The Swiss ZEBRA® Battery System

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Summary

The ZEBRA® battery technology is available on the market again after it has been acquired by MES-DEA. A complete system with controller, charger etc is engineered and the application related issues as there are safety, recycling, life data, abuse behaviour are investigated. The industrialisation has been started.

1. Introduction

The ZEBRA® Battery technology returned to the market. After the discontinuation of the former joint venture that has developed this advanced battery technology within the recent 15 years it has been acquired by MES-DEA S.A. in Switzerland in total. This was possible because the decision for discontinuation was made two years ago for reasons related to the change of strategic considerations of the joint venture companies and not related to the maturity and potential of this technology. Therefore it was possible to start the industrialisation of the ZEBRA® technology now.

MES-DEA S.A. is member of a group of privately owned companies that produce components for the automotive industry (60%) and household appliance industry (40%) in large quantities. This mass production experience is now merged with the existing ZEBRA® technology [1-4].

2. The ZEBRA® Technology

The ZEBRA® battery technology uses nickel and salt as electrode material in combination with a β“-alumina ceramic electrolyte. The cell reaction is

$$Ni + 2NaCl \longleftrightarrow 2Na + NiCl_2$$

There are no other side reactions, the cells are hermetically sealed, the Ah-efficiency is 100%, the theoretical specific energy is 790 Wh/kg.
The molten salt $NaAlCl_4$ provides sodium ion conductivity within the cathode bulk material, overcharge and overdischarge capability, short circuit failure mode and cathode passivation in a crash situation [5].

2.1 ZEBRA® Cells

MES-DEA started production with the standard cell type ML3G – Table 1, Fig. 1.

Fig 1: ZEBRA® Cell

Capacity	32 Ah
OCV	2.58V
Normal charge voltage	2.67V
Fast charge voltage	2.85V
Max regeneration voltage	3.1V
Peak power	185W
(80% DOD, 2/3 OCV, 30s, 335°C)	
Max Current	+112A, -60A
Weight	715g
Dimension L x W x H	36.5 x 36.5 x 232 mm
Specific energy	115 Wh/kg
Specific power	259 W/kg

Table 1: Cell Data Type ML3G

The cells are connected in series and in parallel to achieve the desired voltage and capacity of different battery types. There are practically no limitations on the number of cells to be connected in series and in parallel because of the 100% Ah efficiency in combination with the reversible overcharge and overdischarge capability and the automatic balancing of current distribution due to the internal resistance characteristic respectively. Two other cell heights are available for batteries with 270mm and 210 mm height.

2.2 ZEBRA® Batteries

The production was started with the standard battery type Z5C [Table 2, Fig. 2] in a low voltage (OCV = 278V) and a high voltage (OCV = 557V) version.

The low voltage version is mainly used in cars and vans whereas the high voltage version is used for hybrid and electric buses and trucks.

		Z5-278-ML-64	Z5-557-ML-32
Capacity	Ah	64	32
Rated Energy	kWh	17.8	17.8
Open circuit voltage 0 - 15% DOD	V	278	557
Max. regen. voltage	V	335	670
Min. op. voltage	V	186	372
Max. discharge current	A	224	112
Cell Type / N° of cells		ML3G / 216	
Weight with BMI	kg	195	
Specific energy without BMI	Wh/kg	94	
Energy density without BMI	Wh/l	148	
Energy 2 h discharge	kWh	16.0	
Specific power without BMI	W/kg	169	
Power density without BMI	W/l	265	
Peak power 80% DOD, 2/3 OCV, 30s,335℃	kW	32	
Ambient temperature	℃	-40 to +55*	
Thermal loss at 270℃ internal	W	< 100	
Cooling		air	
Heating time from ambient	h	24 h at 230 VAC	
Periphery		BMI, Fan, Charger	

Table. 2: Battery Data Type Z5C

Fig. 2: ZEBRA® Battery Type Z5C

Prototypes of other battery sizes have been built. They demonstrate various ZEBRA® options [Table 3].

	unit	Z17	DERA
Capacity	Ah	60	128
Rated Energy	kWh	13.6	43.5
OCV	V	227	340
No of cells/cell type		264/ML8	528/ML3
Weight	kg	159	484
Peak Power	kW	29	79
Battery height	mm	210	300

Table 3: Other Prototype Batteries

ZEBRA® batteries are normal charged in 6-8 h (Fig. 3) and can be fast charged with a 1 h rating up to 80% SOC.

