EXPANDING AVAILABILITY HORIZONS: NEW BATTERY TECHNOLOGIES IN INDUSTRIAL UPS SYSTEMS

Copyright Material IEEE
Paper No. PCIC-XXXX

Joe Marquardt
Electrical STP-A
ExxonMobil UIS
27777 Springwoods Village
Parkway Spring TX 77389
USA
Joe.marquardt@exxonmobil.com

Pierre Queyroi
VP Technology
CHLORIDE Industrial
30 avenue Montgolfier
Chassieu, 69684
France
pierre.queyroi@chloride.com

Elena Chernetsova
Industrial Manager
CHLORIDE Industrial
30 avenue Montgolfier
Chassieu, 69684
France
Elena.chernetsova@chloride.com

Emiliano Paolin
Sr Manager Product Application
FZSONICK SA
Via Laveggio, 15
Stabio, Ticino, 6855
Switzerland
emiliano.paolin@fzsonick.com

Abstract – This paper focuses on re-evaluating the traditional industrial AC and DC UPS systems (consisting of power electronics and battery) with the use of new battery technologies and how this can dramatically change the architecture of the industrial sites. The considerations presented review the basic industry demands for battery and UPS performance and how they can be met once some limitations of current battery technologies are removed, including: gas emissions, temperature decay, aging, battery availability, storage, safety and recyclability.

The paper presents several important considerations that need to be made to select the right battery technology based on the underlying application needs e.g. between energy density and power density. It also investigates the positive impact of a new solution on industrial site design requirements including battery rooms and outdoor installation. The thorough testing results are presented as well as field experience feedback. Illustrations for the paper are based on a prior installation references, and lab testing.

Index Terms – AC, DC, uninterruptible power systems, salt battery, lithium battery, power availability, power electronics, footprint, safety, recycling, sodium, aging, storage.

I. "A CASE FOR AN IDEAL INDUSTRIAL BATTERY"

Valve regulated lead acid (VRLA) batteries have been a technology often selected for stand-by power applications (AC and DC UPS) in the oil and gas industry, particularly as capital projects apply heavy weighting to initial (CAPEX) expenditures. The low initial purchase price of VRLA and the allure of being “maintenance free” are a significant part of this technology’s appeal. However, the costs associated with a relatively short “reliable life”, and the production losses associated with the fail-open (i.e. sudden power loss) characteristic of VRLA batteries, create a need for better solutions.

Other areas which can significantly impact the life cycle costs of batteries and are thus open for improvement, include: shipping, storing, handling, commissioning, testing, cell replacements, periodic (4-6 year) complete cell bank replacements and lack of integrated monitoring (i.e. of the UPS electronics and batteries together). Failures of UPS to provide reliable stand-by power on demand (and for the required period of time) can lead to undesirable operational impacts effecting both the production and safety of the facility.

A facility operator’s perspective in regard to what the ideal battery technology would look like in industrial application identifies key performance targets while reviewing currently used technologies and limitations related to their performance. The interdependence between UPS and the battery is discussed as mutually dependent for the reliable power back up system.

Effective performance goals for a system are;

1. Reduce probabilities for “failures on demand” and loss of autonomy (failures modes, capacity loss, battery string redundancy, monitoring)
2. Increase availability (reduce meantime to repair or interactions required)
3. Minimize need for wholesale change outs (address expected life)
4. Mitigate potential for safety incidents (e.g. thermal runaway, leaking cells, chemical or gas exposure, battery fires, safety by design)
5. Reduced space, weight and /or environmental conditioning requirements (power density)
6. Minimization of transportation and storage issues (store “frozen”, ease of transportation and handling)

II. SEARCH OF AN IDEAL INDUSTRIAL BATTERY

A. Comparative Approach

To identify the battery technology that answers most adequately the requirements of the industrial application, it is necessary to identify the parameters that are critical to such applications, compare available technologies using these parameters and lastly compare the performance of each technology against the application requirements. The best visualization technique for such exercise could be to plot the results on radar charts.

The industrial application selected for the purpose of this comparison is the battery used in the uninterruptible power supply system to provide back up for the critical automation of the Floating Liquefied Natural Gas (FLNG) ship. A contrasting application is the battery for the uninterruptible power supply systems used to back up the datacenter servers in case of the power loss.

Four battery technologies have been selected for the comparison:

1) *Valve-regulated lead acid battery (VRLA):* One of the most common battery technologies used across the industry.
2) *Nickel-cadmium battery (NiCd low maintenance): This technology is traditionlly used in the industrial application especially with high ambient operating temperature.*
3) *Lithium ion (Li-ion) (ferrophosphate) battery: New generation of lithium batteries are positioned to be used across multiple industries. Ferrophospate chemistry makes it one of the safest in the lithium family for the industrial applications.*
4) *Sodium-metal chloride battery (SMC): New generation of the sodium based technology is developed for the use in the transportation, energy storage and telecommunication segments. It is part of the sodium beta batteries as described in IEEE 1679-2 [1]. The SMC type was selected as most suitable for industrial applications.*

Using the goals outlined above and the identified battery technologies the following criteria have been identified for comparison purposes that are to be considered in the evaluation.

B. Comparison Criteria

Nine comparison criteria are suggested that reflect the needs of the operators in the industrial application. This choice was also limited to the parameters that could be objectively compared between various technology types and may be mapped to the stated goals.

