Range Extender for Seldom Use in the Electric Car MUTE – Zinc Air Battery
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ABSTRACT: The main problems of electric cars today are the purchase price and the small range. Responsible for both is the battery technology. By including range extender (RE) systems into the car these problems can be reduced. This paper describes a zinc air RE for seldom use in electric cars. Its aim is to enlarge the range in special situations but not for the daily use. A study [1] shows that a range of 100 km per day is suitable for 90 % of the daily trips of a year in Germany. The electric car MUTE includes a zinc air range extender and is designed to show that a small regional used car can fulfil the needs of drivers for commuting and shopping. Using a zinc air range extender, the car is completely independent from fossil fuels. Out of measurements with MUTE zinc air batteries and reference data the zinc air technology for the application as RE is discussed. This contribution shows that zinc air technology has several disadvantages compared to lithium ion batteries or common range extenders with an internal combustion engine.

Keywords: Range Extender, Zinc-Air Battery, MUTE, BEV

1. INTRODUCTION

The main problems of electric cars today compared to cars with internal combustion engine are the purchase price and the small range. These issues are due to the battery technology. One way to solve these problems is of course to enhance the battery technology. Another way is to include a range extender (RE) system into electric cars in addition to the main battery to keep this battery as small as it could be. In the automotive industry small internal combustion engines are favoured for use as REs. Often those kind of RE are planned also to be able to power the electric motor of the car on their own without using energy from the main battery. These kind of electric cars can get almost unlimited range by refuelling them, but the advantage of electric cars, not to produce local emissions, is gone. It is questionable if a RE like this is really desirable and necessary. A study shows that 100 km per day is a sufficient range for car drivers in Germany on 90 % of days in a year [1]. Especially if it is a family that has two cars. The first car could be the one with large range while the second car is only used for commuting and shopping. Drivers who have only one car could use a car with 100 km of range by using other means of transportation if they need more range. The electric car MUTE developed by the Technical University of Munich is designed to reach a range of 100 km in any case. Only for the assurance of also being able to reach the destination in special situations, which cannot be planned beforehand, the electric car MUTE needs a RE. This RE is intended for example for driving around road-work, which we only expect to happen a few times a year. Thus a RE for seldom use would be sufficient. As reported before [2], by using zinc air batteries like RE MUTE an electric car with RE is totally independent from fossil fuels.

The main important application for zinc air batteries today are as power supply for hearing aids. Those batteries have a specific energy of about 1.5 times of lithium-ion batteries [3]. These button cells are primary batteries without the option of recharging mechanically or electrically. Generally it is possible to design zinc air batteries for other applications, e.g. for traction, as rechargeable systems to be recharged either in one or the other [4, 5].

Electric rechargeable zinc air batteries reach a life of a few hundred cycles. This is far from the needs of electric cars if the battery is used as main energy storage. As expected in [6], electrically rechargeable zinc air systems should be feasible and were close to market placement but they have not been placed on the market until today. As shown in [2] the usable capacity of zinc air batteries is decreasing significantly if the battery has to deliver high power like in applications such as traction systems. Thus the advantage in specific energy compared to lithium-ion batteries as described in [3] is much lower for high power applications. The remaining problems of the shape change of the anode caused by the dendrite growth [6] responsible for the poor cycle life and the lower than expected specific energy [2] might be reasons why this kind of zinc air battery has not been successful up to today.

Other challenges are the water management, the realisation of a long-living bifunctional air electrode and to avoid the carbonation of the electrolyte [6]. Reasons why open systems like metal air batteries could not be maintenance free.

To avoid some of the disadvantages listed here, the zinc air battery can also be designed as a mechanically rechargeable system. Then the dendrite growth and the lack of water management do not affect the performance of the battery any more. In this case, the anode consisting of zinc and electrolyte will be replaced after discharging the system and can be regenerated in a plant [6]. This is of course more effort for the car owner than the electrically rechargeable zinc air battery. The necessity to exchange at least the anode material several times a month is not desirable. This might be the reason why systems like that are also not successful as main energy storages in electric cars up to today.

Although both types of zinc air systems seem not to be applicable as main energy storage, the mechanically rechargeable one could be useful as RE for electric cars, which was suggested in [2]. Until today they were not investigated for the use as RE in applications of seldom use per year. Regarding the mentioned study [1], a mechanically rechargeable zinc air system could be feasible for a seldom used RE. Then the anode material or the whole battery only has to be exchanged a few times a year, which might be acceptable for the car owner. As suggested in [2] the manually exchange of zinc air battery modules at service stations is suggested. The electric car MUTE is designed to carry six zinc air battery modules consisting out of 36 cells each. An air management system including a system to avoid the entry of CO_2 into the zinc air cells is suggested to prevent carbonation of the electrolyte.

