Lithium Batteries for Wireless Sensor Networks

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Non-rechargeable batteries with a life of 20 years and more are required today for many smart metering and AMR applications in the US. Tadiran's non-rechargeable lithium thionyl chloride batteries offer a proven life of 25 years. Kohler's new touchless commercial faucet was designed to run even 30 years on a hybrid lithium battery. Similar requirements exist for wireless sensor networks. They can be achieved by diligent optimisation of the power source. This optimisation rests on three pillars: capacity increase, decrease of self discharge and the minimisation of voltage losses. When pulse currents of up to 2.5 Amperes are required Tadiran's ***PulsesPlus***™ technology, combining a secondary high rate element (Hybrid Layer Capacitor, HLC) with a primary high energy cell (3.6 Volts, 1340 Wh / dm^3) is the system of choice. The icing on the cake: Tadiran's TLI battery is a high-end high-power rechargeable element for use in combination with energy harvesting devices or other electrical low power energy sources.

Lithium batteries designed for 30 years

Kohler, a US based manufacturer of kitchen and bath products, has recently announced its new Insight Technology for wall- and deck-mount faucets. This system analyzes and logs feedback from its environment upon initial installation. If the bathroom space has low lighting, or highly reflective lighting, the sensor calibrates its factory default setting to accommodate its new home. As a result, the sensor is precisely tuned to its exact position, and eliminates false actuations. The faucet features a Hybrid Layer Capacitor (HLC), that allows the battery to remain operable – literally maintenance-free – for 30 years or more. The Insight touchless technology uses an extremely low amount of power. Thus, this faucet does not fail or require maintenance even if it’s not used regularly, or if the room’s lighting is less than adequate – two common challenges in other long-lasting power solutions.

Figure 1
Kohler's 30 year touchless commercial faucet is powered by a ***PulsesPlus***™ battery from Tadiran.

Aclara AMR units running for 25 years

Twenty-five years ago, Aclara™ (formerly Hexagram Inc.) began installing hundreds of thousands of battery-powered automatic meter reading (AMR) devices for the utility market. Powered by a single Tadiran AA-size lithium battery, virtually all of these decades-old AMR devices are still operating on their original battery, with laboratory confirming that they had retained nearly 25 % of their original capacity.

Aclara has since introduced a newer generation of STAR™ Network wireless fixed-network AMR systems using an upgraded Tadiran XOL-type AA-size lithium battery. STAR network meter transmitter units (MTUs) are capable of providing multiple daily readings using narrow-band radio frequency to communicate with data collection units (DCUs) strategically positioned on buildings or utility poles located approximately 1 to 2 miles apart. These units combine intelligent energy-saving design with advanced lithium battery technology to deliver proven 25-year service life.

Figure 2
Aclara's STAR™ Network wireless fixed-networks AMR system uses Tadiran's XOL AA-size battery. An older version has been running 25 years and is still going strong.

How can battery life be optimized?

The lithium/thionyl chloride (LTC) battery system is a key to such long operating lives. Tadiran's XOL series has extended operating life because its internal self discharge has been successfully reduced to the lowest level of typically less than 10 % over a period of 15 years. Other major advantages of this battery system include its high energy density of up to 1340 Wh / dm^3, its high stability over a wide temperature range from typically –40 °C to +85 °C and its high operating voltage of 3.6 Volts nominal. The combination of these advantages makes the LTC battery the system of choice for long term operation under low current draw.

In order to achieve a long battery life it is necessary to find the battery system with the highest cell capacity, decrease the self discharge rate, and reduce voltage losses.

Increase cell capacity!

Over the years, Tadiran has improved the material balance in its lithium batteries. The D cell has 19 Amp-hours and sets the standard for the high energy battery market, unachieved by any other primary battery system. Table 1 shows values for other sizes.

Cell size	Capacity	Specific energy
½AA	1.2 Ah	440 Wh / kg
AA	2.4 Ah	460 Wh / kg
C	8.5 Ah	620 Wh / kg
D	19.0 Ah	730 Wh / kg [1)]
[1)] 730 Wh / kg is the highest specific energy available in any commercial cell on the market		

Table 1
LTC battery System.
Cell capacities of Tadiran's XOL series.