Hence the goal stated in the chapter I (points 1 to 6) of this paper were translated as the following parameters, respectively;

- Reduce probabilities for “failures on demand” and loss of autonomy (failures modes, capacity loss, battery string redundancy, monitoring) is represented by the parameter “Operational Continuity”;
- Increase availability (reduce meantime to repair or interactions required) is represented by the parameter “Intervention”;
- Minimize need for wholesale change outs (address expected life) is represented by the parameters “Battery Life Preservation” and “Temperature Derating”;
- Mitigate potential for safety incidents (e.g. thermal runaway, leaking cells, chemical or gas exposure, battery fires, safety by design) is represented by the parameters “Chemical Reaction Safety” and “Personnel Safety”;
- Reduced space, weight and /or environmental conditioning requirements (power density) is represented by the parameters “Long Autonomy” and “Short Autonomy”;
- Minimization of transportation and storage issues (store “frozen”, ease of transportation and handling) is represented by the parameter “Storage”.

1) Operational Continuity: This parameter responds to the first goal of the battery search by the operator. As there is no single way of assessing it, the combination of factors was included.

Calculation method: four continuity parameter including failure mode type (fail-open as 0 or fail-shorted as 1), redundancy (cell or module level), and monitoring (integrated or extra) were assessed for each type and weighted the results are shown in the Table I.

TABLE I

OPERATIONAL CONTINUITY COMPARISON

Battery Type	Failure mode type	Redun-dancy	Monito ring	Ranking 1-10 Higher = Better
VRLA	0	0.5	0.5	2
NiCd	1	0.5	0.5	4
Li-ion	1	1	2	8
SMC	1	1	2	8

2) Intervention: This parameter is based on the frequency of the recommended intervention (any activity by personnel) declared by manufacturer. It was included, as intervention presents significant challenge for industrial applications especially in the offshore or remote applications. These challenges include but are not limited to personnel availability, skills, required permits and licences, safety, etc. The data is based on the manufacturers’ declaration and is averaged per year over a 10-year period of the expected use (as not all operations have similar frequency).

Calculation method: The number of recommended interventions was taken from supplier recommendations including periodic checks, component replacement, safety procedures, etc. It was counted for 10-year period and then divided by 10 to account for interventions that are not annual. The results were then distributed across the 10-point scale (Table II).

TABLE II

INTERVENTION COMPARISON

Battery Type	# of recommended interventions over 10-year period per year	Ranking 1-10 Higher = Better
VRLA	2	1
NiCd	1	2
Li-ion	0.25	8
SMC	0.25	8

3) Temperature Derating (at 0°C): This parameter indicates overall battery sensitivity to the temperatures outside of its “comfort” operating range. It is critical for a lot of industrial applications where the installation is not located in the temperature-controlled environment, but subject to swings and long periods outside of the defined ambient range. In this case the manufacturer’s data was analysed showing the derating requirement for operation at 0°C.

Calculation method: the direct data showing recommended derating coefficient for 0°C was used. Coefficient 1 means there was no derating, coefficient 0.8 means 20% of derating. The results were then inversed to reflect the desirable qualities and distributed across the 10-point scale (Table III).

TABLE III

TEMPERATURE DERATING COMPARISON

Battery Type	Derating (% of performance)	Ranking 1-10 Higher = Better
VRLA	0.80	5
NiCd	0.85	6
Li-ion	0.96	8
SMC	1.00	9

4) Battery Life Preservation (at above 45°C): This parameter is similar to the parameter 3 but assesses the various batteries' performances at higher ambient temperature. The data is based on the manufacturers' declarations.

Calculation method: The direct data showing available battery capacity in % was used. It was then directly distributed across the 10-point scale (Table IV).

TABLE IV

BATTERY LIFE PRESERVATION

Battery Type	Available battery performance %	Ranking 1-10 Higher = Better
VRLA	30	3
NiCd	75	7.5
Li-ion	60	6
SMC	100	10

5) Chemical Reaction Safety: This parameter does not have a single approach to measuring it, though it can be critical in assessing the appropriate battery technology for the use in the hazardous locations or where personnnel exposure is frequent. The thermal runaway point can be used as one of approaches to compare batteries in this category.

Calculation method: Another parameter with multiple factors including the result of different types of abuse testing / normal operational risks (e.g. water consumption) and thermal runaway. Types of abuse testing are shown more detailed in Table XIII. The summary results are presented in Table V.

TABLE V

CHEMICAL REACTION SAFETY COMPARISON

Battery Type	Chemical reaction safety	Ranking 1-10 Higher = Better
VRLA	7.5	7.5
NiCd	7.5	7.5
Li-ion	5.0	5.0
SMC	9.0	9.0

6) Safety Testing for Service Personnel: This parameter is more directly related at how frequently the operational personnel needs to interact with the battery chemistry and how generally safe these interactions are. While VRLA and NiCd batteries require periodical intervention with the active chemicals, Li-ion and SMC only require the periodical intervention with battery management systems that are isolated from the active chemistry.

Calculation method: The ranking is a combination of the parameters including the monitoring, flashover risk, electrical shock risk, specialized training need. E.g. for Li-ion and SMC there is almost no risk due to the BMS (Battery monitoring Systems) reporting data without direct action on battery blocks [2]. Battery is not live during installation and replacement stages. On VRLA and NiCd there is the risk of electrical shock when maintaining the cells, reading voltage on blocks (-3 pts), risk of flash on connections with tools (-2pts). Need of Method Statement / Risk Assessment / training (-2 pts). The battery blocks cannot be powered off. Results shown in Table VI.

TABLE VI

PERSONNEL SAFETY COMPARISON

Battery Type	Testing frequency / safety	Ranking 1-10 Higher = Better
VRLA	3	3
NiCd	3	3
Li-ion	10	10
SMC	10	10

7) Long Autonomy: This parameter has a critical impact on the reliability of the industrial installations. It can be assessed using the notion of the energy density, that is ability to release energy over long period time. Unfortunately, due to the difference in the chemical properties of the batteries, it was not possible to use it for comparison. Hence, the battery dimension (footprint, volume and weight) required to provide such amount of energy over long period of autonomy (4-8 hours) was compared.

