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ZAF Nickel-Zinc LN3 Stop-Start Micro-Hybrid Battery

Background Summary

Incorporated in 2011, with an R&D center in Montana and a low rate production line in Missouri, ZAF Energy Systems develops and commercializes next-generation Ni-Zn battery technologies that use sustainable, non-toxic materials and can be safely and easily recycled. ZAF currently manufactures and develops rechargeable alkaline Ni-Zn batteries for a variety of applications in a 12V G31 form factor where our Generation 1 hybrid and capacity batteries are capable of 146 and 165Ah, respectively. We are further developing the technology to include a Generation 2 hybrid and capacity battery capable of 156 and 190Ah, respectively.

Ni-Zn batteries have excellent intrinsic properties that provide a more simple and elegant solution for meeting the stop-start battery requirements envisaged by passenger and commercial stop-start vehicles. Ni-Zn batteries are a high voltage aqueous battery system providing a combination of high power and energy. They also have more than double the specific energy capability of lead-acid batteries as well as improved life. With a highly conductive electrolyte, Ni-Zn batteries have improved low temperature power over commonly used Stop-Start battery technologies. It is a very safe technology and does not require expensive electronic management at the battery level. Based on initial testing, ZAF has engineered a preliminary design for a LN3 battery optimized for the stop-start performance and cost requirements. This preliminary design is optimized for long life, power, low temperature performance, and cost while also delivering high specific energy in an environmental friendly and safe chemistry.

ZAF Ni-Zn LN3 Battery Concept for Stop-Start Applications and Relevant Testing Results

Our concept of a ZAF Ni-Zn stop start battery, together with projected specifications are shown in Table 1 and Figure 1. The Generation 1 LN3 mimics our current Gen1 G31 design and is not engineered for maximum cold cranking ability, while the Gen2 design is engineered for maximum cold cranking ability with an increased electrode count, engineered high power electrolyte, and optimized anode structure. The advancements in the Gen2 design also allows for increased power capability while maintaining the energy in the LN3 battery. The performance of our G31 size cells and batteries, as shown below, indicates that the ZAF Ni-Zn LN3 will meet and exceed the stop-start battery requirements.

Table 1: Projected Performance Specifications	LN3 Gen1	LN3 Gen2
Nominal Voltage (V)	12	12
Volume (L)	9.2	9.2
Weight (kg)	13.7	13.7
Name plate capacity (Ah)	61	61
Energy C/3 (Wh)	720	720
Cold Cranking Amps (-18C) for 10 sec (A)	766	910
Cold Cranking Amps (-30C) for 10 sec (A)	521	618
Cold Cranking Amps (-18C) for 30 sec (A)	699	830
Cold Cranking Amps (-30C) for 30 sec (A)	480	571
Energy density (Wh/L)	78	78
Specific energy (Wh/kg)	52	52

Figure 1: ZAF Ni-Zn LN3 battery

CCA Testing

We have conducted cold-cranking tests on our G31 cells, at a third-party testing house (Eclipse Energy), at -18°C and -30°C with discharge currents of 700 A, 800 A, 900 A and 400 A, 500 A, 600 A, and 700 A, respectively. These tests were performed on our hybrid 147 Ah G31 Ni-Zn cells, which were designed for a combination of power and capacity. The test results indicate that ZAF's Ni-Zn chemistry is able to cold crank for an extended period of time at both -18°C and -30°C at high rates of discharge, as shown in Figures 2 and 3.