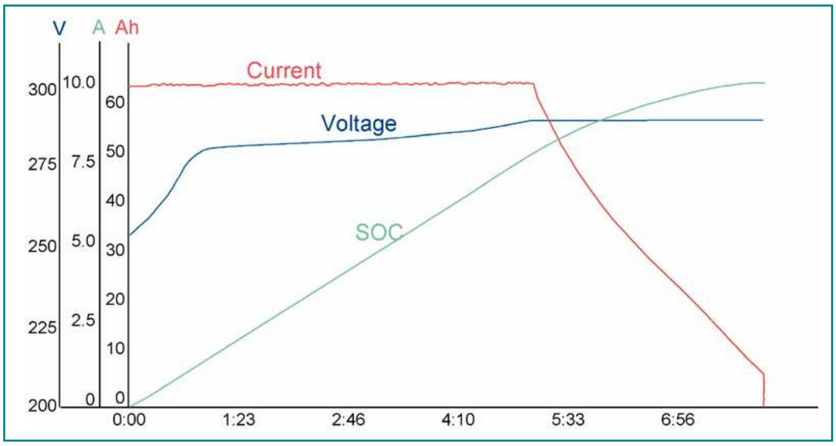

Fig. 3: Z5C Normal Charge in 7.5h

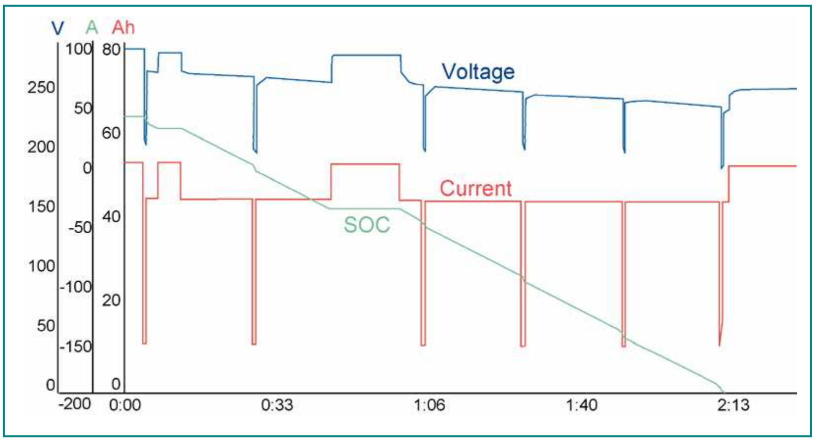

Fig. 4: Z5C 24 Discharge with 30s Peak every 20% SOC

Fig. 4 gives an example for a 2 h discharge with 30 s / 32 kW peak power pulses every 20% SOC. This shows the independance of peak power from SOC (Fig. 5).

2.3 Integrated Booster

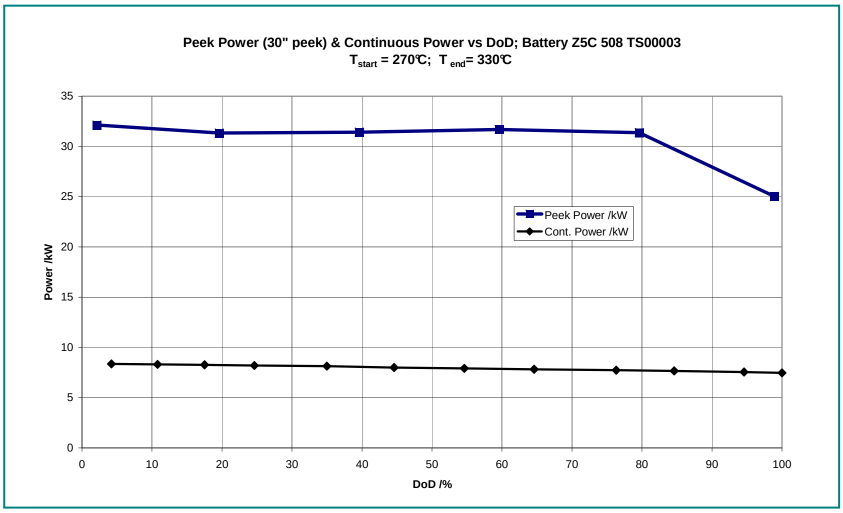

Fig. 5: Peak Power Independent of DOD

The ZEBRA® cell ML3G can be insulated in an equivalent circuit by two parallel cells, one stores most of the energy with the OCV of 2.58 V and the other is low resistive with OCV of 2.35 V. If high power is taken from the cell so that the terminal voltage drops below 2.35 V/cell the low resistive part becomes active. As soon as the terminal voltage rises above 2.35V/cell again, the low resistive part is recharged instantaneously. This results in the desired peak power independent from DOD (Fig. 5). The behaviour is similar to a capacitor operated in parallel to the battery.