In this contribution, the use of zinc air batteries as RE for seldom use is analyzed. The advantages and disadvantages of this technology for this application are discussed.

2. RANGE EXTENDER FOR SELDOM USE

2.1 Approach

In [2] first experiments were reported to estimate properties of a zinc air RE for the electric car MUTE. Out of different starting times of the RE at different states of charge (SOC) of the main battery, possible additional ranges of the car were calculated.

In this contribution a suggestion for a complete zinc air RE concept will be presented at first. The zinc air cells designed for this RE will be measured and analysed. Out of the data the RE of MUTE will be calculated and compared to possible zinc air batteries of other publications. Advantages and disadvantages of the zinc air technology relating to the usage as RE in electric vehicles will be listed.

2.2 Range Extender concept for MUTE

The electric car MUTE is a new concept for an electric car for regional use and was presented at the International Motor-Show in Frankfurt, Germany in 2011. The concept was built by the Technical University of Munich to show that an electric car can be designed to fulfil the needs of drivers for regional use cases while the car is affordable and in total cost of ownership is as cheap as a small car with internal combustion engine of today. This car is cost effective and lightweight due to the small battery capacity of the main battery needed to reach a guaranteed range of 100 km. By the use of small lithium ion battery cells type 18650, a standard used for laptops, a certain safety standard is secured. [7]

MUTE has two power sources. The main battery, which is placed between the seats and the rear wheels, and the zinc air RE, which is placed in the collapsible front part of the MUTE [2]. The position for the RE is feasible because zinc air batteries are short circuit proof [8]. There is no danger of explosion or fire caused by zinc air batteries. This is an advantage of the zinc air technology compared to common lithium ion batteries. The main battery in contrast, which is a lithium ion battery as reported, has to be placed in the safest area in the car.

The zinc air RE is planned to be used only seldom times a year. Normally the capacity of the main battery should be enough for the driver to fulfil his needs. As described in [1] 100 km range is enough for most of the daily uses of the car for commuting, shopping and other regionally based use cases. Only for emergency situations when additional range is necessary should the zinc air RE be employed. If the RE was used, the modules have to be replaced by new ones at a service station. Therefore the user can get access to the zinc air modules by opening a front hood included to the front apron of the car. Now it is possible to take out the modules by pulling them out of the car by hand. For manual handling the modules have a planned weight of about 7 kg and a handle at the front. The discharged modules will be sent back to the plant for regeneration of the anode material. The housing and the air electrode are planned to be used again. After that the modules can be sold again in the service stations.

The RE of MUTE consists of 6 modules including 36 zinc air cells electrically connected in series. The modules of the RE are electrically connected in parallel. In figure 1 a module is shown. On top of each module systems to open and close the air ducts of the cells are included. On one side of the cells the air gets into the air ducts and gets out on the other side again. An air management system for the RE is included to the car and remains in the car while the modules are exchanged. It consists of the fans for the air supply for the modules, actuators to open and close the air ducts and a CO_2 filter system. The task of the air management system is to feed the zinc air cells with fresh air without CO_2 to enable the cells to work. For the RE no additional cooling of the cells is necessary. The RE is connected to the main battery by a DC/DC converter. This is necessary because the main battery has a voltage level of 325 V while the zinc air RE has a voltage level of 50 V. As the RE is placed in the collapsible zone it is important to avoid high voltage systems to be damaged in car crashes. In operating conditions of electric systems, which can be touched by a person, voltages below 60 V are accepted [9].