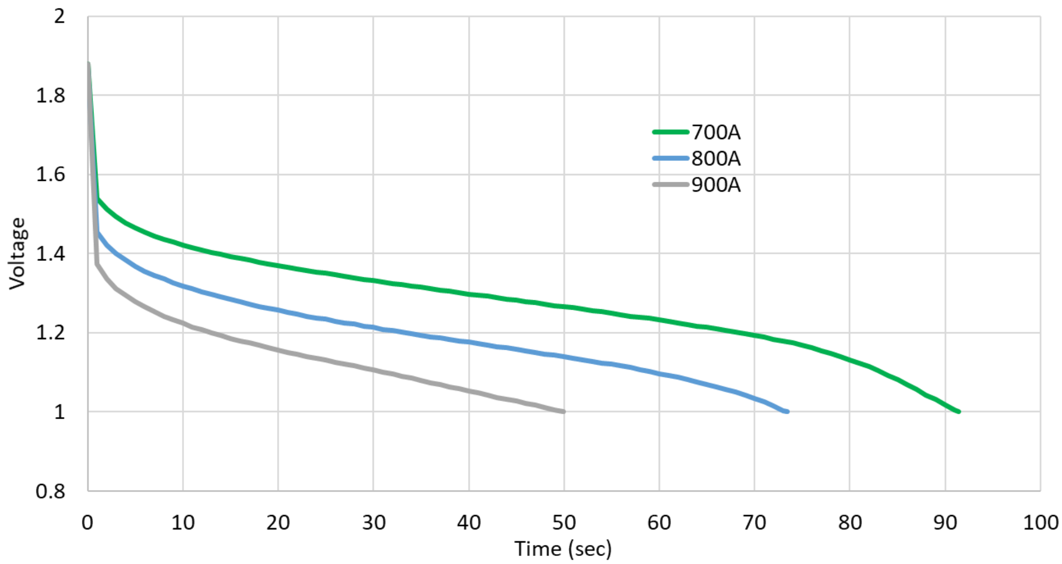

Figure 2: Cold Cranking test results performed hybrid G31 Ni-Zn cells at -18°C

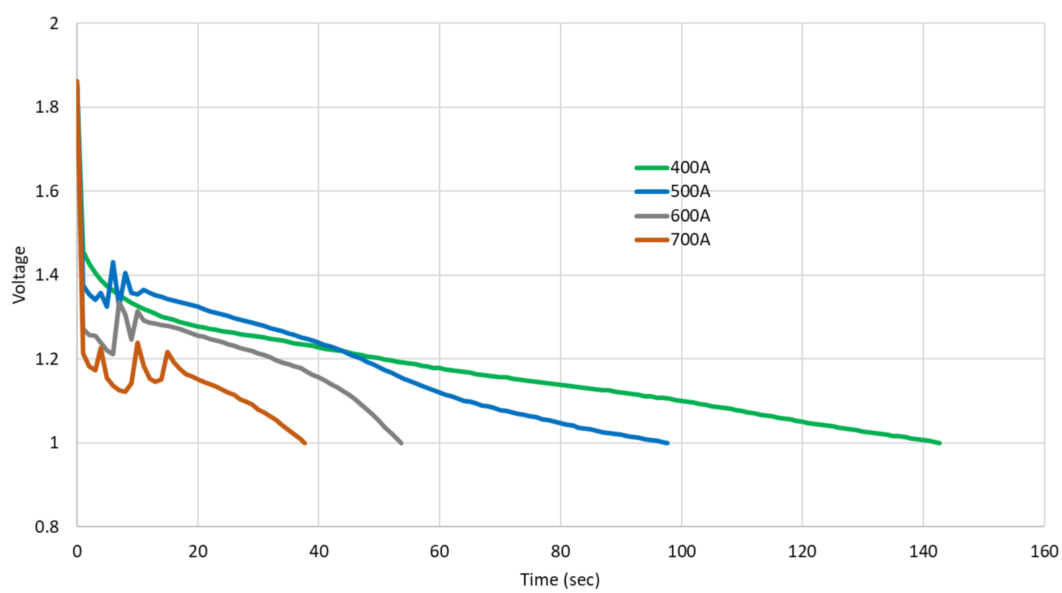

Figure 3: Cold Cranking test results performed hybrid G31 Ni-Zn cells at -30°C

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Due to the proposed Gen2 LN3 design being engineered for power and not capacity, the cold cranking ability will be similar to the much larger format G31 performance (Figures 2 and 3) due to an increase in plate count and similar surface area to the G31. In addition, improved anode structure and higher electrolyte conductivity will lower cell impedance at lower temperatures. The predicted cold cranking performance, based upon ZAF's G31 results, compared to a stop-start lead-acid, current Li-Ion, and future Li-ion is shown in Figure 4. The Gen1 ZAF LN3 projected performance at -18°C is below the future Li-Ion technology and above lead-acid cold cranking currents; however, the -30°C performance is greater than all the other technologies. We are also confident that the Gen2 LN3 Ni-Zn design will outperform all technologies at -18°C and -30°C.

