**High Power and High Energy Wafer Cell Nickel Metal Hydride and Li-Ion Batteries for Utility and Transportation Applications[1]**

James Landi (Electro Energy, Inc. Danbury, Connecticut, USA) jlandi@electroenergyinc.com; Michael Reed, John Dailey (Electro Energy)

## Abstract

As a departure from classic cylindrical or prismatic battery packaging approaches, Electro Energy, Inc. (EEI) has developed a flat wafer cell design for the nickel-metal hydride and Li-Ion chemistries. This design results in a battery that eliminates the need for conventional terminals, tabs, current collectors, and cell containers, thus reducing system weight and volume, or increasing energy, when compared to conventionally designed batteries of the respective chemistries. In addition, because in a stacked wafer cell design the battery current flows in a direction normal to the plane of the electrodes, the overall battery impedance is reduced, making this design particularly effective for high-voltage, high-power applications.

Through continued programs with the Department of Energy and Sandia National Laboratories, EEI has developed and demonstrated high-power and high-energy bipolar wafer cell nickel metal hydride batteries to meet the broad requirements of energy storage for stationary utility applications. Through this work, unique manufacturing processes have been developed, and high-energy and high-power systems have been built and tested with favorable results. The technology has also been demonstrated in hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) applications, which are bridging the gap between stationary and transportation applications. PHEVs not only provide fuel savings and environmental benefits, but could also serve as mobile UPS and peak shaving systems when connected to the grid. EEI is developing an aftermarket HEV-to-PHEV conversion package that would incorporate the NiMH or Li-Ion battery designs. Grid connected capabilities will also be investigated.

In this paper, we will discuss developments made with both the NiMH and Li-Ion designs, as well as the application designs and testing of 600 V high-energy Inverter systems and PHEV systems.

## Introduction

As the energy and power requirements of society become increasingly more demanding, and the concerns of energy costs and pollution become more prevalent, advanced rechargeable batteries provide the ability to address these issues. From a stationary application standpoint, these batteries can function as an energy reservoir, a back-up source of energy, or provide peaking energy when a demand for electrical power exceeds primary generating capabilities. In the transportation market, advanced rechargeable batteries have lead to the introduction of hybrid electric (HEV) and plug-in hybrid electric vehicles (PHEV), which has resulted in significant increases in gas mileage, and enables a reduced dependency on foreign oil and environmentally harmful fossil fuels. In addition, PHEVs could also serve as mobile UPS and peak shaving systems when connected to the grid. This concept is bridging the gap between the stationary and transportation energy market.

Available rechargeable batteries generally fall short of the required mix of characteristics necessary to make these systems competitive with alternative approaches with regard to performance and economics. However, through EEI's advanced product line and domestic high-volume manufacturing capabilities, EEI has positioned itself in the market to satisfy the increasing rechargeable battery needs for these energy storage markets. EEI's flat wafer cell design, shown in Figure 1, for the nickel-metal hydride (NiMH) and Li-Ion chemistries offers significant advantages over existing battery designs. It results in a battery that eliminates the need for conventional terminals, tabs, current collectors, and cell containers. When compared to conventionally designed batteries of the respective chemistries, this design reduces system weight and volume, while providing equivalent or increased energy. In addition, a stacked wafer cell design allows the battery current to flow in a direction normal to the plane of the electrodes. Therefore, the overall battery impedance is reduced, making this design particularly effective for high-voltage, high-power applications. This is illustrated in Figure 2.

[1] Funded in part by the Energy Storage Systems Program of the U.S. Department Of Energy (DOE/ESS) through Sandia National Laboratories (SNL)