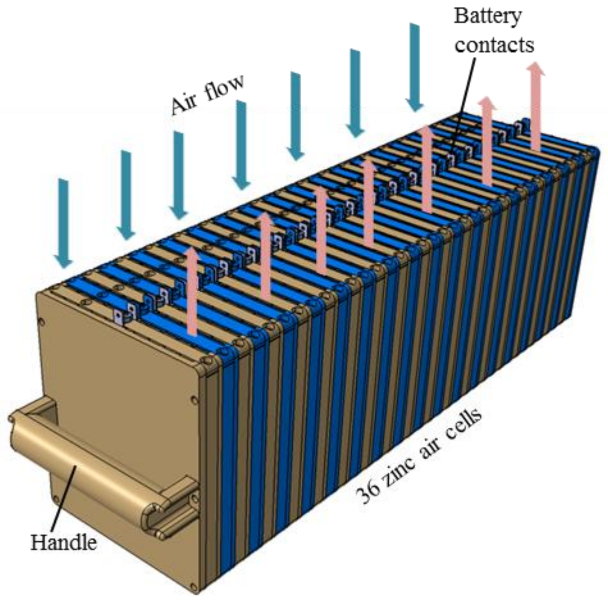

Figure 1: Zinc air module of MUTE

The MUTE RE works as a charging system for the main energy storage or to drive the electric motor by the RE or partly by the RE together with the main energy storage. Especially for accelerating phases, the output power of the RE is too low to feed the electric motor on its own. Hence, an energy management is required, because it is necessary to start the RE at a certain SOC of the main battery to be able to use the RE. There must be some energy left in the main energy storage for accelerating. [2]

2.3 Experiments

2.3.1 Zinc air cell for MUTE

The zinc air cells for MUTE were designed at the Institute of Automotive Technology of the Technical University of Munich. They have a width of 114 mm, a height of 133 mm and a length of 11 mm. The surface of both air electrodes together is 220 cm². The assembly of the cell is shown in figure 2. The main body which carries the anode bag filled with zinc powder has two air electrodes on the front and the rear side. The cell is sealed by several seals between the air electrodes and the main body as well as between the main body and the top cover. The top cover has a hole to be able to fill the finished cell with electrolyte. Afterwards the hole can be sealed by a screw. The air electrodes are stabilized by cappings including air ducts. Thus air can flow along the surface of the air electrodes from the top of the cell downwards and upwards again. For the application in the modules of MUTE there is always one capping between two cells including the air ducts for both cells.

The anode contact is realized by metal rod extended into the anode bag with the zinc powder. It goes through the top cap so that it can be connected electrically. The cathode contacts are placed at the top of both air electrodes. They are squeezed together with the air electrode by the cappings. They also can be connected electrically on the top of the cell.

An important property of zinc air batteries has to be taken in consideration. During discharge the volume of the anode material grows. Thus additional volume has to be provided in the cell. In the MUTE cell this is realized by the structure of the main body. At the sides and on the bottom of the main body flexible walls are integrated. During discharge and volume growth, they will be pushed to the walls of the main body. Thus the anode material has enough space for volume growth. This structure has a positive side effect that can be used for the cell. Between the flexible walls and the walls of the main body there is only electrolyte without zinc powder. Due to the volume growth of the anode material this electrolyte will be pumped through small holes into the anode bag and refreshes the electrolyte there. To avoid the leakage of the cell during this process, the cell is not filled with zinc powder and electrolyte up to the top.

The employed air electrodes for the MUTE zinc air cells are BiPlex gas diffusion electrodes with porous PTFE-foil from the Gaskatel GmbH, Germany. They comprise of manganese oxide and carbon plated on a gold-plated nickel mash. The zinc powder derives from the Grillo-Werke AG, Germany. The used type G 8-0/300Bi/300/ln has a very good surface-to-volume ratio which is important for high power applications. The main particle size lies between 25 and 75 µm. As electrolyte potassium hydroxide solution with 40 % potassium was used.

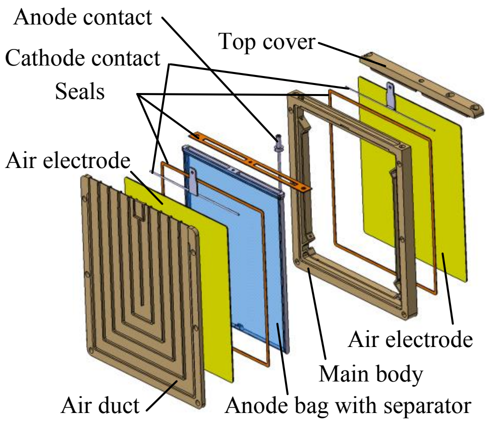

Figure 2: Zinc air cell of MUTE

2.3.2 Experimental setup

For the experiments, the cells were simplified. Since there is no need for mechanically recharging, anode bags like the ones shown above are not necessary. The separators are placed directly at the air electrodes. Through the hole on the top of the main body it is possible to fill the cells with zinc powder and electrolyte. The pump mechanism for the electrolyte during discharge and volume change of the anode material works without problems then. For every experiment a new cell was built.