Calculation method: 3 dimensions are calculated for each autonomy period of 4 hours and 8 hours, then average value is taken. VRLA is used as reference on the scale and is rated as 1. E.g. 0.7 of SMC footprint means that it takes 0.7 times the footprint of VRLA for the same autonomy. The footprint and the volume are then given the weightage of 1 while weight has the weightage of 2. The lesser ranking is considered as more desirable, and the results are inversely distributed on the 10-point scale (Table VII):

TABLE VII

LONG AUTONOMY COMPARISON

Battery Type	Footprint	Volume	Weight	Ranking 1-10 Higher = Better
VRLA	1	1	1	4.8
NiCd	2.3	2.3	1	2.9
Li-ion	1.5	1.8	0.6	4.1
SMC	0.7	0.6	0.4	9.0

It is typically expected that the FLNG would target lowest footprint and a data center does not consider long autonomy a key performance.

8) Short Autonomy: This parameter contrasts the previous one to highlight the different needs for the shorter autonomy applications. Usually they also require higher power during short period of time and can be characterized by power density properties. The calculation was done for 10-minute autonomy period.

Calculation method: The same approach based on the three dimension parameters as in the previous calculation. The results distributed on a 10-point scale are shown in Table VIII:

TABLE VIII
SHORT AUTONOMY COMPARISON

Battery Type	Footprint	Volume	Weight	Ranking 1-10 Higher = Better
VRLA	1.0	1.0	1.0	3.4
NiCd	3.2	3.3	1.5	1.4
Li-ion	0.5	0.6	0.3	9.0
SMC	1.1	1.3	1.5	3.4

9) Storage Duration (at 20°C): This parameter can be very important to industrial applications as the battery installation does not always happen with the rest of the systems and keeping it in stock may deteriorate its performance. It is also important for the maintenance-related activities, where batteries need to be “on hand” for swapping when needed.

Calculation method: The data in the Table IX is based on manufacturers’ declared storage recommendations and limitations as shown in years. E.g. NiCd batteries are recommended to be stored at 20°C for maximum of 2 years.

TABLE IX
STORAGE DURATION COMPARISON

Battery Type	Recommended maximum battery storage period at 20°C (years)	Ranking 1-10 Higher = Better
VRLA	0.5	0.5
NiCd	2	2
Li-ion	2	2
SMC	>10	10

C. Battery Peformance against Selected Application Parameters.

The selected nine parameters were then assessed for their importance against the application profile and different technologies mapped against it.

For visualization purposes the radar charts include contrasting applications such as FLNG: typical industrial setting that prioritizes long autonomy, and data center: typical commercial use that prioritizes shorter autonomy. Below are four resulting charts for the selected battery types.

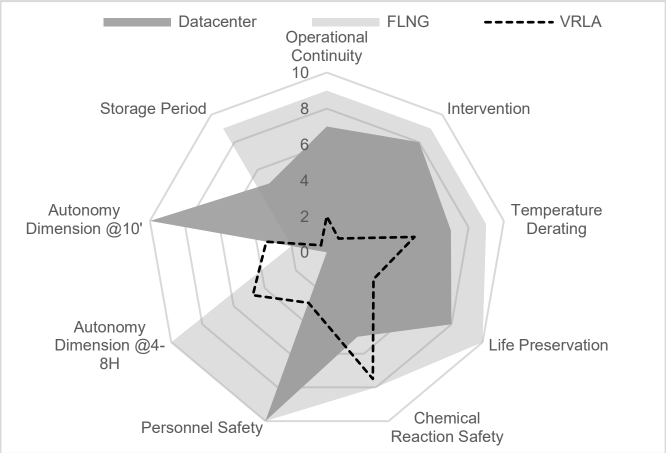


Fig.1 VRLA Battery Performance against Selected Application Criteria.

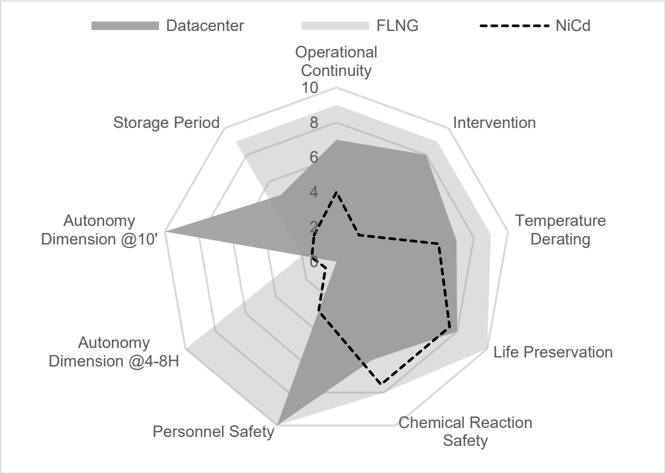


Fig.2 NiCd Battery Performance against Selected Application Criteria.