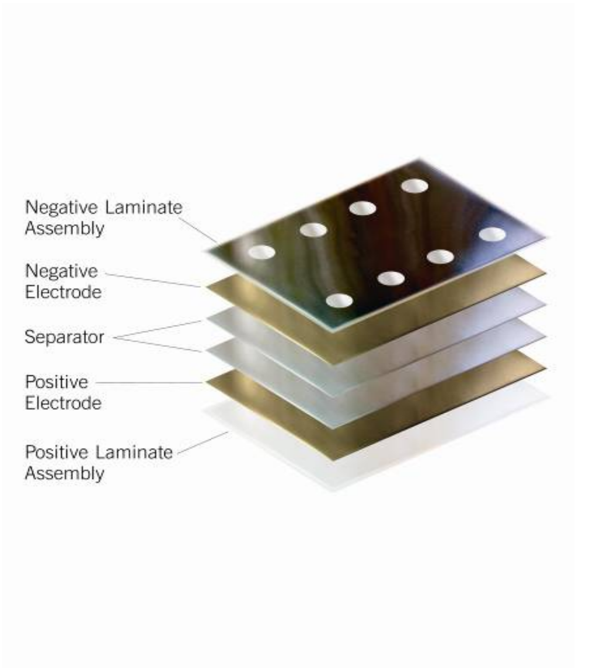


**Figure 1: Schematic of EEI's Bipolar Wafer Cell**

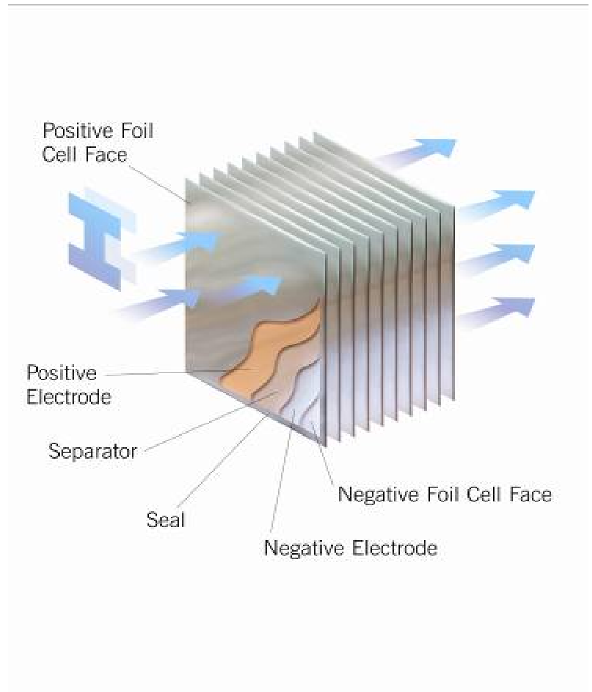


**Figure 2: Current Flow in the Bipolar Cell Stack**

Figure 3 shows a bipolar, wafer NiMH cell, while Figure 4 shows a wafer Li-Ion cell. Individual flat wafer cells are constructed with outer contact faces having one positive electrode, a separator, and one negative electrode. The contact faces serve to contain the cell and make electrical contact with the positive and negative electrodes. The contact faces are sealed around the perimeter to contain the electrolyte. To fabricate a multi-cell battery, identical cells are stacked one on top of each other such that the positive face of one cell contacts the negative face of the adjacent cell, thus making a series connected battery. The current is collected at the ends of the cell stack. Structural integrity of the cell stack is obtained by housing the stack in an outer container, which holds the cells in compression [1].