2.4 ZEBRA® battery safety

For every battery type as an energy storage device the safety concept has to be regarded. For the ZEBRA® battery this has been worked out in great detail and investigated independently (Fig. 6) [3, 6]:

Fig. 6: Pole Crash Test with 50 km/h

1. The ZEBRA® chemistry contributes inherently to safety by the reaction of the liquid electrolyte with the sodium in case of a ceramic crack ($NaAlCl_4 + 3Na \longrightarrow 4NaCl + Al$). This reaction produces 1/3 less energy than the normal cell reaction, absorbs the available sodium and partially passivates the cathode. All materials have low vapour pressure even at high temperatures [7], so that no material escapes.

2. The container of ZEBRA® cells is made of steel and remains closed at high temperatures even if it is squeezed. This is confirmed as part of the cell qualification tests.

3. The Battery container is double walled and made out of stainless steel with a high temperature resistant thermal insulation (>1000℃). By the design even in the worst case of an internal short of a fully charged battery all the stored energy converted into heat is contained.

4. The battery controller permits operation only within the safe parameterwindow. A two pole circuit breaker is part of the battery and is opened if this window is surpassed.

5. When cooled down below 150℃ the battery is inactiv e, does not deliver energy and does not age.

2.5 ZEBRA® battery recycling

The recycling of ZEBRA® batteries is tested, established and included in the purchasing price. Nearly all material is reclaimed [8].

The worn out cells are sold to steel production plants where the contained nickel and steel is utilized in the stainless steel production process in which the salt and the ceramic content contributes to the slag.

2.6 ZEBRA® Life data

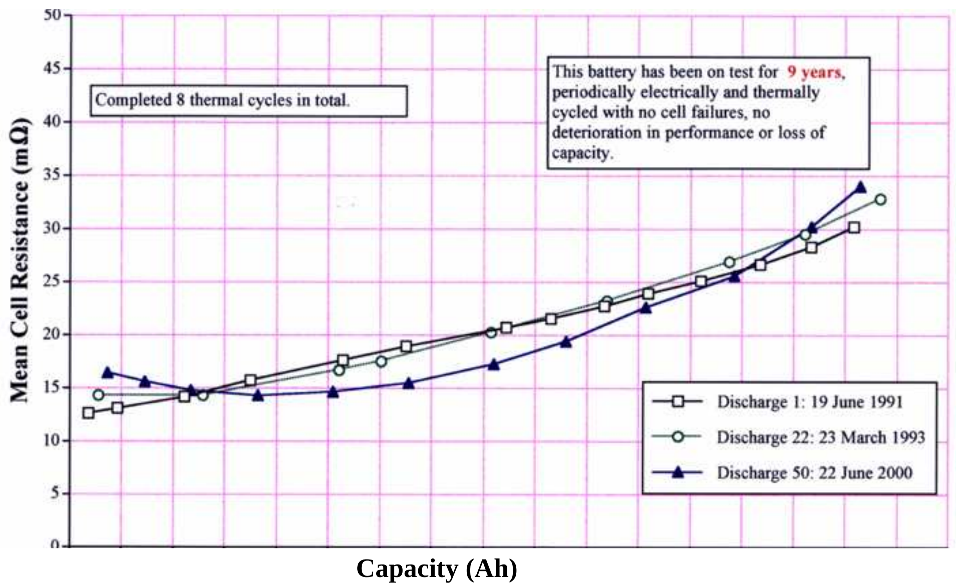

Fig. 7: Calendar Life Test

ZEBRA® is a long lasting battery because none of its materialpairs suffer corrosion. A calendar life test is ongoing since June 19, 1991 (Fig. 7) and confirms the accelerated test results that predict the potential for more than 10 years calendar life.