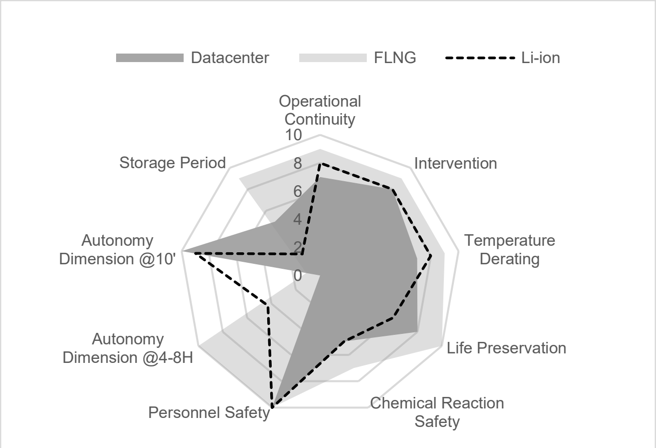


Fig.3 Li-ion Battery Performance against selected application criteria.

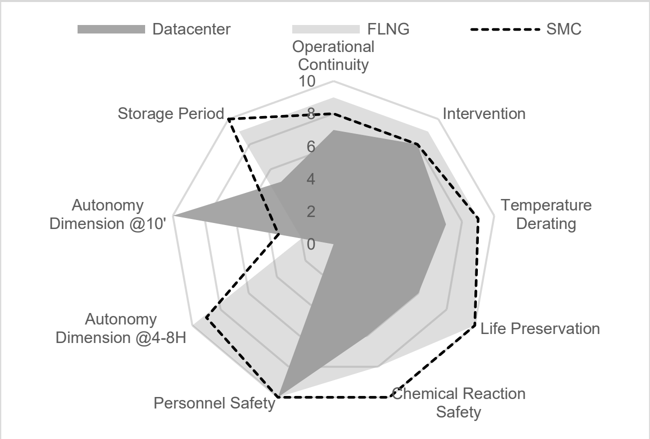


Fig.4 SMC Battery Performance against selected application criteria.

D. *Comparison Results and Conclusions*

The mapping shows that both Li-ion and SMC batteries as technology solutions offer comparative advantages across the variety of the parameters over NiCd and VRLA. Especially when it comes to operational continuity due to integrated monitoring solution, cell-level redundancy and safer failure modes.

While both technologies can satisfy various applications, their innate chemical performance is more optimized to certain conditions. The Li-ion batteries can provide the longer autonomy required at the industrial applications, but this will be achieved at the expense of their volume and cost.

At the same time SMC batteries can be used for shorter autonomies as well, but most likely will not be the most efficient solution in terms of space and cost.

Safety of any battery is also a crucial factor for industrial applications, and any technology able to improve on this parameter is becoming more attractive for operators.

As a result of the comparison, SMC is clearly positioned to be considered for industrial UPS applications. Meeting the initial goals stated of low intervention and increased availability, the architecture of the sodium-metal chloride sytem may allow for additional system performance improvements through reduced degradation, hot swappable units, and self-test capabilities.

The next chapter will look into more details of all these technical parameters to understand why this technology sets itself apart and how the higher ranking could be achieved.

III. SODIUM METAL CHLORIDE BATTERY DESIGN AND ELECTRICAL PERFORMANCE

A. *Cell Chemistry*

The Sodium Metal Chloride (SMC) cell is a high temperature secondary battery. Its cathode is based on metals, mainly Nickel (Ni) and Iron (Fe) and common table salt (NaCl) while the anode consists of molten Sodium (Na). The anode and the cathode are separated by a solid electrolyte made of sodium-beta”-alumina, a ceramic material that shows fast transport of sodium ions at temperature above 200°C.

During the charge process the sodium ions move from the cathode through the beta”-alumina electrolyte to reach the anode compartment where they are reduced to metallic sodium; in the cathode the metal powders are oxidized to produce solid metal chloride. During the discharge process the sodium ions move back to the cathode compartment to form solid sodium chloride salt. There are no side reactions and no gaseous elements are produced therefore the cell can be hermetically sealed without the need of any venting valve.

(discharged cell) $2NaCl + M^* \leftrightarrow M^*Cl2 + 2Na$ (charged cell)

(in this simplified formula M represents the metal content of the cathode mainly Ni and Fe)*

The ceramic electrolyte is a fully dense ceramic material that acts also as a separator, therefore the anodic and the cathodic active materials are completely separated [3].

TABLE X
CHARACTERISTICS OF AN SMC 40AH CELL

Capacity (C/5)	40Ah
Open Circuit Voltage @100% SOC	2.58V
Weight	690g
Dimensions	36x36x235mm
Specific Energy	140 Wh/kg
Energy Density	317 Wh/l

The ceramic separator allows fast transport of sodium ions only and ensures the electrical insulation between anode and cathode. For this reason, the SMC cell has the characteristic of non-intrinsic self-discharge, that allows an easy connection of cells in series without the need of equalization.

B. *Cell Design*

The main components of an SMC cell are:

Metal case made of nickel-plated carbon steel. The case is hermetically sealed through laser welding and assures a leak proof containment of the chemicals. The positive pole is located on the upper face of the metal case, while the negative pole is composed by the case itself.

Ceramic electrolyte shaped as a four-lobed tube. This shape was designed in order to maximize the surface area of the electrolyte. The inner volume of the ceramic tube defines the cathodic compartment while the volume in between the tube and the metal case contains the anode.

Ceramic lid (α-alumina, compare to β-alumina doesn’t conduct sodium ions) which embodies two nickel collars by thermocompression bonding

Positive collector made with a shaped nickel wire used to collect the electrons during the development of the reaction.

C. *Battery Design and Assembly*

An SMC battery is a complete battery system consisting of the number of cells arranged in a cell pack and a battery management system (BMS).

The cells are connected in series to form strings reaching the designed string voltage. Multiple strings can be connected in parallel to reach the designed battery capacity. The cell pack is enclosed in a battery container, designed to achieve an optimal thermal management without compromising safety and performances. The cell operating temperature is around 265°C; while the cells are housed in the hot environment, the external battery box surface is on average 10°C above ambient temperature.