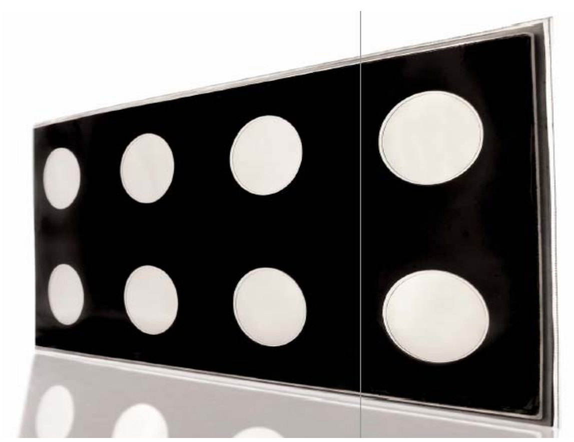

**Figure 3: EEI Bipolar, Wafer NiMH Cell**

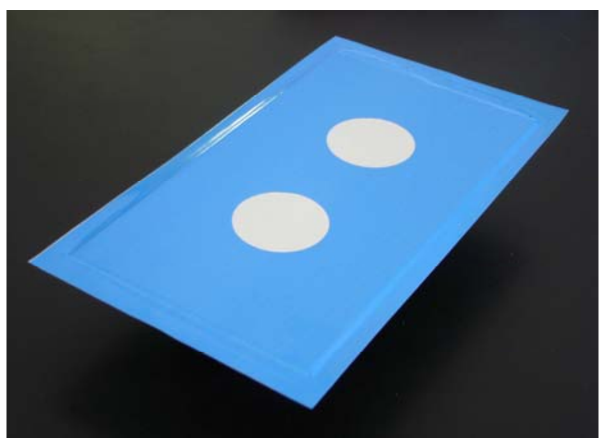

**Figure 4: EEI Wafer Li-Ion Cell**

**Wafer Cell Bipolar NiMH Battery Improvements**

Through continued programs with the Department of Energy (DOE) and Sandia National Laboratories (SNL), EEI has developed and demonstrated the high-power and high-energy wafer cell bipolar nickel metal hydride batteries, and significant recent improvements have been realized. EEI has focused on improving cell and battery components to meet the high performance requirements of stationary and transportation applications. For the high power design, the baseline cell has a capacity of 7 Ah and an active electrode area of 72 $in^2$. It presently has a typical weight of 164 grams and provides 47 Wh/kg and 145 Wh/l of energy and greater than 1.6 kW/kg and 4 kW/l of 10 second pulse power at the cell level. With next generation improvements under development, the target design will provide 54 Wh/kg and 157 Wh/l of energy and greater than 1.8 kW/kg and 4.8 kW/l of 10 second pulse power at the cell level. As an example of recent nickel electrode improvements, the power capability is shown in Figure 5, during a 10 second 200 A pulse discharge, comparing an improved nickel foam electrode, to EEI's previous roll bonded electrode.

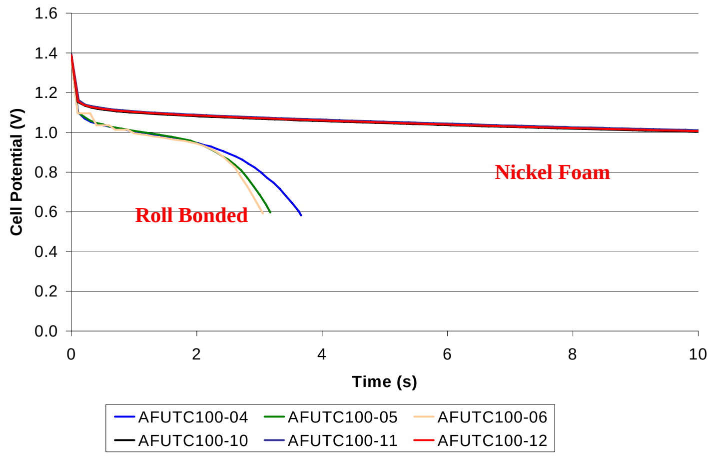


**Figure 5: 10 Second Pulse Discharge at 200 A on a 7 Ah NiMH Wafer Cell**

The power of the new foam based electrode is clearly superior to a roll-bonded electrode, maintaining a high, constant voltage level over the duration of the high power pulse. In addition to the performance capabilities, the thin foam electrode is a more producible and lower cost electrode at high volume production levels.

As compared to the high-power cells, thicker cells with capacities of 15 to 20 Ah and an active electrode area of 72 $in^2$ have been identified as the baseline high-energy products. The present baseline designs have typical weights of 307 to 386 grams and provide more than 63 to 67 Wh/kg and 190 to 200 Wh/l of energy at the cell level. With next generation improvements under development, the target designs will provide 74 to 84 Wh/kg and 245 to 278 Wh/l of energy at the cell level. The energy design will still provide more than sufficient power to meet the demanding requirements of the market. Figure 6 shows the continuous 100 A rate capability of EEI's present 15 Ah cell pack design. The design is able to provide 90% of rated capacity at a continuous 7 C-rate.

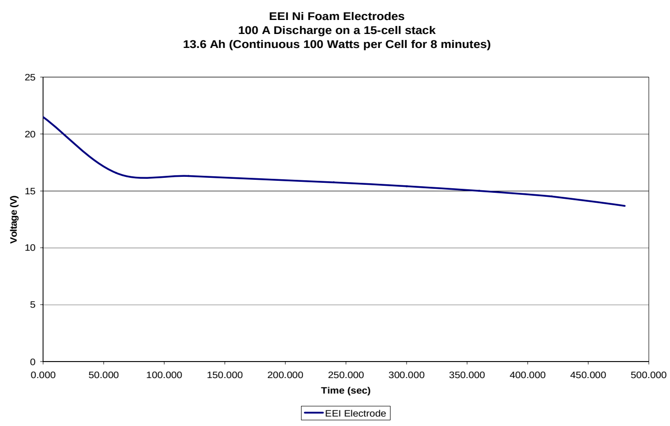


**Figure 6: Continuous Rate Capability of a 20 Ah NiMH Wafer Cell**

In addition to the improved nickel electrode production processes, other design and process improvements have been, or are being, made to the wafer cell NiMH battery, as EEI's transitions to commercial production. A key design issue was the optimization of the negative-to-positive ratio resulting in improved performance and increased cycle life. From a process development standpoint, EEI has developed an in-house capability to produce hydride electrodes for energy cells, and a thin coating process for hydride electrodes for power cells.

Finally an automatic electrolyte filling process and sealed stack formation process have been implemented.