The measurements were done at the Institute for Electrical Energy Storage Technology, Munich, Germany with the measurement system BaSyTec HPS from the BaSyTec GmbH. Therefore the same test program as in [2] was used. It starts with 3 secs of measurement with time steps of 20 msecs to get a high resolution of the discharge curve at the beginning, followed by 300 secs of measurement with time steps of 1 sec. Finally the measurement period is changed to time steps of 20 secs until a voltage of less than 0.1 V is reached.

Table 1: Fillings of the test cells

	Cell 1	Cell 2	Cell 3
Weight of zinc [g]	186.0	195.1	175.5
Weight of electrolyte [g]	60.0	62.0	54.4
zinc-to-electrolyte ratio	3.1	3.1	3.1
Weight of the filled cell [g]	348.6	360.5	334.3

The discharge was done with a constant current of 16.2 A while the voltage and the energy content of the test cell were measured. In total three test cells were built and measured. To ensure a constant air flow through the cells a fan was placed on one side of the top of the cell. It was connected to an external power source.

2.3.3 Results

The discharge curves show in general the expected shape of discharging zinc air batteries as shown in [2]. Figure 3 shows the discharge of the three zinc air test cells at 16.2 A of constant current. Compared to the test cells of [2] with the equivalent discharge current relating to the surface of the air electrodes, the MUTE zinc air cells show a larger voltage drop than the small test cells of [2]. In Table 2 the measured properties of the cells are listed.

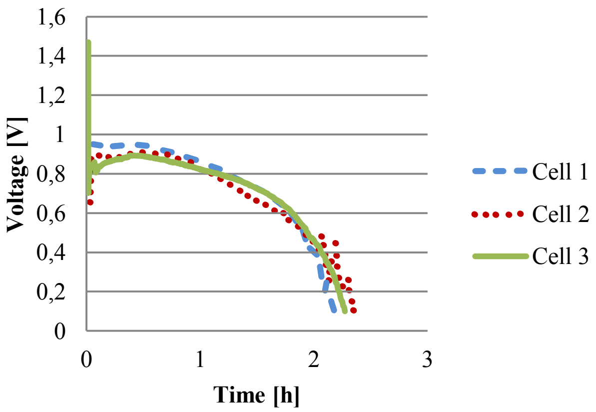

Figure 3: Discharge curves

Table 2: Properties of the cells

	Cell 1	Cell 2	Cell 3
Open circuit voltage [V]	1.45	1.45	1.47
Capacity [Ah]	34.7	38.0	36.5
Capacity [Wh]	26.7	26.6	26.4
Energy density [Wh/l]	40	40	40
Specific Energy [Wh/kg]	77	74	79
Specific Power [W/kg]	44	41	43

2.3 Zinc air range extender

Out of the measurement data a range extender for MUTE was calculated. Calculations based on cell 1 show that the RE does not exceed a maximum power of 3340 W. This is less than expected in [2] and is due to the higher than expected voltage drop of the cells at a constant current of 16.2 A. On the contrary the capacity of 5770 Wh is higher than needed for the MUTE. The total weight of the anode material in this case is 53 kg. In Figure 4 the power output of this zinc air range extender is shown. Compared to common range extender systems with internal combustion engine the power output is not constant. It decreases during discharge.

For MUTE a zinc air range extender with 4000 W of maximum power, 4000 Wh of capacity and 40 kg of anode material was planned [2]. Taking into consideration that in this configuration the capacity and thus the weight of the anode material are too high, a correction can be calculated. Then the capacity is reduced to

4000 Wh by reducing the weight of the anode material to 37 kg. The maximum power remains at 3340 W. While the energy density decreases to 28 Wh/l and the specific energy decreases to 53 Wh/kg, the specific power increases from 44 W/kg up to 55 W/kg. If the MUTE zinc air battery would be redesigned, the energy density and the specific energy could stay the same while just the specific power is rising because cells could be designed smaller.

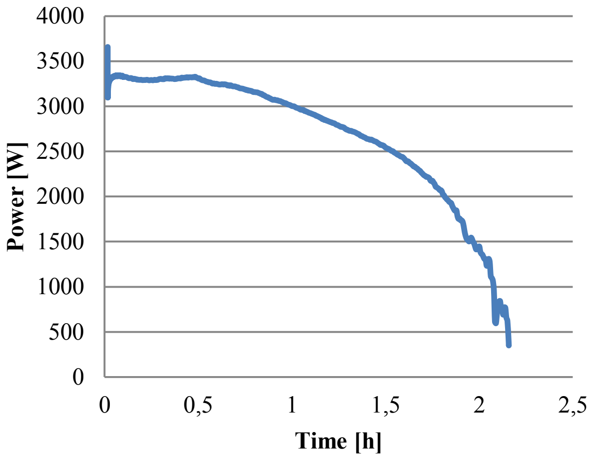

Figure 4: Power output of the range extender

The measurements and calculations show that a system like that is feasible although the power output is not as high as expected. Additionally it is important to consider, that the power output is not constant. It decreases over the whole discharge time as shown in figure 4.