Cycle life data from laboratory and more than 500 batteries in the field result in an expected cycle life of more than 1000 nameplate cycles. This is supported by the ECN life cycle test (Fig. 8) in which

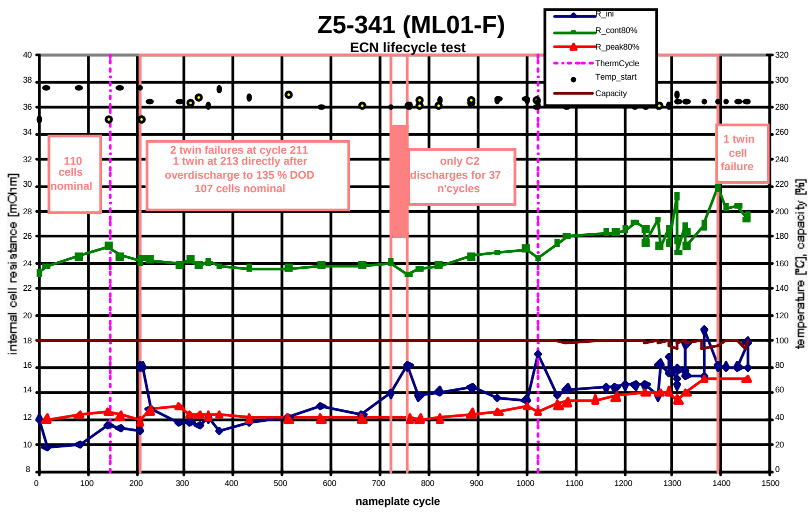

Fig. 8: ECN Life Cycle Test

even in case of cell failures after 211 cycles due to overdischarge of 135% because of a fault in the cycles 1450 nameplate cycles were demonstrated in a standard battery.

The cells just remained in the battery and no maintenance was done. A performance change was nearly not recognised. For shallow cycles like hybrid applications the indications lead to 1500 to 2000 expected nameplate cycles though the data base for this application is much smaller.

2.7 Comparison between ZEBRA® and NiMH

Both batteries are used for electric vehicles. A comparison of the technologies is summarised in table 4.

	ZEBRA®	NiMH
Specific Energy	high	medium
Specific Power	high	high
Ultra high power	not designed	available
Ah efficiency	100%	< 100%
Cell voltage	2.58 V	1.2 V
Cell capacity	32 Ah	96 Ah [11]
Delivered product	System	Modules
Cell failure mode	low resistive	different
Ambient temperature	-40 ℃ / +55 ℃ (*)	-10 ℃ / +40 ℃
Internal temperature	270 ℃ / 350 ℃	-10 ℃ / +50 ° C
Raw material	< 2 kg Ni/kWh	6.3 kg Ni/kWh [9]
Thermal management	included	-
Recycling	included	?

(*) due to electronic

At present NiMH batteries are used mainly in cars whereas ZEBRA® is mainly used in electric and hybrid vans and buses

Table 4 Technology of ZEBRA® and NiMH

3. ZEBRA® System Design

The ZEBRA® technology is engineered into a complete battery system ready to be assembled into a vehicle. (Fig. 2, 9)

It includes the battery controller, main circuit breaker, thermal management and on board

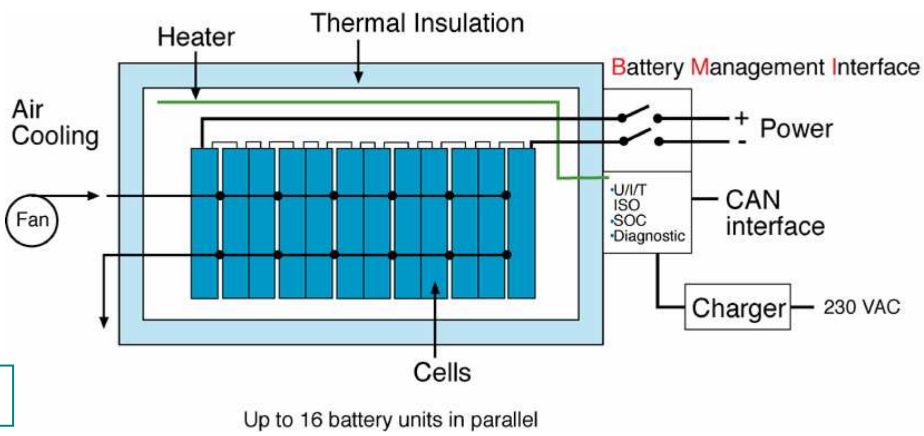

Fig. 9: Complete Battery System

charger. Up to 16 units equivalent to 285 kWh can be paralleled.

The thermal Losses of the battery are minimized by using a very good insulation with only 0.006 W/mK thermal conductivity.