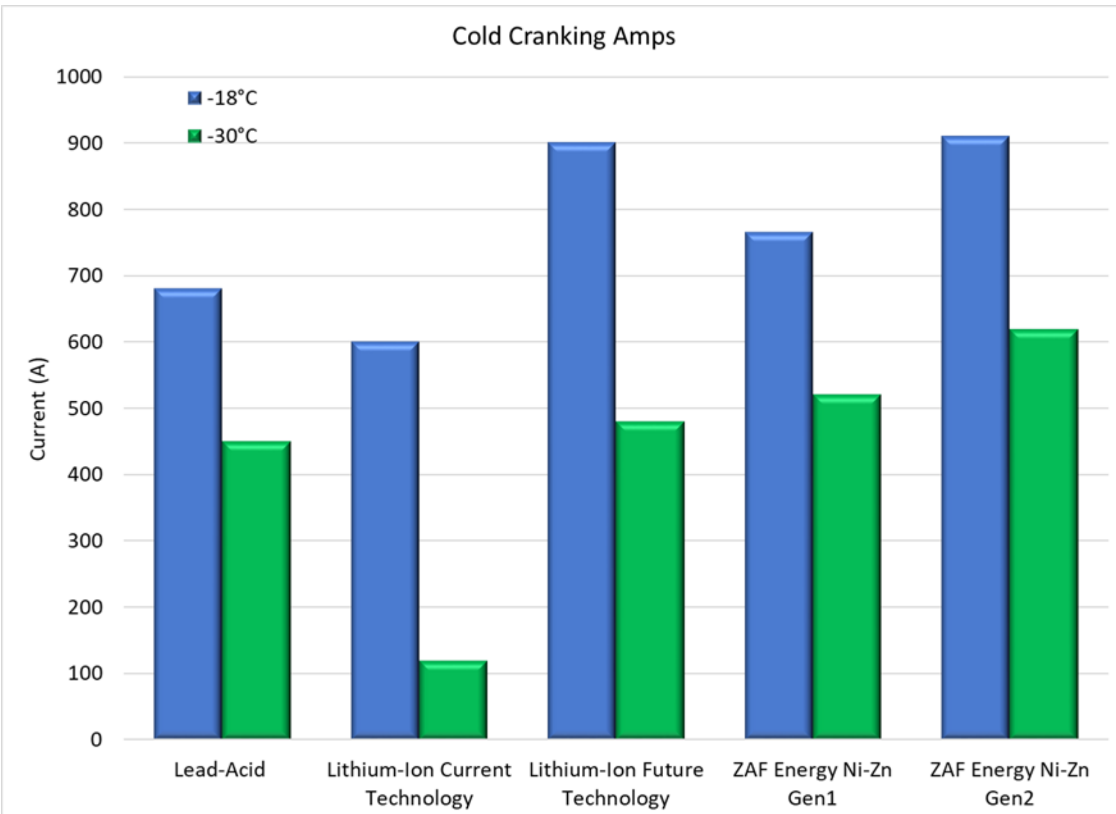

Figure 4: Cold Cranking Comparison between Lead-Acid, Lithium-Ion, and Ni-Zn

Multi-Rate Discharge Utilization and Constant High-Power Discharge

Third party deep discharge testing of a ZAF 147 Ah G31 hybrid Ni-Zn cell was conducted at five different rates, ranging from C/20 to 6C, as shown in Figure 5. The Ni-Zn cell showed only a 13% drop in utilization from C/20 to 6C, at 102.8 % to 90.98 % utilization, respectively. While these tests indicate that the G31 Ni-Zn cell can deliver high utilization at multiple C-rates, we believe that our LN3 concept designed for high rate applications will show much better utilization at 6C and above, with less overall polarization.