A comparison of other lithium battery systems is shown in figure 3. It includes the Alkaline battery system, a standard for household batteries. The chart shows the battery voltage over capacity per unit volume during a low rate discharge. In this form, the area below each curve represents the energy density of the system. The chart intuitively shows the superiority of the LTC battery system. It can also be seen that the LTC system has the highest voltage level of all major battery systems, namely 3.6 Volts.

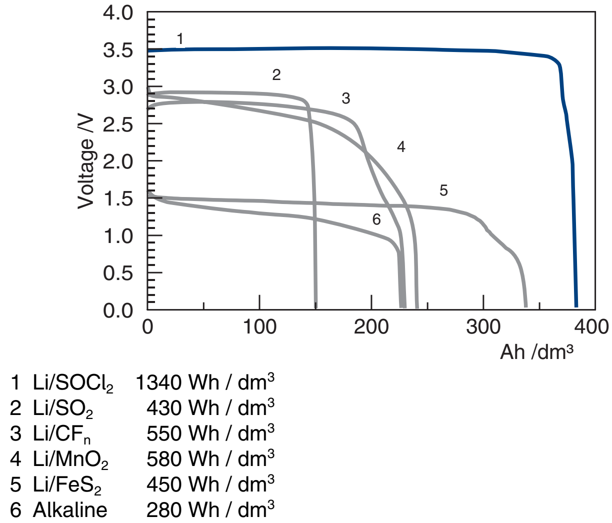

Figure 3
Comparison of different battery systems by voltage level and energy density.

Decrease self discharge!

The electrolyte composition of Tadrian's XOL series has been carefully engineered so as to minimize self discharge while keeping anode passivation at an acceptable level. Diligent purification of electrolyte ingredients as well as sophisticated quality assurance methods contribute to maintaining self discharge constantly at this low level. Basically, there are three independent methods to verify the level of self discharge. These include the classical method by direct measurement of the capacity loss after real time storage, an accelerated ageing method and the measurement of heat dissipation associated with self discharge, by a method called microcalimetry.

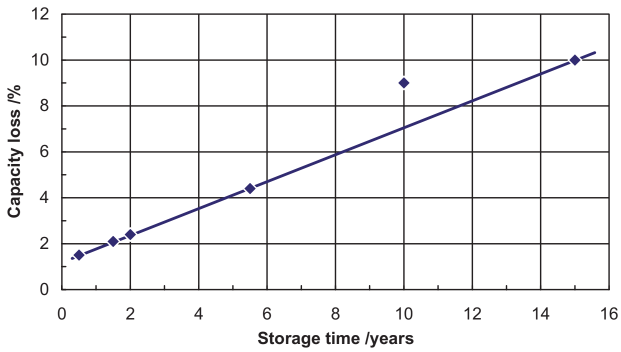

Figure 4
Self discharge of $Li/SOCl_2$ cells based on discharge data of AA size cells at RT.

Figure 4 shows results of the classical method. AA size batteries were stored at room temperature (RT) for different periods ranging from ½ year to 15 years. They were then discharged to determine their residual capacity. The curve shows that even after 15 years of storage, self discharge accumulated to less than 10 %. It is therefore justified to say that these batteries have less than 1 % self discharge per year.

Accelerated ageing can typically be conducted by storage @ 72 °C. It is common practice to assume that a chemical reaction like self discharge of a battery increases by a factor of approximately 2 for every 10 degrees of temperature increase, based on Arrhenius' equation. Therefore, a rule of thumb says that 3 months @ 72 °C correspond to 10 years @ RT.

Figure 5 shows results of an accelerated ageing test with AA cells of the XOL System. The batteries were stored @ 72 °C for different periods between 0 and 12 months and then discharged on a load of 1.8 kΩ. As can be seen, only a minor capacity loss was observed.

