary/standby service the battery rarely discharges. Infrequent discharges may reduce the BMS's ability to accurately determine SOH and SOC, thus increasing the importance of capacity or functional discharge testing.

VLA batteries should be maintained in accordance with IEEE 450 and VRLA batteries should be maintained in accordance with IEEE 1188. NiCd batteries should be maintained in accordance with IEEE 1106. Following these maintenance, testing, and replacement standards ensure that the battery will always support the connected load.

Sizing Alternative Chemistry Batteries

Presently, there are no industry standards for sizing alternative chemistry batteries for the complex load profiles common in most stationary applications. Sizing batteries for simple load profiles used with UPS or telecom applications is straightforward, and guidance is provided in the latest edition (2022) of IEEE 1184. However, sizing batteries for complex load profile such as those in switchgear and power plant operation is not as simple. IEEE P3163 Draft Recommended Practice for Sizing Lithium Batteries for Stationary Applications is in development.

Alternative chemistry battery manufacturers normally have proprietary software for their products that are used for sizing. In the absence of industry standard guidance, the user must rely on the chosen alternative chemistry battery manufacturer to size the battery for their application without independent verification.

LA and NiCd batteries each have specific industry standards for sizing:

1. IEEE 485 IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications
2. IEEE 1115 Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications

LA, NiCd, and LIB batteries can typically provide very high currents. SMC batteries are typically better suited to medium-to-long-rate discharge currents. This doesn't mean that SMC batteries can't or shouldn't be used in high current applications, as they can be, but the costs may be higher than with other chemistries. This is also true for long duration VLA cell designs.

Cost and Physical Size Factors

This paper began with the premise of replacing an existing 125 Vdc 200 Ah lead-acid battery with a comparable alternative chemistry battery. As previously discussed in the Reliability section, the alternative chemistry must have an additional parallel battery for reliability (N+1 redundancy).

Figure 2 shows the cost and size factors for 125 Vdc 200 Ah VLA, VRLA, NiCd, Compact NiCd, Lithium Titanate (LTO), Super LFP (lithium-iron-phosphate), and SMC batteries. Sodium-ion batteries are not included in Figure 2 because currently there are no products designed and offered to the stationary/standby market at the comparison voltage.

Considerations were made to establish a direct comparison between the selected chemistries based on industry/manufacturer standard installation practices. Cost and dimensions for VLA and NiCd systems as shown in Figure 2 include spill containment for liquid electrolyte hazard, while the VRLA system does not have spill containment due to its classification as "non-spillable".

Similarly, the alternative chemistries included are considered based on their respective manufacturer standard installation practices; each employing their own proprietary racking, cabinets, monitoring, and interface. For comparison's sake, it can be noted that liquid electrolyte spill containment is not a typical consideration for any of the alternative chemistries. The size factors in Figure 2 are based on a typical installation of each chemistry, though other configurations exist. For example, one of the advantages of VRLA technology when compared to VLA or NiCd is the ability to mount cells horizontally in compact modules. This allows for system volume and particularly footprint to be minimized as demonstrated by the sub-unity factors shown in Figure 2. Similarly, the compact NiCd is a solution aimed at reducing the size of traditional NiCd batteries while maintaining the benefits. This is accomplished using multi-cell front terminal battery modules and relay style racking traditionally used in telecom applications. The form factor improvement addresses the drawback of higher footprint present in traditional NiCd systems without introducing the complications of an alternative chemistry and the additional componentry required.

One of the most widely touted benefits of the alternative chemistries is energy density in terms of volume and weight. The comparison below demonstrates the reality of the space saving ability of alternative chemistries systems at the scale considered. In terms of volume, the Super LFP (SLFP) system considered shows improvement over VLA, though the LTO system exceeds the base VLA system, defying the expectation.

Footprint is a common limitation in substation switchgear building design making this comparison potentially more influential to typical industry decision making. Again, in this comparison the SLFP system shows improvement over VLA, and in this case the LTO system also shows improvement, however minimal.