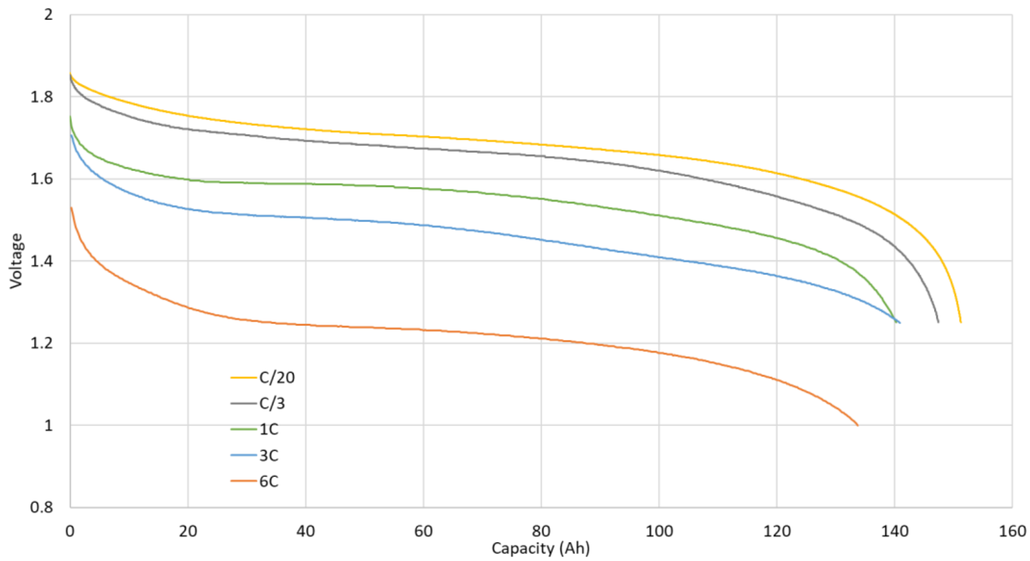

Figure 5: Multi-rate discharge tests performed on hybrid G31 Ni-Zn cells

Third party high rate testing was also performed on G31 hybrid Ni-Zn cells in constant power mode at 25°C. The cells could hold constant power of 1000W and 1200W down to 1V for more than 5.6 and 9.1 minutes, respectively. The voltage profiles and current levels are shown in Figure 6. The extracted capacity at 1000W is 122Ah and 1200W is 93.5Ah, respectively, for a 147Ah cell. Based on this performance ZAF is expecting that the smaller footprint LN3 battery will be able to provide constant power of 830W and 1000W for 5.6 and 9.1 minutes, respectively, when the Gen 2 technology has been incorporated.

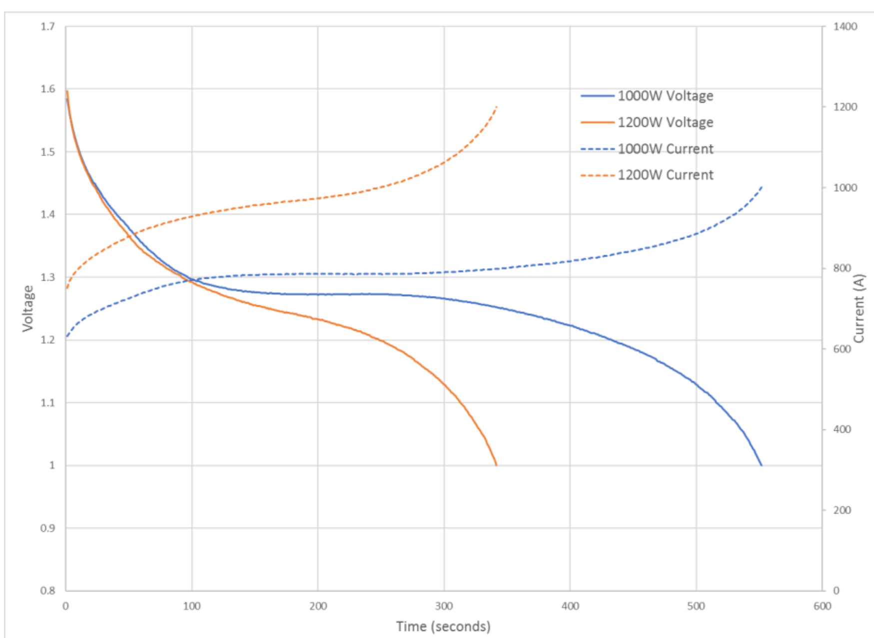

Figure 6: Voltage and current profiles of a 147 Ah G31 Ni-Zn cell during constant power discharge at 25°C

Temperature Driven Utilization

Utilization as a function of temperature is shown in Figure 7. In this testing, a single G31 sized cell was discharged at a C/3 rate at multiple temperatures ranging from -30°C to 40°C. The utilization of the cell was ≥ 96% at 0°C and above. The cell was also able to achieve 71% and 62% utilization at -20°C and -30°C, respectively. The high utilization at low temperatures is attribute to the high conductivity and low freezing temperature of the Ni-Zn alkaline electrolyte. The Ni-Zn chemistry also performs very well at high temperatures as shown in the J2801 testing in the following section.