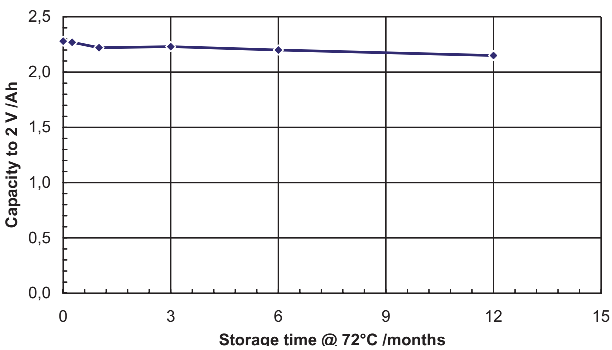

Figure 5
Self disharge analysis after accelerated storage @ 72 °C. AA-XOL under 1.8 kΩ.

The microcalorimeter method requires a test chamber with very efficient thermal insulation and extremely sensitive temperature sensors. The instrument can measure the heat output of a battery in the micro-Watt range. This heat output is associated with a battery's self discharge and can be easily transformed into the self discharge current, using basic thermodynamic considerations.

Figure 6 shows the results for XOL type batteries of sizes AA and ½AA. As can been seen from this figure, self discharge rapidly decreases after production and stabilizes at very low levels clearly below 5 µA when the cell is less than a year old.

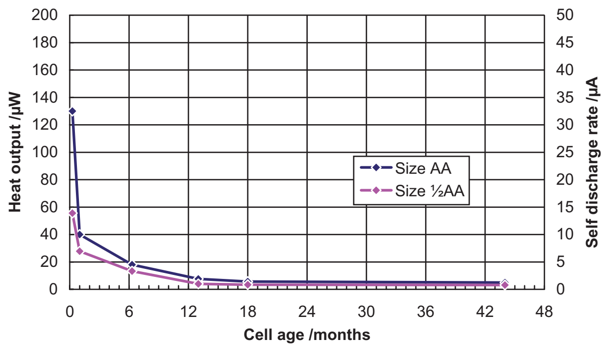

Figure 6
Heat output of XOL type AA and ½AA cells @RT

Self discharge may vary when a cell is being used under a continuous load. This situation was also investigated and figure 7 shows the results. The blue curve shows capacities of AA-cells determined by electrical discharge under various loads. Starting from 200 Ω, cell capacity reaches a maximum of 2.4 Ah, its nominal capacity, under a load of 3.6 kΩ. Smaller loads (i.e. higher current draws) represent an overload condition resulting in a reduction of available (effective) capacity. Increasing the load further results in battery lives beyond 3 months. Under these conditions, self discharge plays an increasingly important role. However, this battery type has so low self discharge that battery lives even beyond 20 years can be demonstrated. The red curve represents data found by the microcalorimeter method and the chart clearly demonstrates that both methods yield consistant results.

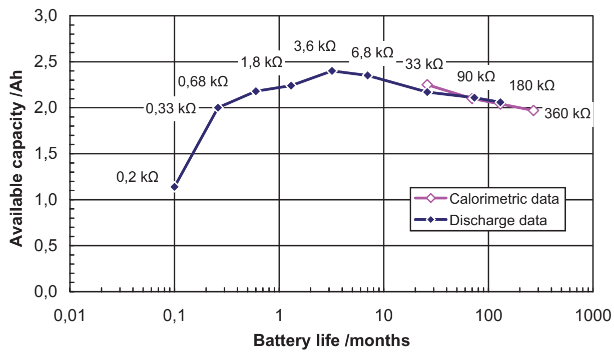

Figure 7
Operating life of AA size cells. Calorimetric vs. discharge data.

An impressing result has been obtained by discharging Tadiran's SL-550 cells under small current draw at a temperature of 85 °C over a period of almost 15 years. SL-550 is a ½AA size lithium thionyl chloride battery, modified to withstand the increased internal pressure associated with high temperature, but otherwise chemically identical to Tadiran's standard cells. Figure 8 shows discharge curves of a sample of 10 cells demonstrating the longevity of the system under extreme conditions.

