

# Development of New Types of Zebra Batteries for Various Vehicle Applications

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## Abstract

Several new types of Zebra batteries have been developed for various vehicle applications. The standard Z5 Zebra battery is produced primarily for the bus and commercial vehicle market. Other vehicle applications such as small city EV's, small hybrid vehicles and some large vehicles require very different specifications to the standard Z5 battery. Most small EV's require low overall height batteries <250mm, small hybrids require high power density >350W/kg and with extremely large vehicles there is an advantage in battery size being increased to over 40kWh. The development of cells and batteries to meet these different applications is described. A new low height cell has been developed and batteries produced from these cells have been tested in SMART vehicles. A high power cell has been developed and tested based on a multi-tube ceramic structure. A 60 cell prototype battery with a nominal energy of 6kWh has been tested. Using the present standard 32Ah cells, large 43kWh single unit batteries with a 30 second pulse power at 80% DOD of 80kW have also been developed and tested. The results from these various batteries show that the Zebra system can be developed to meet the many varied requirements of electric and hybrid vehicles. Potential future improvements are also discussed.

**Keywords:** Sodium-nickel-chloride, battery

## 1 The Zebra System

The Zebra cell has a central positive electrode consisting mainly of nickel and sodium chloride together with a liquid electrolyte tetrachloroaluminate contained within a beta alumina tube electrolyte. A schematic of the cell is shown in Figure 1. The cell operates in the temperature range 270°C - 350°C and during charging sodium ions move through the wall of the beta alumina to form the liquid sodium negative electrode which is contained by a square section mild steel cell case. The cells are contained in a thermally insulated box.

The main cell reaction involves chlorination of nickel to form nickel chloride and sodium. The overdischarge reaction allows assembly of cells without addition of elemental sodium.

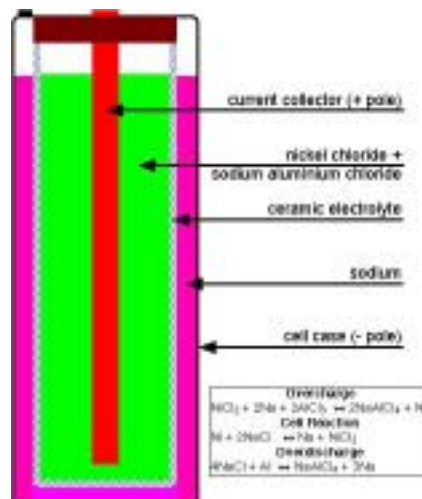


Figure 1: Schematic of Cell

## 2 Key Features of the Zebra System

- The original development of the system was started because of the high energy density that could be achieved. Batteries are now currently being produced that are >100Wh/kg for the complete Zebra system ie cell pack, battery housing, cooling system, management system etc. This enables pure electric vehicles to have ranges greater than 120 miles and with the present power density of >150W/kg these EV's have a performance similar to IC powered vehicles.
- The chemistry, design and construction of the system gives many other very important benefits that contribute to the life, reliability, abuse resistance, safety and general wide applicability of Zebra.
- The sodium ion conducting beta alumina is an electronic insulator and as there are no chemical side reactions the cell is 100% coulombically efficient (Ah charge in = Ah discharge out). There is no self discharge and the cell is fully sealed and maintenance free (there is no overcharge gassing reaction as in lead acid). Accurate charge control and measurement is therefore easily possible and cell in series chains can not get out of step. These features also confer a high efficiency on the system.
- Zebra cells fail to low resistance so series connected strings containing failed cells will continue to operate. This feature, and the fact that cells can not get out of step, enables high voltage chains to be used with no high over voltage cell safety problems. Electronic by pass devices and balancing charging methods are not needed. 600V Zebra batteries are currently being used in several bus applications.
- Unlike several other systems the discharge capacity is independent of the rate of discharge (the energy obtained is only reduced at high rates by the reduced voltage efficiency). Cells can also be cycled to full nameplate capacity at high rates without any deleterious effects. They are not limited to 70-80% capacity as with some other systems.
- There is an overcharge and an overdischarge reaction which enables cells to be relatively abuse resistant. (In routine safety tests cells are overcharged to 50% above the normal charging voltage).
- The high temperature operation gives the system many advantages. As the cells operate at around 300°C within a well insulated box the battery performance is completely independent of ambient temperature. This has been demonstrated with vehicles tested in desert and arctic condition and in climatic chamber tests from -40°C to +70°C. Thermal management in high power applications is much easier than with ambient temperature systems because of the large temperature difference between the operating cells and the coolant. The battery can also be utilised as a heat store (the battery cooling system can be integrated into a vehicle heating system). This is particularly useful for pure electric vehicles, as it avoids the use of a polluting fossil fuel cab heater and instant heat is available at the start of a journey.

## 3 Standard Z5C Battery

The specification of the Z5C production battery is shown in Table 1. A Z5C production battery is shown complete with a battery management interface in Figure 2. The battery contains 216 cells and is available in two voltages 278V and 557V. It has a specific energy of 91.2Wh/kg and a specific power of 164W/kg; the height of the battery is 300mm.