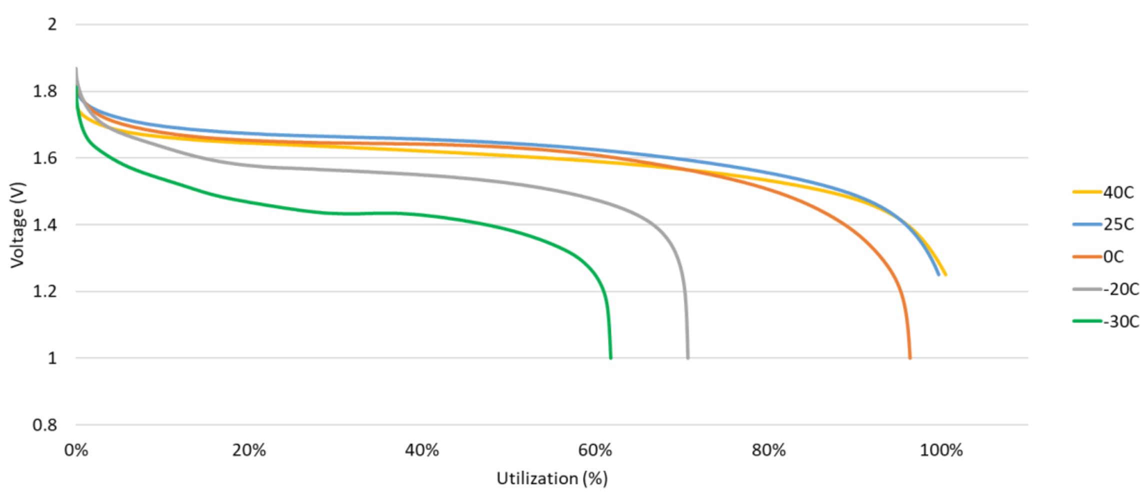

Figure 7: Voltage profiles of a 147 Ah G31 Ni-Zn cell at various temperatures during C/3 discharges

SAE J2801 Comprehensive Life Test and 10% DOD Life Cycling

ZAF is currently conducting cycle testing at 75°C according to the SAE J-2801 publication. This test is intended to test batteries to some of the harshest conditions under the hood of a car. After 10 weeks of ongoing testing, ZAF's Ni-Zn G31 hybrid shows no sign of degradation as shown in Figure 8. This testing is ongoing and we anticipate many more weeks before battery failure. It is important to note that the cell design being cycled at 75°C, is the same cell design that performed the CCA results in Figures 2 and 3. There has been no modifications to the electrolyte or other cell components, underscoring the versatility of this design.

We have also performed low depth of discharge cycle life testing as shown in Figure 9. This test was performed on a 100 Ah prismatic cell that was cycled at 10% DOD at 50% SOC at a 1C rate for both charge and discharge. Each discharge and charge segment lasts 6 minutes with no overcharge allowed. A significant decline in capacity was observed only after about 8500 cycles.