Regarding other zinc air cells built in the past improvements of the MUTE zinc air cells are to be expected. In [10] a zinc air system is described as having an energy density of at least 160 Wh/l and a specific energy of at least 220 Wh/kg while the specific power of at least 60 W/kg is not much higher than the calculated specific power of 55 W/kg for the revised MUTE zinc air cell presented here. The maximum specific power of 80 W/kg mentioned in [10] would lead to a RE of at least 50 kg of weight if the RE should have a power output of 4000 W.

In times when energy in general is getting more and more expensive, it is important to use the energy provided with high efficiency. But the efficiency of battery systems varies strongly from one cell chemistry to another. Especially zinc air systems show low efficiencies. Starting from the electrons that one zinc atom can deliver, the capacity in Ah of a certain amount of zinc was calculated. With a charge of one electron of $1.6022*10^{-19}$ C, an atom weight of zinc of 65.409 u - u being equivalent to $1.660540*10^{-27}$ kg [11] - a theoretically available charge of the MUTE zinc air cell 1 was calculated of 152 Ah. The measurement shows a capacity of 34.7 Ah. The difference is caused by discharge overpotentials [6]. The reduction of the usable capacity increases by higher discharge rates as reported in [2]. Thus the efficiency of the MUTE zinc air cells can be calculated to 23 % in this high power application. In [12] an efficiency for the Electric Fuel zinc air battery system of 57 % is reported. There the efficiency was measured as the difference between the energy invested during charging and the energy returned from the battery during discharge.

3. DISCUSSION

Zinc air systems were investigated several times for different applications like button cells or main energy storages for electric vehicles since the 1960ies. Until today only special applications like button cells for hearing aids seem to achieve acceptance. In this contribution the application as RE system for seldom use in electric vehicles was analysed.

To be able to evaluate zinc air batteries for the application as RE for seldom use, advantages and disadvantages are considered. One advantage is the long storage life if the cells are sealed. This is a very important property and can be seen as a basic requirement for a RE which will be used only seldom times a year. Electric storage systems in general enable vehicles to become independent from the finite resources of fossil fuels and to use renewable energy sources for traction applications, which is another advantage of the technology.

But there are several disadvantages of the zinc air technology. As described before, the efficiency of zinc air systems does not exceed 57 % [12]. In times when energy costs increase, and thus efficiency is becomeing more important, this result is not satisfying in consideration of the efficiency achievable by using lithium ion batteries which is reported to be at least 97 % [13] for the discharge. In [14] the charging efficiency of lithium ion batteries was analysed. The minimum efficiency was reported to be around 90 %. Combining both efficiency values, the efficiency of charging and discharging of lithium ion batteries is about 87 %, which is significantly higher than the comparable value for zinc air batteries presented in [12].

Regarding figure 4, it is obvious that the discharge characteristic of zinc air batteries leads to a strong decrease of the power output. Discharge curves of lithium ion batteries as presented in [13] show only a small reduction of voltage and thus of power output. The best characteristic of this property is obvious for common RE with internal combustion engines, which have a constant power output.

Also the low specific power forms another disadvantage of zinc air systems compared to lithium ion batteries or RE with an internal combustion engine. The system described in [10] showed a maximum specific power of only 80 W/kg. In [13] a specific power of lithium ion batteries up to 2660 W/kg was reported. The specific power is one of the limiting properties of zinc air batteries. In theory they have a capacity that is higher than the one of lithium ion batteries as reported in [3] but in high power applications this advantage is eliminated by the drop of usable capacity in real use as described in [2]. This is strongly depending on the characteristic of the power output of zinc air batteries. It is to be expected that lithium ion batteries of the same volume or weight show a better performance for traction systems with the need for high power supply of the drive chain.

Other disadvantages like the manual handling which has to be done by the car driver should also be investigated. It is to be expected that drivers do not wish to handle the zinc air battery modules. They might prefer an electrically rechargeable system, even if they have to handle the mechanically rechargeable ones only a few times a year, because these systems could be easily charged at the same time as the main battery which is most likely a lithium ion battery. Thus there would be no extra work for the car driver.