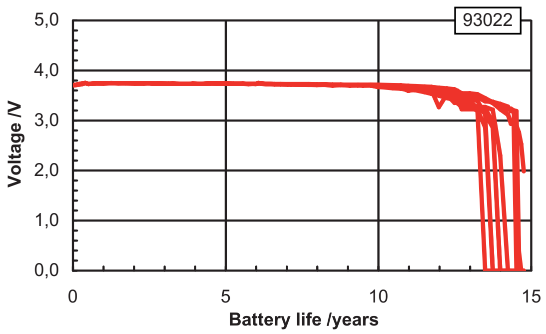

Figure 8
10 cells SL-550 on 560 kΩ (~6 µA) @85 °C

How to predict a 20 year battery life

Tadiran has tabulated self discharge results for the batteries over the range of temperatures and current draws and can therefore precisely predict a battery's operating life in many typical applications. Table 2 shows a typical application where average and maximum current draw are such that a battery life of 20 years can be achieved.

Generic 20 years application	
Quiescent current Pulse Average current draw Annual consumption	9 µA 2 mA for 50 ms every 5 min 10 µA 81.76 mAh / yr
End voltage	3.0 V
Temperature profile	–40 °C ... +85 °C, avg. +20 °C
Average self discharge	1.9 µA
Battery type Nominal Capacity Nominal Voltage	SL-860 (AA) 2.4 Ah 3.6 V
Calculated Battery Life	20.9 yr

Table 2
Generic 20 years application

From the current profile, a straight forward calculation yields the charge consumption of 81.76 mAh / year.

From the tables for SL-860, Tadiran's XOL type AA size cell, an average self discharge of 1.9 µA is determined. It is slightly higher than during storage at room temperature because both temperature and current draw lead to an increase of internal reactions consuming active mass. As indicated earlier, some additional voltage loss needs to be taken into account. It comes from the cell's internal resistance which rises as the cell is discharged and approaches its end of life.

Taking all losses into acount, a battery life of 20.9 years remains, which amounts to a capacity yield of not less than 76 % of the nominal capacity.

Wireless sensor networks require higher pulse currents than 2 mA from a 2400 mAh cell as in the preceding example. Pulse currents may actually be up to 1000 times higher if the wireless sensor network includes a GSM module. High Energy Lithium batteries would not be able to deliver such high currents for 20 years and more.

Therefore, Tadiran has developed its Hybrid Layer Capacitor (HLC). This element is a secondary cell, based on lithium intercalation compounds and – despite its small size – can be used like a very large capacitor. The system is marketed under the trade name ***PulsesPlus***™.

Figure 9 shows an example composed of a high energy D-size primary cell and HLC-1520 (15 mm diameter, 20 mm height).

Figure 9
PulsesPlus™ Battery (D + HLC-1520)

Minimize voltage losses!

Connecting an HLC in parallel to a high energy lithium battery adds some volume, basically maintains the high energy density of the system – but reduces the internal resistance of this battery system by a factor of typically between 100 and 1000. Thereby, both voltage delay problems and voltage loss due to a rise of internal resistance disappear.

Figure 10 shows a comparison of the initial 10 seconds when an AA size cell after more than 8 years storage is first connected to a load. The blue curve shows that voltage will drop to less than 2.5 Volts when the load is 10 mA, slowly recovering to slightly under 3.0 Volts within a period of 10 seconds. The red curve shows the situation when an HLC was connected in parallel to the cell. The current was 100 times higher but no voltage delay was observed. During the entire 10 second period, voltage did not drop below 3.4 Volts.

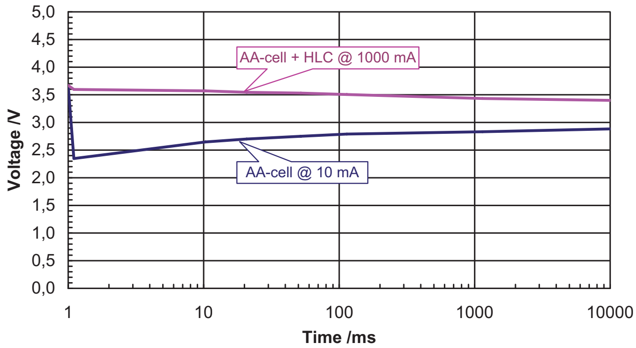

Figure 10
Voltage - time transient of AA cells after 104 months storage with and without an HLC.