**Stationary/Utility Applications**

Previously, EEI designed and built a 20 kW, 35 kWh, 600 V battery system integrated with a grid-tie inverter manufactured by Ballard, Inc. Figure 7 is a photograph of the system deployed, and tested, at EPRI in Knoxville, TN. The goal of this effort was to be able to operate the inverter at a power level of 20 kW for up to two hours. The energy storage portion of the system consisted of 1,920 cells, housed in 16 individual battery modules. The 16 modules were arranged in four parallel strings of four modules connected in series. Two battery cabinets and one control cabinet made up the system. Each battery cabinet provided a controlled temperature (regulated by an air conditioning unit), and contained eight modules (two strings of four modules each). The control cabinet housed one charger and the charge/discharge control circuitry [2].

**Figure 7: Ballard inverter (background) with EEI energy storage modules (foreground)**

Based on results from EPRI testing, it was concluded that the system demonstrated the potential to use wafer-cell designs and advanced manufacturing techniques to build high voltage battery strings for electric power applications. The system performed very well under a pulse profile. Cycle and calendar life were not yet validated, due to control issues and some issues with the previous cell designs.

To demonstrate the recent developments and improvements of the wafer cell NiMH technology, a new system is being designed and built. It will be rated at 600 V, 20 kWh, 10 kW, and a schematic representation is shown in Figure 8. It will be designed to provided storage at a transformer of 10 kW for 2 hours, and will be comprised of 3 parallel strings of 480 15 Ah cells. The cells will be housed in twenty-four (24) 72 V, 15 Ah modules, arranged in an 8 series, 3 parallel configuration.

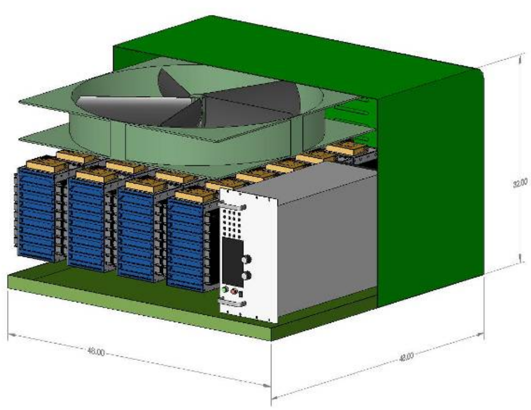

**Figure 8: Schematic Representation of Next Generation Wafer Cell NiMH Battery System**

**Transportation Applications**
Using the wafer cell design, EEI is developing and demonstrating batteries for multiple transportation applications including HEVs, PHEVs and EVs, as well as heavy duty transportation applications. One application of significant interest is a PHEV, which utilizes a significantly larger battery than a typical HEV, with the objective to be able to operate for a significant driving range, of 10 to 50 miles, on battery power alone. Once the battery is drained, or if there are sufficiently large load requirements, the car reverts to conventional HEV mode, utilizing the gasoline engine as required. Utilizing the wafer cell NiMH technology, EEI previously designed and demonstrated a prototype PHEV conversion using the Prius as a test bed. The prototype configuration battery served as a definitive demonstration of the bipolar NiMH battery used for a PHEV application.

EEI is now introducing a Generation 1 PHEV conversion kit, where EEI redesigned the NiMH battery modules to provide the same capacity in a smaller overall package. Although the individual modules grew slightly in size, only four modules were used (as opposed to the previous six), yielding an overall volume reduction from 94 liters to 72 liters. The specifications for the Generation 1 system are listed below:

- Four modules (two strings, two modules per string)
- Nominal 216 V, 30 Ah, 6.5 kWh
- 25 miles of plug-in electric range
- Dimensions: 13.7” x 37.3” x 8.4”
- Weight: < 360 lbs (including control system and integration)

The present generation 1 battery modules are shown in Figure 9 and the Toyota Prius PHEV conversion battery enclosure is shown in Figure 10.

As a next generation technology, EEI is developing a wafer cell Li-Ion PHEV battery design, previously discussed. The Li-Ion battery is projected to increase the energy by two times that of a system utilizing NiMH batteries while occupying only about less volume. This would result in significantly more range-extending energy, with an ultimate goal of 40+ miles of all-electric driving from each recharge cycle.