Considering all these aspects, zinc air batteries seem to be unsuitable for usage as RE even if they are used only several times a year. Thus, the usage of lithium ion batteries as RE, or a part of the main battery being used as RE, is to be preferred, especially if the RE has to be independent from fossil fuels. Otherwise a RE with internal combustion engine can be integrated into the car.

4. CONCLUSION

For this analysis zinc air battery cells for the RE in the electric car MUTE were designed and measured. Out of the measurement data and reference data zinc air systems were discussed for a RE for seldom use. The measurements show that it is possible to build a RE for small electric cars like MUTE which has the power to partly drive the engine or charge the main battery. But the power characteristic of these systems is not satisfying considering that today’s lithium ion batteries reach a better performance. This is due to the larger drop of usable capacity of zinc air batteries compared to lithium ion batteries. Another problem of the zinc air technology used as RE is the strongly decrease of the power output during discharge as shown in figure 4. As zinc air systems have a low specific power this increases that problem.

Additionally the efficiency of zinc air systems is not satisfying. The efficiency of 57 % for charging and discharging is much lower than the value for lithium ion batteries which is about 87 %. An important point considering the increase of energy costs.

Finally it is to be expected that the effort for manual handling of the mechanically rechargeable zinc air batteries will not be accepted by car drivers. Taking those aspects into consideration, it is preferable to use lithium ion batteries as RE if a RE has to be independent from fossil fuels. Otherwise a common RE with internal combustion engine can be used.

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6. REFERENCES

[1] Boecker, J. et al. “VDE-Studie Elektrofahrzeuge”, VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., Frankfurt am Main, Germany, April 2010, p 5.

[2] Eckl, R. et al. “Alternative Range Extender for Electric Cars – Zinc Air Batteries”, Conference on Future Automotive Technology: Focus Electromobility, Munich, Germany, 26-27. March, 2012

[3] Dixon, J. “Energy Storage for Electric Vehicles”, IEEE International Conference on Industrial Technology (ICIT), Viña del Mar - Valparaiso, Chile, March 2010.

[4] Danczyk, L.G., Scheffler, R.L. and Hobbs, R.S. “A High Performance Zinc-Air Powered Electric Vehicle”, Future Transportation Technology Conference & Exposition, Portland, OR, USA, August 1991.

[5] Cooper, J.F. et al. “A Refuelable Zinc/Air Battery for Fleet Electric Vehicle Propulsion”, Future Transportation Technology Conference and Exposition, Costa Mesa, California, USA, August 1995.

[6] Haas, O. et al. “Metal/air batteries: The zinc/air case”, in Handbook of Fuel Cells – Fundamentals, Technology and Applications, Volume 1, Part 4, John Wiley & Sons, Ltd, Chichester, 2003, pp 382–408.

[7] Lienkamp, M. “Elektromobilität”, Springer Verlag Berlin Heidelberg, Germany, 2012, p. 39.

[8] Cheiky, M.C. et al. “Rechargeable Zinc-Air Batteries in Electric Vehicle Applications”, Future Transportation Technology Conference and Exposition, San Diego, California, USA, August 1990.

[9] Kiefer, G. “VDE 0100 und die Praxis”, 13. Auflage, VDE Verlag GmbH, Berlin / Offenbach, Germany 2009, p.104.

[10] Pauling, H.J., Weissmüller, G. and Hoffmann, E. “Jahrestagung GDCh“, Fachgruppe Angewandte Elektrochemie, Wien, Austria, 1997, Abstract pp. 35

[11] Mortimer, C.E. and Müller, U. „Chemie“, 8. Auflage, Georg Thieme Verlag, Stuttgart, Germany, 2003, pp. 18, p. 22, pp. 766.

[12] Koretz, B., Harats, Y. and Goldstein, J. “Operational Aspects of the Electric Fuel Zinc-Air Battery System for EV’s“, 12th International Seminar on Primary and Secondary Battery Technology and Application”, Deerfield Beach, Florida, USA, March 6-9, 1995.

[13] Nelson, P. et al. “Advanced Lithium-Ion Batteries for Plug-in Hybrid-Electric Vehicles”, Proceedings from the Electric Vehicle Symposium-23, Anaheim, California, December 2-5, 2007.

[14] Keil, P., Jossen, A. “Vergleich von Ladeverfahren für Lithium-Ionen-Batterien“, 20. DESIGN&ELEKTRONIK-Entwicklerforum Batterien & Ladekonzepte, Munich, Germany, 2012.