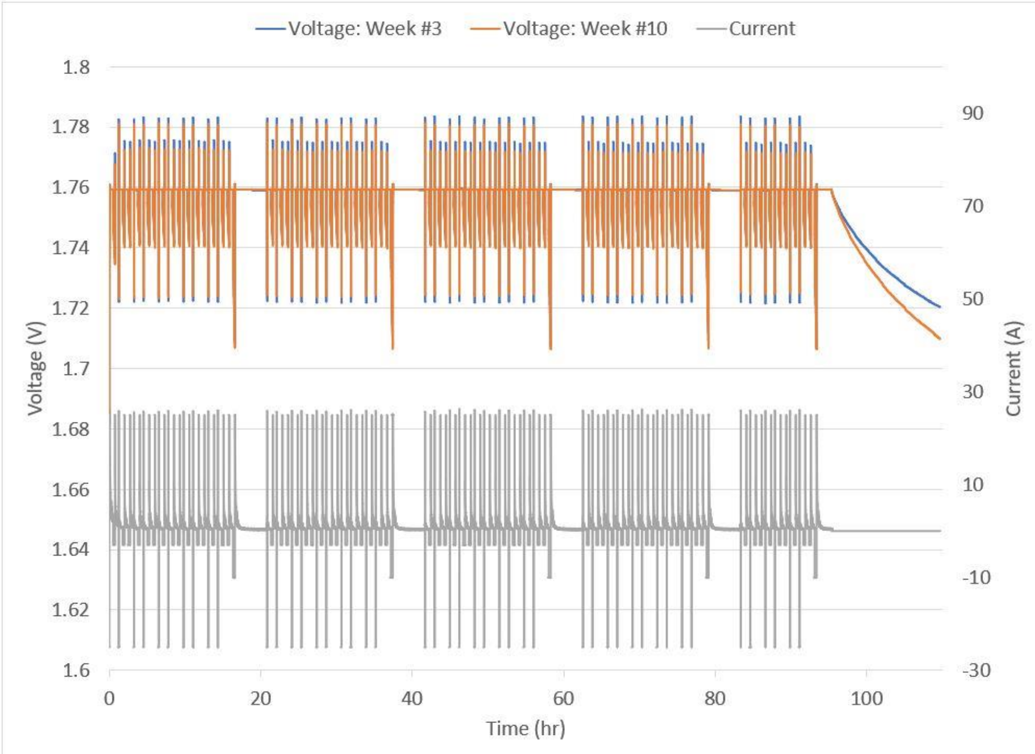

Figure 8: J2801 testing results

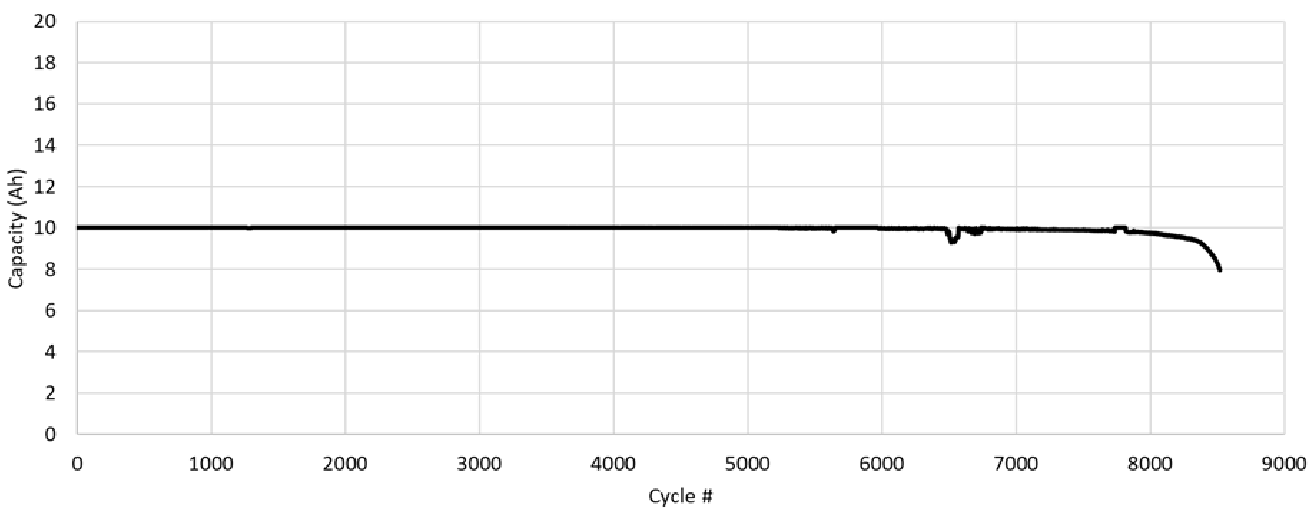

Figure 9: 10% DOD cycle test of a ZAF Ni-Zn 100Ah cell at a 1C-rate charge and discharge schedule

Small Prototype Testing

ZAF have also performed stop-start cycles on small prototype Ni-Zn test cells. The test profiles on these cells were scaled from the 12V Stop-Start Cycle Life test profile in the USABC Battery Test Manual. The results are shown in Figure 3. The Ni-Zn cells rapidly stabilized providing efficient stop-start operation at 1,000 cycles and nearly identical performance at 10,000 stop-start cycles, in this preliminary test. The energy efficiency was also excellent over 10,000 stop-start cycles, as illustrated in Figure 4. The efficiency of about 98% exceeds the USABC target set at 95%. This is a testament to the high discharge power capability and the high charge acceptance of Ni-Zn batteries.