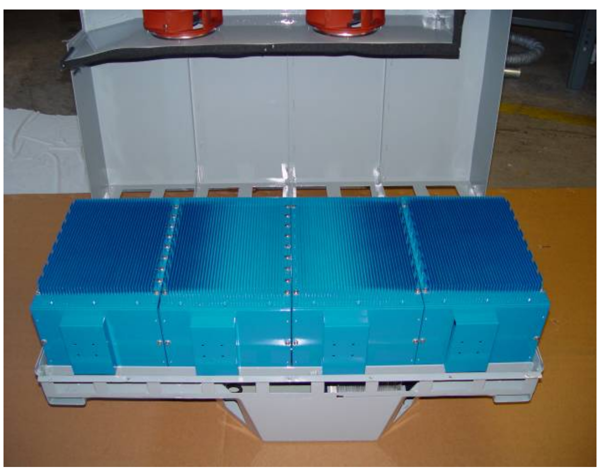
**Figure 9: Generation 1 Battery Module**

**Fig. 10: The Generation 1 Battery Enclosure**

With further integration this, PHEV battery system could be utilized as a grid-connected UPS system. The concept of the PHEV remains the same, although, when connected to the grid during recharge, the battery system could serve as a residential UPS system or a energy source to provide peak shaving and load leveling.

**EEI’s Wafer Cell Li-Ion Technology**
High energy Li-Ion cells, which exceed 200 Wh/kg and 500 Wh/L at the cell level, have been constructed. The cell maximizes the specific energy and the energy density by eliminating “dead” weight. The high energy cell uses a stacked electrode technology, where cells are stacked upon each other in parallel to make multi-cell stacks. Any reasonable capacity cell, therefore, can be made from a single footprint by simply varying the cell

thickness. By minimizing the "dead" weight of the cell, envelope and current collectors, an extremely high specific energy is realized as Figure 11 shows.

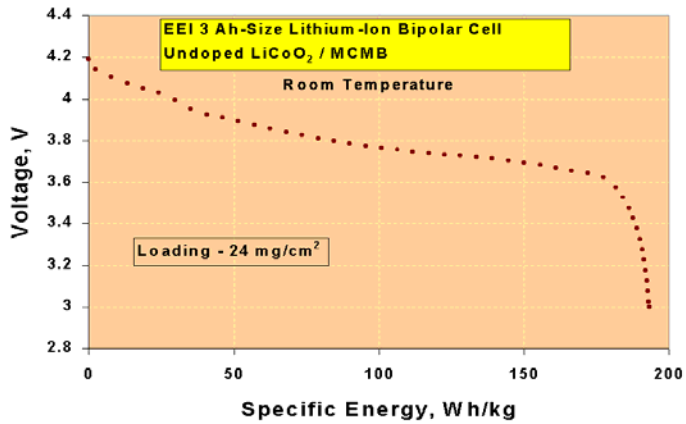


**Figure 11: Specific energy for EEI's high energy single cell stack discharged at a C/2 rate**

To serve as a development baseline, EEI has done a preliminary battery design that would meet the requirements of the high energy/power ratio PHEV battery. The wafer cell building block for this battery has a nominal voltage of about 3.6 V and a capacity of 20 Ah. The cell dimensions are 9.1" x 4.8" x 0.3", with a weight of 437 g. The PHEV battery pack is built from 1.44 kWh battery modules, each having a nominal voltage of 36 V and a capacity of 40 Ah. Each module has two 36 V / 20 Ah sub-modules consisting of ten 20 Ah cells connected in series.

Ten battery modules, each 36 V and 40 Ah, would be connected in series to form a nominal 360 V / 40 Ah battery pack with an energy content of 14.4 kWh. The energy density of the proposed battery pack is 170 Wh/l and its specific energy is 110 Wh/kg. The complete battery pack would have a power density of up to 1 kW/kg, which would allow the battery to provide continuous power of more than 140 kW.

Conclusions

The EEI wafer cell technology & battery designs offer cost and performance advantages. Ni-MH technology is mature and ready for commercialization, while the wafer cell Li-Ion solution would provide superior performance. Designs for both chemistries are continually being improved, and production processes are being developed for volume manufacturing. High-voltage modules/systems have demonstrated high levels of performance, for multiple applications. EEI Florida facility positions EEI to become the largest domestic manufacturer of specialty rechargeable batteries, and exclusive Li-Ion battery producer for multiple applications.

References

[1] M. Reed, J Landi, Z. Johnson, S. Cordova, K.M. Abraham, *Advanced Battery Solutions for Vehicle Applications*

[2] J. Dailey, R. Plivelich, L. Huston, J. Landi, M. Klein, *The Bipolar Nickel-Metal Hydride Battery for Advanced Transportation and High Voltage Power and Energy Storage Systems*

**Acknowledgments**

The authors would like to thank the United States Department of Energy for their sponsorship of this work. In particular EEI would like to thank Dr. Imre Gyuk, of The Department of Energy and Nancy Clark and David Ingersoll of Sandia National Laboratories for Program Management.