Figure 11 shows how the Pulses Plus battery overcomes the voltage loss problems when high current pulses occur. The blue curve shows the voltage of a D-size cell when short pulses of 150 mA are applied. The battery is able to deliver this current at a voltage level of 3 Volts, at least for a period of 2 years. From the low average current draw of 50 µA, one would be mislead to assume that the battery could continue to deliver these pulse currents for more than 10 years. However, after 2 years, the voltage level under pulse load starts to decline reaching as low as 1.5 Volts after 5 years. At this voltage level, most applications would stop to work and the battery would be considered as discharged. However, it is not, as can be seen from the red curve showing the battery voltage under background load. It stays at 3.6 Volts, even after 5 and 10 years. Connecting an HLC in parallel solves the problem. The HLC maintains its low internal resistance throughout the remaining battery life. Even after more than 10 years in this test, pulse voltage did not drop below 3.4 Volts again.

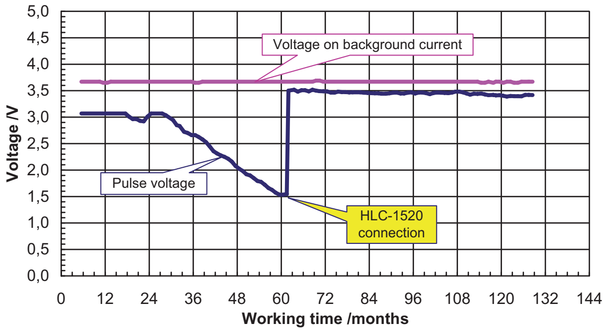

Figure 11
Long term pulse test, D-cell @ RT.
68 kΩ background load (~ 50 µA), pulses 150 mA

Adding a capacitor in parallel to a battery always means to add a potential source of self discharge. It is therefore important to make sure that the HLC has a low level of self discharge, matching the low self discharge of the high energy primary cell.

Table 3 shows self discharge values of different HLC-sizes over the operating temperature range.

Temperature	HLC-1520	HLC-1020	HLC-1020L
0 C°	1,0 µA	0,6 µA	0,8 µA
25 C°	1,2 µA	0,8 µA	1,0 µA
35 C°	2,1 µA	1,3 µA	1,5 µA
42 C°	2,7 µA	1,8 µA	2,1 µA
55 C°	3,0 µA	2,2 µA	2,5 µA
65 C°	4,0 µA	2,8 µA	3,1 µA
72 C°	4,5 µA	3,2 µA	3,5 µA

Table 3
Self discharge of various HLC's

Figure 12 shows the stability of the ***PulsesPlus***™ battery system under accelerated ageing conditions over a period of almost 8 years at 72 °C. No degradation, no substantial increase of internal resistance, no self discharge, no voltage loss.

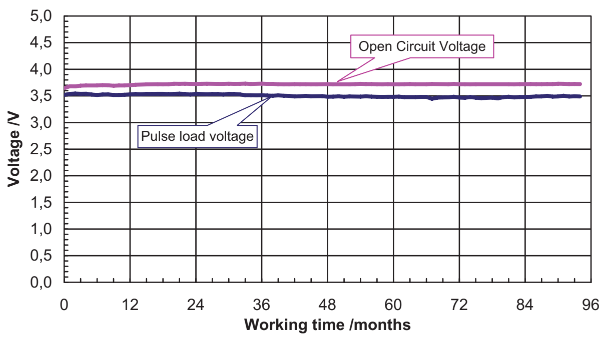

Figure 12
Accelerated ageing test @ 72 °C.
½AA + HLC-1520, pulses 500 mA, 1 s, once per week

How to predict a 30 year battery life

When major pulse currents play a role so that voltage losses would prematurely terminate the useful life of the battery, the design engineer first of all should determine the proper HLC size. The HLC has to buffer all current pulses – even at the lowest occurring ambient temperature. Battery life is then determined virtually only by the self discharge, both of the primary cell(s) and the HLC(s). Table 4 gives an example where a battery life of 30 years is required – and achieved. The application consumes 456 mAh / year.