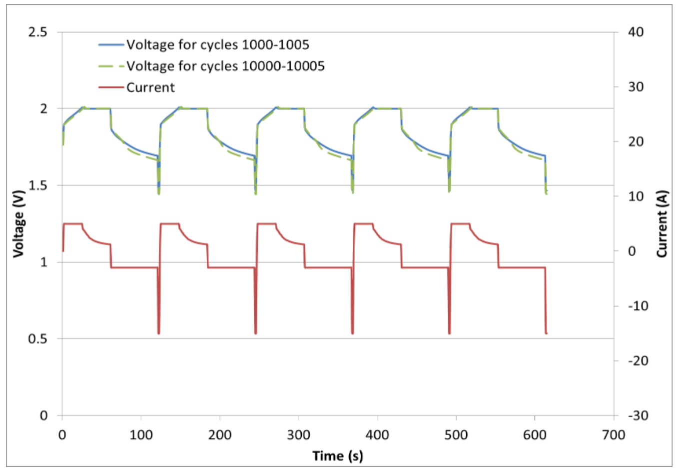

Figure 10: Stop-start cycles performed on a prototype Ni-Zn cell

Summary of Production Costing Assumptions

The preliminary materials analysis of ZAF's LN3 design projects a total cost of $159 per battery. We believe that the materials cost of the battery will improve with procuring large scale pricing and materials improvements through research and development. The cost breakdown per component is shown in Figure 11. Labor costs will be determined by the degree of automation which will be a business case determined by volume of batteries produced. In a highly-automated battery factory, labor can approach 10-15% of total cost. In a low-volume production line, labor can equal or exceed material cost.

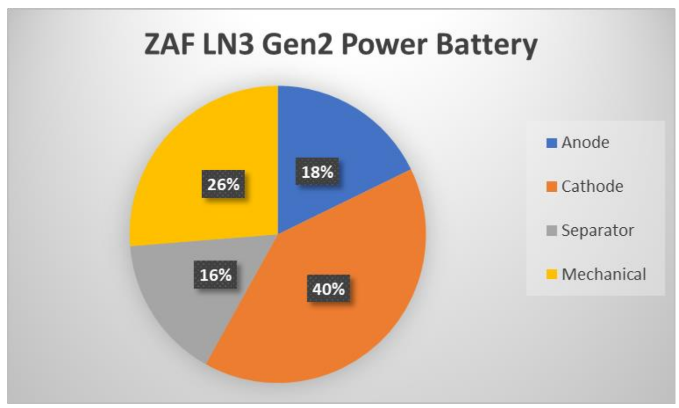

Figure 11: Total cost percentage of battery components

Intellectual Property

ZAF uses patents as well as trade secrets to protect its technology. ZAF currently has four issued US patents: US 9,099,753, US 8,871,394, US 8,728,671, and US 8,535,851 and 16 other US patent applications in all stages of prosecution. Of the 16 patent applications, 13 are innovations in Ni-Zn battery technology. The applications include but are not limited to: Improved separator systems, high capacity nickel cathodes utilizing modified materials exhibiting multi-electron transfer, improved zinc anodes, and zinc ion stabilizing electrolytes.

Company/Team

ZAF's 35,000 ft^2 low rate production facility is located in Joplin, MO. This facility has 23 operators and engineers and houses a low rate production line for G31 Ni-Zn cells and batteries. This line is equipped with tape casters, presses, and slurry mixing equipment. It also contains cell assembly, activation stations, and a test lab for cell formation. ZAF's Research and Development facility is currently located in Columbia Falls, MT and will be moving to our new location in Bozeman, MT June 1st. This 8,000 ft^2 facility will house 12 employees, including scientists, engineers, and technicians and is equipped with analytical tools and battery testing units.

Key personnel at ZAF that will be extensively involved with this project are Randy Moore (CEO/President), Dave Wilkins (CSO), Dr. Adam Weisenstein (CTO), Tom Shireman (VP of Manufacturing Operations), Dr. Eivind Listerud (VP of Engineering), and Allen Charkey (Consultant). These people combine for over 100 years of R&D, engineering, manufacturing, and management at various battery companies, such as Energy Research Corporation, EaglePicher, Yardney, and Evercel.