The heating source for the battery can be internal or external and is the choice of the system design. The external charge source will be required for the startup sequence.

The battery container comprises an internal steel box containing the cells and an outer steel box slightly larger than the inner one. The volume in between the two boxes contains micro-porous insulating materials. Stainless steel metal boxes with proper thickness are used in order to provide containment with a long-life corrosion resistance.

The BMS is installed on the external front side of the cell pack and performs the following functions:

1) thermal management (activating the heating system in order to reach and maintain the service temperature or de-activate it over the upper temperature limit);
2) charge regulation (optimal charging of the cell pack);
3) monitoring and diagnostic (provides warning signals and disconnects the SMC battery in case of a critical alarm);
4) remote maintenance and supervising (able to collect and store battery data).

D. Cell Performances at various discharge rates

The discharge curves for a single SMC cell at various rates between C/10 and 1.5C are shown in Fig.5; the data are the average voltage of a ten-cell string. The discharge is terminated when a maximum limit of Ampere-hours is reached (at low rates) or when a minimum voltage is reached (at high rates). On figure 5, C/10 curve is the top one and 1.5C is the bottom one.

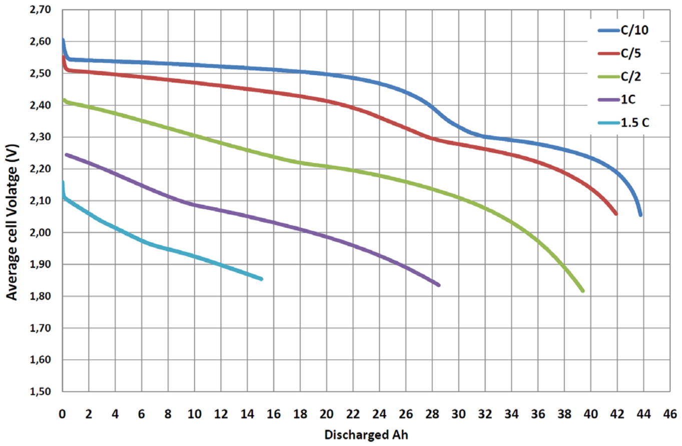


Fig 5 - Discharge curves at various rate for an SMC cell. The data are taken from the average of a ten cells string

In the ten hours discharge curve it is possible to identify two plateau regions: the first one is associated to the reduction of nickel chloride to nickel metal while the second one is related to the reduction of iron chloride. Iron is added to the cathodic active material as an additive to provide better peak power capabilities at low states of charge; the pulse power capability of the cell at 80% Depth of Discharge (DOD) is about 130 Watt over a 10 second discharge pulse at 1.72 Volt. The SMC cell has an internal resistance of about 7-8 mOhm at full state of charge (measured with an AC-impedance meter at 1kHz). Cell performances are not affected by the environmental temperature as they are kept at 270°C [4].

E. Battery Power/Energy performances at various rates

The electrical performance of an SMC battery is shown in Fig. 6 as a function of the discharge rate. The battery delivers the highest amount of capacity at discharge rates between eight and two hours, with an almost constant capacity output. At higher rates, as typical of batteries, the decrease of output capacity is more pronounced. It is worth mentioning again that the performances are constant, irrespective of the environmental temperature. At lower rates, the self-consumption effect inducted by the heat loss compensation decreases the deliverable capacity.

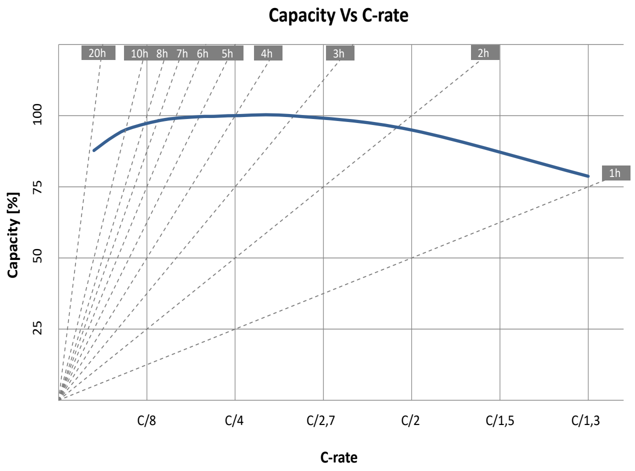


Fig. 6 - SMC battery delivered Capacity vs. discharge Rate

F. Influence of environmental temperature on battery performance

The high operational temperature of the cells allows the operation of the SMC batteries in a wide ambient temperature range defined by the electronic controller design (typically: -20°C to +60°C), without affecting performance and life. The only direct effect related to the ambient temperature range is a small variation of the power consumption to compensate the heat losses, with no limitation on charge and discharge performance.

Table XI shows the results of discharge cycles at different environmental temperatures on a SMC battery. The tests were performed in a climatic chamber with an accuracy of ±1°C on temperature set-point; for each test temperature, a fully charged battery was stabilized for 24 hours before starting the discharge. It can be noticed that the discharged capacity does not show significant dependence on the environmental temperature. The only effect of the environmental temperature is on the power consumption of the heating system that keeps the internal temperature of 270°C; at lower temperature the power consumption increases due to the higher thermal gradient between the inside and the outside of the battery case.