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	VLA	VRLA	NiCd	Compact NiCd	LTO	Super LFP	SMC
Capacity (kWh)	24.000	24.000	22.632	25.392	25.392	27.027	28.800
Length (in)	136.00	25.90	105.00	23.92	59.00	48.03	26.00
Depth (in)	21.00	16.25	24.00	25.11	44.50	20.08	24.06
Height (in)	47.49	95.22	66.30	83.94	80.80	90.94	72.91
Weight (lb)	3,015.00	2,662.00	2,535.00	1,406.80	2,270.00	1,931.58	1,450.00
Volume (in^3)	135,631.44	40,075.72	167,076.00	50,416.98	212,140.40	87,707.80	45,602.44
Volume (ft^3)	78.49	23.19	96.69	29.18	122.77	50.76	26.39
Cost Factor	1.00	1.10	1.56	2.45	5.06	5.48	2.09
Footprint Factor	1.00	0.15	0.88	0.21	0.92	0.34	0.22
Volume Factor	1.00	0.30	1.23	0.37	1.56	0.65	0.34
Weight Factor	1.00	0.88	0.84	0.47	0.75	0.64	0.48
Cell Count	60	60	92	192	576	280	400

Notes and Assumptions:

*Battery with Racking/Cabinets - Typical Cost for 200Ah System
- 1.0 Factors Based on Flooded System
- NiCd Price Includes Cost for Factory Commissioning
- Assumed No Seismic Requirements
- Assumed 125VDC, 200Ah System (or next commercially available size)
- Assumed N+1 Redundancy for SMC, LTO and LFP Systems (redundant string not considered in the capacity calculation)
- LIBs Come With Startup/Installation Req'd by Supplier"
- The cost factors for LIBs do not include the costs of fire/explosion detection/suppression.

Figure 2 Battery System Cost Factor, Space, & Weight - VLA v VRLA v NiCd v LIB v SMC

The savings of footprint space shown for the alternative chemistries are in line with the expected benefits, however, none of the alternative systems considered compare well to either the VRLA or compact NiCd solutions on volume or footprint. This shows that the energy density of alternative chemistries at this scale is less benefit over traditional technologies than perceived, particularly as manufacturers continue to innovate on their proven product lines.

Analysis of the weight factors of each system shows the expected reduction in weight for alternative chemistries over lead-acid chemistries. Here the delta between the alternative chemistries and the baseline is minimized by the need for additional components and cabinetry, showing that the improvement in energy density by weight is less dramatic than perceived.

System costs compared here are based on typical sale to customer prices using even margins across the board and typical distributor costs for each system. In this case distributor costs include a similar discount off list across all equipment manufacturers compared. Cost factor is the widest deviation of the comparisons made. It can be clearly seen that the cost of commercially available alternative chemistries for use in stationary/standby 125 Vdc systems is, at this time, significantly higher than LA and NiCd battery storage. Benefits of smaller size/weight and less frequent/involved maintenance must be balanced with budget expectations.

The authors note that at the time of this writing the number of commercially available alternative chemistries designed to work with 125 Vdc stationary/standby applications is relatively low compared to the same battery chemistries designed for other applications such as BESS and EVs. This reduces the available pool for input data, however, the systems considered are each from industry leading manufacturers. This ensures that the comparison is as even as possible in terms of system reliability.

Conclusion

Can alternative chemistries be used in stationary/standby battery systems in place of traditional LA or NiCd battery systems? Yes, they can, but it's not a straightforward battery swap.

First, the alternative chemistry battery must be sized for the worst case connected load. This usually isn't as simple as finding an alternative chemistry battery of the same amp-hour size. Second, will the selected chemistry BMS allow enough current through to trip/clear the overcurrent protective devices in the existing system? This needs to be verified before a small load fault shuts down the entire DC system. Third, is the alternative chemistry battery compatible with the existing charger/rectifier? Fourth, is N+1 redundancy sufficient? This extra battery is for redundancy, not capacity, but it will affect charger sizing. Fifth, are you willing to marry the battery manufacturer? Given the few alternative chemistry manufacturers and lack of industry standards you will likely need to rely heavily on the battery manufacturer. If details are missed, and things don't work out, parting will be expensive.

On top of the five considerations above, it is always necessary to weigh cost against benefits in any project/procurement. The most relevant benefit provided by the alternative technologies in the context considered is the reduction of footprint (volume and weight are secondary). The comparison performed shows that the obvious choices for reduced footprint are VRLA and compact NiCd. These solutions use less floor space than the alternative chemistries for a fraction of the price. They avoid the need to introduce new complications, and they retain the reliability made possible by a long history of study, use, and standardization.

All the alternative chemistries discussed in the paper have vastly superior cycle lives as compared to LA and NiCd. While this is a great attribute, it is of no use or value in traditional stationary/standby battery systems.

Lastly, the safety requirements of LIBs and sodium-ion batteries make them undesirable for most stationary/standby battery applications at this time. SMC batteries do not have the same safety risks; however, they also do not offer the reliability of the traditional chemistries due to the required BMS. While the SMC systems may be highly reliable in concept, they likely require additional training, commissioning efforts, and nuanced operation to achieve their peak reliability.

The comparison performed in this paper begs the question; is the alternative chemistry battery really an improvement, or are we simply trading one set of problems for another and spending more money in the process?

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