A radio transmitter requires 800 mA for 1 second 4 times per day. This pulse can be delivered by an HLC-1550 down to $U_{min} = 2.8$ V and a temperature of –10 °C. The self discharge with a D-cell having a nominal capacity of 19 Ah will be 9.3 µA. A battery life of 30 years is calculated.

Generic 30 years application	
Quiescent current Pulse Average current draw Annual consumption	15 µA 800 mA for 1 s every 6 hr 52 µA 456 mAh / yr
End voltage	2.8 V
Temperature profile	–10 °C …+50 °C, avg. +20 °C
Average self discharge	9.3 µA
Battery type Nominal Capacity Nominal Voltage	TLP-93111/A (D + HLC-1550) 19 Ah 3.6 V
Calculated Battery Life	30.7 yr

Table 4
Generic 30 years application

Battery type	Battery life	Quantity	Device - hours	Failure Rate
	years	batteries	10^9 hrs.	fit
HLC-1550 in medical applications	5	400 k	4.1	< 0.1
TLP-93311/A/ST	7	6 000 k	12.9	< 1.0
TLP-92311/A/ST	7	7 000 k	7.1	< 1.0
AA-size cell for AMR application	10	2 100 k	80	2.5
1 Ah wafer cell	7	18 000 k	673	< 1.5

Table 5
Field reliability data of Tadiran lithium batteries

Tadiran's field experience

Tadiran's high energy lithium batteries are on the market since the late 1970's, the HLC and PulsesPlus battery were introduced to the market in the year 2000. Since then, more than 30 millions flat cells have been used for toll road and other automotive applications. The number of Tadiran's small cylindrical cells sold to the market for metering, tracking, medical and other instrumentation etc. is over 150 millions. And more than 30 million big cells (C, D and DD) were used, mostly for metering applications.

The important question is, however, how many of these batteries were returned because they failed. Engineers measure reliability in fit (failures in time). 1 fit corresponds to 1 failure in a billion (10^9) device-hours. Table 5 shows numbers. They prove that it is justified to consider this battery system as the most reliable one in the market.

The TLI – a High-end energy storage device

Sometimes, a primary battery is not needed but an energy storage device is necessary having a wide temperature range, low self discharge rate, high reliability or otherwise outstanding performance. In such cases, some customers are happy that the HLC is also available by itself. In this case it is marketed as TLI-type battery, usually equipped with additional safety devices, such as a PTC (re-settable fuse, Polyswitch). The temperature range of the TLI battery is from –40 °C to +85 °C, the leakage current is typically between 1 µA and 3 µA. A TLI battery of the 1020 size (diameter 10 mm, length 20 mm) has a nominal capacity of 30 As while the 1550 size (diameter 15 mm, length 50 mm) has 560 As. It is important to ensure that the charge conditions of the TLI device comply with its specification.

The charging mode is CCCV (constant current with constant voltage limitation). The maximum charging voltage must not exceed 4.1 + 0.05 Volts. The charging current must not exceed 6 mA for the small TLI battery and 100 mA for the large one. The TLI should not be discharged below 2.5 Volts because it may undergo irreversible degradation otherwise. Tadiran should have verified that the application data comply with these requirements. This ensures that the field reliability and safety level match those of Tadiran's primary and ***PulsesPlus*™** batteries mentioned above.

Tadiran Batteries GmbH

Tadiran Batteries GmbH is one of the leading manufacturers of primary (non rechargeable) lithium batteries in Europe. The company was founded in 1984 and has successfully served the market for 25 years.

Its **Lithium Thionyl Chloride (LTC) technology** is well established for more than 30 years. Tadiran LTC-Batteries are suitable where a 3.6 Volt high energy primary battery is required for up to 25 years stand alone operation, for example in smart utility metering.

The **PulsesPlus technology**, providing high current pulses in combination with high energy, has been successfully introduced into the market and plays a significant role especially in the asset tracking and monitoring market segment.

The **TLM technology** has been developed recently for applications requiring high power discharge after a long storage time, e.g. as a back up battery for emergency call devices in automotive telematic systems.

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