As Zebra cells fail to low resistance long series chains can be connected. This feature, and the fact that cells can not get out of step, enables high voltage chains to be used with no high over voltage cell safety problems. The standard Z5C production is being produced primarily for the bus and commercial vehicles which mainly require high voltage systems ~600V. Figure 3 shows a bus powered by 557V Z5C production batteries.



Figure 2: Z5C Battery

Table 1: Technical Data MES-DEA production Z5C Zebra Battery

Type	unit	Z5-278-ML-64	Z5-557-ML-32
Capacity	Ah	64	32
Rated energy	kWh	17.8	17.8
Open circuit voltage	V	278.6	557
Max regen. voltage	V	335	670
Min operating voltage	V	186	372
Max Discharge current	A	224	112
Cell type /No. of Cells		ML3/216	
Weight with BMI	kg	195	
Specific energy	Wh/kg	91.2	
Specific Power	W/kg	164	
Energy 2h discharge	kWh	16	
Peak power	kW	32	
Thermal loss	W	<120	
Cooling		Air	
Heating Time	h	24 at 230Vac	
Ambient temperature	° C	- 40 to + 70	
Dimensions (WxLxH)	mm	533 x 833 x 300	



Figure 3: Autodromo Bus

## 4 Low Overall Height Batteries

A new lower height cell has been developed named ML8 and low height B1 batteries (210mm high) produced from these cells have been tested in SMART vehicles. The specifications of the ML8 cell and B1 battery are shown in Tables 2 and 3 respectively. The battery contains 264 cells configured in 3 parallel chains of 88 cells. It has a specific energy of 85.5Wh/kg and specific power of 182W/kg. The battery is shown in Figure 4.

Table 2: ML/8 Cell Specification

Type	unit	
Capacity	Ah	20
Rated energy	Wh	51.6
Open circuit voltage	V	2.58
Max regen voltage	V	3.1
Min operating voltage	V	1.72
Max Discharge current	A	80
Cell type		ML/8
Weight	kg	0.464
Specific energy	Wh/kg	111
Specific Power	W/kg	220
Energy 2h discharge	Wh	46.0
Peak power	W	102.1
Dimensions (WxLxH)	mm	36.5x36.5x146.4

Table 3: B1 Battery Specification

Type	unit	
Capacity	Ah	60
Rated energy	kWh	13.6
Open circuit voltage	V	227
Max regen voltage	V	273
Min operating voltage	V	151
Max Discharge current	A	240
Cell type /No. of Cells		ML/8 264
Weight with BMI	kg	159
Specific energy	Wh/kg	85.5
Specific Power	W/kg	182.4
Energy 2h discharge	kWh	12.0
Peak power	kW	29
Thermal loss	W	<100
Cooling		Air
Heating Time	h	24 at 230Vac
Ambient temperature	° C	- 40 to + 70
Dimensions (WxLxH)	mm	490x970x210



Figure 4: Smart Battery

The battery fits across the vehicle and under the floorpan of the SMART vehicle leaving the vehicle interior virtually standard. The vehicle has a top speed limited to 100Km/h and a range of approximately 100km under normal urban driving conditions. Figure 5 shows the SMART vehicle.



Figure 5: Smart Car

Using a low height cell has slightly reduced the specific energy, however, it is still above 85Wh/kg and the specific power has improved to  $>180\text{W/kg}$ .

## 5 Large Single Unit Batteries

Large 43kWh batteries have been developed for military use. The requirements for a battery system for a military hybrid vehicle are:-

- High power density
- High energy density
- Low cost
- Reliability
- Safety
- Abuse resistant
- Long term cold storage

As already discussed in the key features, the Zebra battery meets these requirements. The ability to be stored indefinitely with no deterioration and no requirement for maintenance is especially useful. In military applications batteries could be stored for many years before they are used in service [1]. The specification of the B3 battery is shown in Table 4. A B3 battery is shown complete with the Battery Management Interface (BMI) in Figure 6.

Table 4: B3 Battery Specification

Type	unit	
Capacity	Ah	128
Rated energy	kWh	43.5
Open circuit voltage	V	340
Max regen voltage	V	409
Min operating voltage	V	227
Max Discharge current	A	448
Cell type /No. of Cells		ML/3 528
Weight with BMI	kg	492
Specific energy	Wh/kg	88.4
Specific Power	W/kg	160.6
Energy 2h discharge	kWh	38
Peak power	kW	79
Thermal loss	W	<200
Cooling		Air
Heating Time	h	24 at 230Vac
Ambient temperature	° C	- 40 to + 70
Dimensions (WxLxH)	mm	940x960x315

The maximum peak power delivered at the end of a 30 second pulse versus depth of discharge at cycle 4 is shown in Figure 7. It can be seen that even at 100% depth of discharge 65kW of power is available. Figure 8 shows a typical land-based vehicle in which B3 batteries can be installed