TABLE XI

INFLUENCE OF AMBIENT TEMPERATURE ON THE SMC BATTERY PERFORMANCE

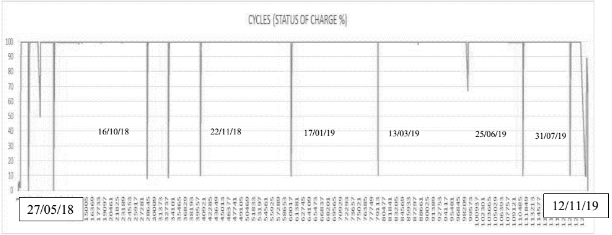
Ambient temperature	Discharged capacity @ C/3 deviation (ref 20°C)	Ah Discharged @ C/10 deviation (ref 20°C)	Power consumption deviation in floating condition (ref 20°C)
-20°C	100%	98 %	+10%
40°C	100%	100%	-7%
60°C	100%	100%	-10%

Various tests demonstrated the ability of an SMC battery to operate in hot climate applications with no degradation of the performance.

In the following example, a battery was installed into an outdoor cabinet with no ventilation in a high temperature environment for more than 1 year.

Fig.7 – Outdoor test for an SMC battery, high temperature environment

The recorded ambient temperature went up to 60°C while the battery was completely discharged every two months showing no degradation in the delivered capacity.



FULL DATA RECORDED: TEMPERATURE

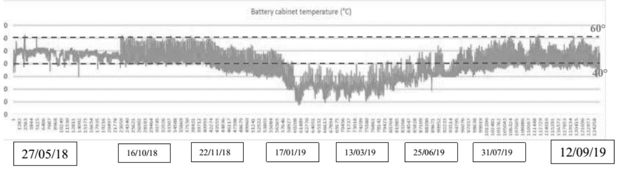


Fig. 8 – One-year outdoor test, capacity tests and temperatures

TABLE XII

OUTDOOR TEST RESULTS

Total test time	399 days
Total deep cycles	18
Average operating temperature	39°C
Maximum temperature	60°C

Capacity test date	Measured backup time
2018/10/16	1h 52’
2018/10/31	1h 52’
2018/11/22	1h 51’
2019/01/17	1h 51’
2019/03/19	1h 51’
2019/06/25	1h 51’
2019/07/31	1h 51’

IV. SODIUM METAL CHLORIDE BATTERY SAFETY

As a general consideration, a battery is a tank of electrochemical energy that, if released or dissipated in an uncontrolled way, could result in a hazard. The SMC battery technology is addressing the safety concerns at multiple levels.

A. Safety Level 1: Cell Chemistry

The major hazards on the cell level are related to the chemical components:

Positive Electrode

Nickel metal and nickel chloride powders are considered hazardous however during the first charging cycle, these powders present in the cell positive electrode undergo a thorough sintering process and are transformed into a porous solid body. Therefore, nickel fine powders are not present in the battery during service.

Nickel chloride (NiCl2) does not support combustion and is not considered to be a fire hazard, nor is it considered to be particularly reactive.

Sodium chloride (NaCl), that is the common salt, is not considered to be particularly hazardous.

β”-Alumina Ceramic Electrolyte

Sodium β”-alumina is incombustible, nonreactive and is not known to present any health hazards. Upon exposure to air, it absorbs CO2 and water without significant heat evolution.

Negative Electrode

Sodium metal (Na) is highly reactive especially when it gets in contact with water. It should be noted, that SMC product safety is designed around minimizing any metallic sodium available in the event of a failure of one or more of the systems as discussed below.

Other Cell Materials

Materials such as copper, aluminum, mild steel and the alumina used in the seals do not pose significant intrinsic safety or health hazards.

B. Safety Level 2: Cell Containment

The SMC cells are contained within a hermetically-sealed, nickel-plated steel case. Enclosure within the case makes exposure to nickel, nickel compounds, or sodium unlikely during normal operation. The cells do not vent gases or other substances during normal operation, and do not contain materials characterized by having high vapor pressures at the temperature ranges associated with such operation.

Among the different chemicals inside the operational cell, metallic liquid sodium (Na) has the higher vapor pressure, but it boils at 882°C, i.e., at a temperature about 600°C greater than the normal operating temperature of the battery (265°C), that is very unlikely to be reached, even in failure conditions.

C. Safety Level 3: Battery Containment

SMC battery cells are housed within a temperature-controlled, stainless-steel double-walled, mechanically-insulated battery case that does not include any combustible materials. This battery case or enclosure is intended to both protect the outside environment from the effects of mishaps within, and to protect internal battery components from external hazards (high-low temperature, water, humidity, corrosive agents, fire, impact, mechanical damage, etc.).

The microporous silica insulated enclosure prevents heat build-up on the outside of the product even in the event of minor mechanical damage to the exterior of the product. Accidents resulting in the penetration of the battery case can be expected to compromise its insulating and containment functions, and, if severe enough, to rupture the cells contained inside, and, most likely the β”alumina tube that separates positive and negative electrodes, thus resulting in combining of Na with molten sodium tetrachloroaluminate (NaAlCl4) to salt (NaCl) and metal aluminum (Al), minimizing or excluding the possibility of a liquid Na release outside the battery.

D. Safety Level 4: Electronic Control (BMS)

The Battery Management System (BMS) is an electronic control and safety interlock, preventing and protecting cells against unwanted physical/electro-chemical deviations that could lead to hazardous conditions. Redundant safety micro-controllers watchdog all processes to ensure compliance to design intentions. The system utilizes multiple temperature sensors to measure operating parameters at various points in the product, in order to provide proper control in changing environmental conditions. A microprocessor-controlled overcurrent disconnect protects equipment and personnel in the case of external short circuits. Mechanical fusible links provide redundant protection to critical components should a control system fault occur.