The effective thermal loss of the battery is further reduced dependent on the idensity of usage because the internal electric losses are stored as thermal energy using the heat capacity of the cells.
Fig. 10 shows the reduction of the effective thermal loss dependent on the usage. As a standard cycle a 2 h discharge with 6 times peak power according to fig. 4 is assumed. This is just used as an example, the temperatur is controlled by the battery controller (BMI)

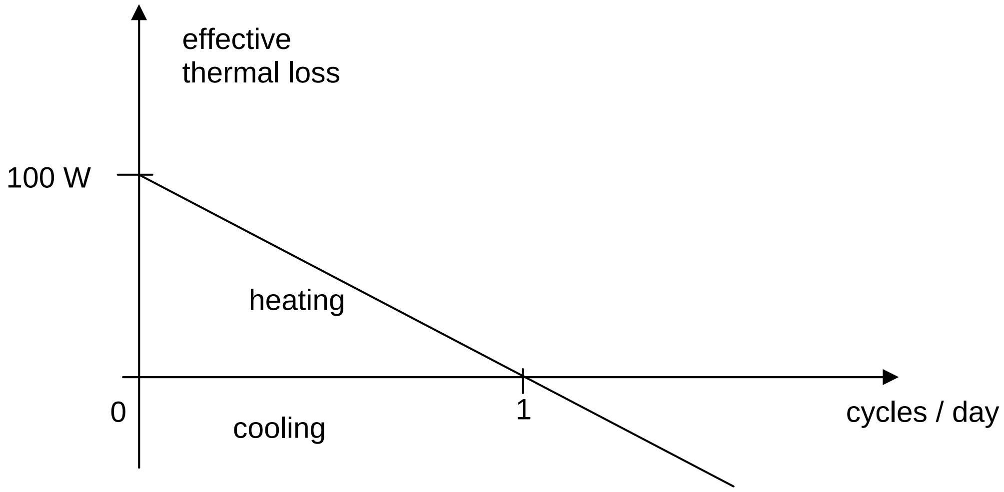

Fig. 10: Effective Thermal Loss Vs Intensity of Usage

The controller and main circuit breaker are integrated in one unit which can easily be unplugged for replacement. The modular charger can be 3kW or 6 kW per module. The battery life data are continuously updated and permanently stored at the battery. This allows to establish a life data base.

The interface of the ZEBRA® battery system is reduced to:

- power lines 300V or 600V
- AC-input
- Ignition key input
- 12V or 24V auxiliary system voltage
- CAN communication
- emergency switch input

4. ZEBRA® Battery Production

The ZEBRA® battery production facilities are in operation again and additional equipment is ordered. A new plant is under construction (Fig. 11).

Fig. 11: The New ZEBRA Plant

The production ramp up is planned in phases of 400, 5k, 30k and probably more units per annum dependant on the demand.

5.Applications

The smallest reasonable unit size is about 10kWh for ZEBRA® whereas there is no principle limit at the upper end. The present standard battery is the Z5C which is used for different applications. A very well accepted vehicle is the DimlerChrysler VITO for city logistics fig. 12 (10) and as another example the bus fig. 13 which is available in an electric and a hybrid version both with ZEBRA®.

Capacity	**6+1 Seating**
Payload	**600kg**
Drive	**AC**
Drive Power	**40 kW**
Type of Battery	**2 x Z5C**
Energy Content	**35,6 kWh**
Battery Voltage	**279V**
Weight Battery	**400 kg**
Maximum Speed E	**120km/h**
Range	**120 – 150 km**

Fig. 12: DaimlerChrysler VITO for the German Postal Service

	Hybrid	Electric
Capacity	**10+1 Seating**	**10+1 Seating**
	29 Standing	**29 Standing**
Drive	**Brushless DC**	**Brushless DC**
Drive Power	**50 kW**	**50 kW**
Type of Battery	**2 x Z5C**	**5 x Z5C**
Energy Content	**35,6 kWh**	**89 kWh**
Battery Voltage	**279V**	**279V**
Weight Battery	**400 kg**	**1000 kg**
Maximum Speed	**50km/h**	**60km/h**

Fig. 13: AUTODROMO City Bus in Bologna, Italy. In Service

Other projects for transit buses (214kWh), School buses (125kWh) and shuttle buses are in preparation. Part of our test program uses Twingo's (Fig. 14). The availability of this battery technology will enable the operation of electric and hybrid commercial vehicles in a more extended way.

Fig. 14: TWINGO Component Test Fleet

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