Figure 6: A 43kWh B3 Battery

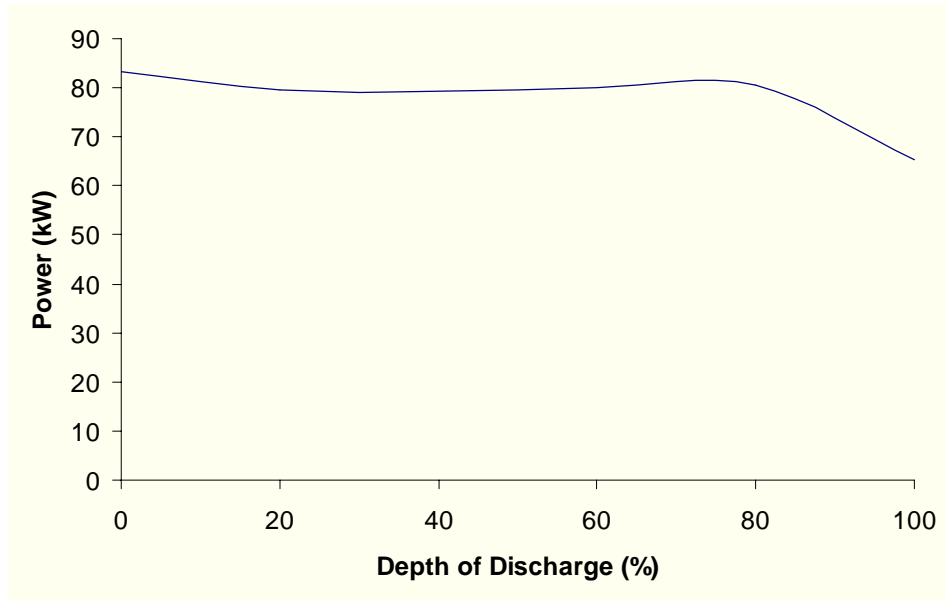


Figure 7: Power vs DoD for B3 Battery



Figure 8: A Typical Combat Vehicle

## 6 High Power Batteries

The power output is highly dependent on the available surface area of the beta alumina ceramic and the positive electrode thickness. To achieve the present battery power density of approximately 160W/kg a circular beta alumina tube was replaced with a cruciform shaped ceramic which increased the surface

area by a factor of about 1.5. The present batteries are suitable for pure electric and large hybrid vehicles such as hybrid buses. Other hybrid vehicles such as small cars require higher power densities, for which Zebra cells would require a large increase in beta alumina surface area and reduction in electrode thickness. High surface area multi-tube type cells have been demonstrated which achieved power densities of 400W/kg. The beta alumina ceramic assembly for the design tested consisted of 25 small tubes each individually sealed to a common heater. A 60 cell prototype battery with a nominal energy of 6kWh and specific energy of 72Wh/kg and a specific power of 295W/kg was constructed and tested. The specification of the battery is shown in Table 5.

Table 5: Multitube Battery Specification

Type	unit	
Capacity	Ah	38
Rated energy	kWh	6.0
Open circuit voltage	V	155
Max regen voltage	V	186
Min operating voltage	V	103
Max Discharge current	A	250
Cell type /No. of Cells		MT/ 60
Weight without BMI	kg	83
Specific energy	Wh/kg	72
Specific Power	W/kg	295
Peak power	kW	24.5
Thermal loss	W	<75
Heating Time	h	24 at 230Vac
Ambient temperature	° C	- 40 to + 70
Dimensions (WxLxH)	mm	415x663x260

The cell design was too complicated and costly with the individually sealed tubes. However, recently a project has commenced called CHEETAH sponsored by the European Commission, to develop a low cost extruded high surface area thin wall ceramic. This will enable batteries to be produced with a specific power up to 800W/kg.

## 7 High Specific Energy Batteries Operating at Extreme Temperatures

Development of Zebra batteries for an unusual vehicle was recently commenced. The vehicle is a geostationary platform held at 20km altitude capable of remaining on station for 5 years. Payloads are to include high speed internet services, direct broadcast TV, digital radio, mobile telecomms and surveillance. The battery requirements are for a high specific energy (>110Wh/kg) for a complete system, high reliability and stability of performance (>5 year life and <10% reduction in performance) and operation low temperatures (-55°C).

Zebra is ideally suited for this application. The performance has been shown to be completely independent of ambient temperature [2], a calendar life >10years has been demonstrated [1] and modules and batteries have demonstrated the required electrical cycle life. Improvements in energy density for road vehicle applications are underway [3] and high specific energy (110Wh/kg) telecomms batteries have been demonstrated. A demonstrator vehicle is shown in figure 9.



Figure 9: StratSat Communications Platform

## 8 Summary

The various batteries that have been described illustrate the various attractive features of the Zebra system. Complete single unit systems have been demonstrated from 6 to 43kWh with specific energies up to 110 Wh/kg and power densities up to 295W/kg. The flexibility of geometry and overall size, the ability to achieve high voltages, performance independence of extreme temperatures and development to give high power densities has been shown. The series production of standard traction Zebra batteries has started at the MES-DEA factory in Stabio and development work is progressing to further improve future performance.

## 9 References

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