E. Abuse testing and thermal runaway propensity

Industrial batteries may experience mechanical stresses including bumps, drops and even high-speed impacts from moving objects such as automobile collisions with a fixed battery installation. Further, electrical stresses such as overcharging, overvoltage and short-circuits are very common in the industrial energy storage space and have been the cause of premature failure in a number of industrial batteries. Finally, various environmental stresses directly impact the proper operation of batteries. Many environmental stresses may cause irreversible damage to the energy storage systems. These abusive conditions and the ability of the SMC batteries to safely withstand each are explored [5].

The table XIII summarizes the tests that were carried out on SMC battery and its results. The findings of these tests support the high ranking of SMC battery on chemical reaction safety and personnel safety.

TABLE XIII

SMC BATERRY TESTING RESULTS

Type of test	Test Conditions	Test Results
Complete submersion in salt water	Complete submersion in a free-flowing conductive medium consisting in a solution of 3.5% saltwater. The test was continued until all reactions ceased (2.5 hours).	No fire created and no explosions occurred.
Exposure to petroleum fire and water hose stream	Exposure of an operating SMC battery to a petroleum fire of 850°C positioned 610 mm (24 inches) below for 35 minutes. Immediately followed by high-pressure water stream from a 76 mm (3 inch) fire hose for 1 minute.	Severe mechanical weakening occurred. The case did not rupture. There was no explosion or escalation of fire and self-extinguished once the petroleum was extinguished.
High-speed impact in both as-installed and as-shipped conditions	Exposure of 3 separate operating SMC in various states to 48 km/h (30 mph) impacts with a stationary section of a telephone pole, dropping them from the height of 10 meters and experiencing forces above 4G. The states include: crated-cold (shipping set up), uncrated-cold (shipping set up), and hot-functional.	Welded metal cases of the SMC were all dented at the point of impact, none of the cases ruptured. The shipping crate (packaged test only) was damaged. None of the batteries exhibited a temperature rise as a result of the test.
Overcharge	Exposure of a fully charged operating SMC battery to an overcharge as a result of overvoltage. The battery protections were bypassed.	The SMC continued to operate normally up to and including 145% of the nominal voltage and resisted the stress at least 4 separate times, with no negative impacts.
External short circuit (battery terminals)	Exposure to the low-impedance short circuit to the customer terminals, allowing the maximum current to flow from the terminals of the battery.	The battery protected itself by disconnecting from the load. This allowed it to continue to operate after the short circuit event.
External short circuit (cells) according to UL9540A [6]	2 initiating cells inside an SMC battery were driven to thermal runaway by external short circuit.	No observed indication of cell venting. Traces of methane were detected (total volume of less than 1L). No hydrogen gas was measured during the test. No sparks or embers were ejected from the module. No flaming occurred and, accordingly, no heat release rate was measured, and no re-ignitions occurred. There was minimal damage to the module and no thermal runaway propagation to other cells, so the same sample was used for the 2nd module test.

Nail penetration according to UL9540A	Nail penetration was used to initiate a thermal runway in an SMC battery module, through the 2 outer stainless-steel walls, through 1 cell, and halfway through the next cell.	The thermal runaway event (after 5 minutes and 17 seconds) propagated throughout the entire module. After the initial stage, cell gas vented (49L of methane, 3L of carbon monoxide). Hydrogen was not detected. No sparks or embers were ejected. No flaming or heat release was measured, no re-ignitions occurred, and no flying debris was observed.
Overheat in furnace according to UL9540A [7]	SMC cell was heated inside a furnace up to 800°C. The furnace was held at 800°C (1472°F).	The liquid salt electrolyte began to vaporize above 780°C (1436°F). Pressure inside the cell rose rapidly as the electrolyte vaporized, resulting in a violent rupture of a welded seam along the bottom of the cell. The overheating condition did not result in self-heating or thermal runaway.
Deep penetration into the case of the battery followed by water exposure	The SMC battery was penetrated by a 20 mm (0.75 inch diameter) rod to a depth of 200 mm (8 inches). After removing the rod, the exposed sodium could react with the ambient air. Once sodium-reactions began, water was applied to accelerate the reactions.	The penetration exposed the sodium contents of multiple cells. Only after prolonged delay the reactions of the exposed sodium and ambient air were observable as a small flame within the battery case. At this point, water was applied. The product of this reaction was steam vapor, mixed with small quantities of smoke from the flame and cell-air-water reaction product.
Accidental drop scenarios while in the as-installed condition	Exposure of an operating fully-charged SMC battery to a 2.1 meter (82 inch) drop scenario directly on the BMS to replicate fall from rack's top shelf. After the drop, the SMC was rotated upside down to improperly orient the internal cells [8].	BMS no longer was functional. No liquids or materials were observed escaping from the enclosure. There was no detectable temperature rise on the surface of the battery. The test resulted in no fire or explosion of parts.

V. IMPACT OF SMC TECHNOLOGY ON THE UPS DESIGN AND PERFORMANCE CRITERIA

The UPS system reliability and availability depends on both sub-elements; the UPS (basically a charger and an inverter) and the battery. The overall UPS system availability is highly improved when both elements share their measures, status and alarms and take actions based on their communication.

This dedicated connectivity bus between the UPS and the SMC battery allows the following:

- UPS control "senses" individual battery modules and not just the overall battery bank. Degradation or failure of a module is therefore automatically detected and proper action is taken to provide most reliable standby-power on demand.
- to share accurate information regarding the state of charge (SoC) and depth of discharge (DoD) and then take automatically proper actions regarding the end of charge and discharge, manage load shedding (today only relying on timers or voltage thresholds).
- if a battery module is faulty, to automatically manage, through the UPS control, the connection of the standby (hot) redundant module(s), on the battery bus.
- to have a single protocol, single point of connection and synchronization of the UPS and battery events for the remote connectivity solutions (monitoring station).

In order to benefit from the opportunities presented by new battery technologies and optimize the UPS availability, it is important to have UPS electronics integrated with the battery BMS control to allow the power control logic have a complete visibility of the system status.

VI. NEW POWER BACKUP SOLUTION: WHAT DOES IT MEAN FOR INDUSTRIAL SITES DESIGN REQUIREMENTS

The significant changes in technology of the new generation of batteries and consequent changes in the application rules allow operators to rethink the restrictions and limitations that are imposed by current technologies. The below list shows some examples of where this implication could occur.

A. Footprint improvement

The significant improvement in energy density leads to much more compact footprint and weight that will allow to save some capital expenditure for new sites as well as increase total secured load at the existing sites. The improved site layout that reduces amount of cabling is another consideration.

B. Battery room

As new battery technology does not emit gas, the specialized battery rooms may no longer be required allowing the battery to be installed as convenient next to the UPS units or even above or below them (double floor). This also can lead to cabling reduction and more optimized facility layout.

C. Replacement units

As some new batteries like SMC can be stored for a very long periods of time pre-charged and without any loss of the performance, it could be considered to have some replacement units on site for hot swap replacements. This also allows to increase the overall availability of the power backup systems.

D. Outdoor installations

Low sensitivity to the ambient temperature in the range of -20°C to 60°C allows consideration for outdoor installations with some minor protection (e.g., canopy). This could be advantageous in the remote sites where the infrastructure is minimal.

E. Maintenance schedule

If automated online self-testing and annunciation of pending or identified failures were to be available the technician periodic inspections could be removed or extend significantly beyond current norms. The SMC individual battery connections to the UPS and N+1 configurations offer the ability to engage in development of potential reductions to maintenance activity or possible enablement of a "no-periodic scheduled maintenance condition".

VII. CONCLUSIONS

The case for an ideal industrial battery highlights that a reliable, available, low interaction, small footprint, low weight, safe battery is a desired condition. This paper explored a means to evaluate the available technologies and delved into a promising technology, sodium-metal chloride batteries, that has the opportunity to meet the stated objectives. Evaluations performed highlighted the sodium-metal chloride batteries can meet all six of the ideal performance goals;

1. Reduce probabilities for "failures on demand" and loss of autonomy by installing modular redundant batteries that can self-monitor their own health with an internal BMS.
2. Increase availability by being capable of replacing individual batteries while system remains online while maintaining ability to deliver power.
3. Minimize need for wholesale change outs by reducing degradation modes and environmental impacts to the battery life.
4. Mitigate potential for safety incidents by removing off-gassing or disconnecting output during a battery terminal short.
5. Reduced space, weight and /or environmental conditioning requirements by using a smaller footprint solution that can be installed outside of a typical power distribution center.
6. Minimized transportation and storage issues by being able to ship and store batteries in a 'frozen state' that is not impacted by typical temperature ranges.

VIII. REFERENCES

[1] IEEE Std 1679.2-2018 Guide For The Characterization And Evaluation Of Sodium-Beta Batteries In Stationary Applications

[2] A. Miraldi, S. Restello, *"Sodium Metal Chloride Battery Safety in Standby Applications",* Fiamm SoNick, 2013

[3] S. Restello, E.Paolin, *"Sodium-Nickel Batteries for Telecom Applications: Design, Performance and Field Operational Overview"*, Fiamm SoNick, 2011

[4] S. Restello, E. Paolin, N. Zanon, *"Sodium Nickel Batteries for Telecom Hybrid Power Systems",* Fiamm SoNick, 2013

[5] T. Chatwin, *"Abuse Testing of Sodium Nickel Chloride Batteries*", General Electric, 2013

[6] UL LLC., *"UL 9540A Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, Module Level Test Report",* 2018

[7] UL LLC., "*UL 9540A Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, Cell Level Test Report",* 2018

[8] R. Manzoni, *"Sodium Nickel Chloride Batteries in transportation applications",* Fiamm SoNick, 2009

IX. ACKNOWLEDGEMENTS

The following people have contributed to the paper and we would like to thank them for their important work on the subject.

1. Don P. Bushby, Senior Technical Consultant at ExxonMobil Upstream Integrated Solutions
2. Luca Visconti, Product Application Manager at FZSONICK.

X. VITAE

Joe Marquardt graduated from Clemson University with a BSEE in 1995 and has worked for ExxonMobil performing roles in electrical, instrument, and process engineering with additional roles in project management. He is presently in global roles of Senior Technical Professional Advisor for Electrical Safety and Senior Technical Professional Advisor for Projects.

Pierre Queyroi has a master's degree in Electronics and Electrical Engineering with a specialization in Power and Control Electronics. He started his career in 1985 designing Chloride AC and DC uninterruptible power supplies. He spent most of his career designing UPS, managing engineering and product management teams. Today Mr. Queyroi holds the position of VP Technology for industrial UPS.

Elena Chernetsova graduated from Chelyabinsk State University in 2007 and subsequently worked in various product groups of industrial automation in Emerson. Most recently she became responsible for Chloride Industrial UPS product line in Vertiv. In 2013 she also received the MBA degree from Washington University of St. Louis. She has previosly authored a paper for PCIC Europe conference.

Emiliano Paolin is the Product Application Senior Manager for Standby, Energy Storage System and Mobility applications at FZSoNick SA. He has a master's degree in Microelectronics and 20 years' experience in battery technologies. He started working with Lead Acid projects and then in 2008 joined the R&D department dedicated to the Sodium Metal Chloride technology. Currently leading the Product & Application team.