

## Article

# Performance Comparison of Rechargeable Batteries for Stationary Applications (Ni/MH vs. Ni–Cd and VRLA)

Michael A. Zelinsky \*, John M. Koch and Kwo-Hsiung Young 

BASF/Battery Materials–Ovonix, 2983 Waterview Drive, Rochester Hills, MI 48309, USA;  
john.m.koch@basf.com (J.M.K.); kwo.young@basf.com (K.-H.Y.)

\* Correspondence: michael.a.zelinsky@basf.com; Tel.: +1-248-293-7234

Received: 22 November 2017; Accepted: 22 December 2017; Published: 25 December 2017

**Abstract:** The stationary power market, particularly telecommunications back-up (telecom) applications, is dominated by lead-acid batteries. A large percentage of telecom powerplants are housed in outdoor enclosures where valve-regulated lead-acid (VRLA) batteries are commonly used because of their low-maintenance design. Batteries in these enclosures can be exposed to temperatures which can exceed 70 °C, significantly reducing battery life. Nickel–cadmium (Ni–Cd) batteries have traditionally been deployed in hotter locations as a high-temperature alternative to VRLA. This paper compares the performances of nickel/metal hydride (Ni/MH), Ni–Cd, and VRLA batteries in a simulated telecom environment according to published testing standards. Among these three choices, Ni/MH batteries showed the best overall performance, suggesting substantially longer operating life in high temperature stationary use.

**Keywords:** nickel metal hydride battery; nickel–cadmium battery; valve-regulated lead-acid battery; stationary application; telecom

## 1. Introduction

Nickel/metal hydride (Ni/MH) battery technology is very well suited for stationary energy storage applications because of its high power, long cycle life, compact size, unsurpassed safety, and wide operating temperature range [1–3]. These merits have been validated in laboratory testing and field evaluations alongside nickel–cadmium (Ni–Cd) and valve-regulated lead-acid (VRLA) batteries. Supported by these results, Ni/MH batteries of varying designs ranging from small cell telecom [4] and data storage [5] back-up power to substation-scale energy storage systems [6,7] have begun to appear on the stationary market (see the Supplemental Material for specific examples).

Although specialized versions had been used earlier for select applications, Ni/MH batteries first appeared on the mainstream commercial market in the late 1980s. These small rechargeable cylindrical cells created a new generation of consumer electronics by enabling widespread deployment of digital cameras, cellphones, laptop computers, and personal digital assistant. A decade later, prismatic Ni/MH batteries became the dominating technology for powering hybrid electric vehicles (HEV). Since 1997, more than 12 million HEV equipped with Ni/MH batteries have been introduced to the world’s roadways [2]. The annual production of consumer-type Ni/MH battery is now over one billion cells [8]. Today’s development focus on large-format Ni/MH batteries is setting the stage for stationary power, energy storage on the electrical grid, and a variety of other industrial battery applications.

A basic Ni/MH cell consists of a metal hydride (MH) negative electrode and a nickel hydroxide positive electrode in a highly conductive aqueous potassium hydroxide-based electrolyte (typically 30 wt %) in a sealed structure. This chemistry provides a nominal voltage of 1.2 volts per cell, below the electrolysis voltage of water. Although its voltage is lower than that of a VRLA, Ni/MH is characterized

by higher gravimetric and volumetric energy density, higher heat tolerance, and better cycle stability at deeper discharge depths, which makes it an attractive alternative for stationary applications [1]. In addition, unlike its Ni–Cd rival, Ni/MH contains no toxic materials and is commercially recyclable, although not yet to the same extent as lead-acid batteries.

The ability of Ni/MH to tolerate high heat conditions for extended durations [3] is particularly important for stationary back-up power applications, including remote, outdoor installations. In addition to ambient environments, high heat can result from a number of other conditions including rapid cycling, high rate discharge, or fast charging. While this paper focuses on high temperature telecom environments, improved heat tolerance is equally important for grid energy storage or UPS/data center applications, where thermal management concerns add excessive cost and system complexity.

## 2. Experimental Section

In 2012, Telcordia (Piscataway, NJ, USA) published GR-3168-CORE, “Generic Requirements for Nickel Metal Hydride (Ni/MH) Battery Systems in Telecommunications Use” [9]. This document outlines various testing protocols and requirements for stationary Ni/MH batteries, grouped by level of deployment, covering areas such as general design, safety, performance, and service life. One of the most interesting tests specified by GR-3168-CORE is the Varying-55 °C aging test.

The Varying-55 °C Test is intended to determine the service life of an Ni/MH battery. Batteries are aged using a continuous 24 h environmental cycle with an average temperature of 55 °C. The algorithm is composed of four stages designed to simulate the temperature environment inside an outdoor telecom power cabinet from nighttime low temperatures to the highs of the day, including solar loading:

- Stage 1 12 a.m.–9 a.m.: 45 °C
- Stage 2 9 a.m.–12 p.m.: 45–65 °C
- Stage 3 12 p.m.–9 p.m.: 65 °C
- Stage 4 9 p.m.–12 a.m.: 65–45 °C

Daily exposure to 65 °C represents an extreme case and is not common in the field, especially when considering seasonal changes over the course of an entire year. In an alternative Varying-45 °C aging test, the temperature profile is reduced by 10 °C, i.e., 9 h at 55 °C, 9 h at 35 °C, and 6 h in transition between 35 and 55 °C. This temperature profile is far more commonly experienced in outdoor telecom cabinets. Nonetheless, both temperature profiles were tested to evaluate the effects of long-term heat exposure on Ni/MH and incumbent battery chemistries.

Thermotron model S-32-8200 Environmental Test Chambers (Thermotron Industries, Plano, TX, USA) were used to control the daily thermal profiles for simultaneous testing of various 12 V battery modules typically used in stationary applications, including a 100 Ah FT-type thin plate pure lead Monobloc VRLA [10], an 80 Ah (10 cells) maintenance free Ni–Cd telecom module [11], a 4 Ah (10 cell) Ni/MH module type A (standard long life industrial type), and a 4 Ah (10 cells) Ni/MH module type B (equipped with an advanced high temperature cathode).

At first glance, it may appear that this wide range of battery sizes is an inappropriate mix of test subjects. However, the objective of the investigation was to determine the effects of heat exposure on battery chemistry, not battery construction or configuration. As such, the smallest commonly deployed unit of each chemistry was selected. In actual use, multiple modules are routinely connected in parallel to achieve batteries of higher capacity. Discharge rates were scaled proportionally to the nominal capacity of each individual module (C-rate) to ensure similar loading conditions. Modules were float charged at a constant voltage of 13.5 V as they would be if installed in an actual telecom cabinet [9]. Charging and discharging were controlled using a Bitrode battery cycler (Bitrode Corporation, St. Louis, MO, USA).

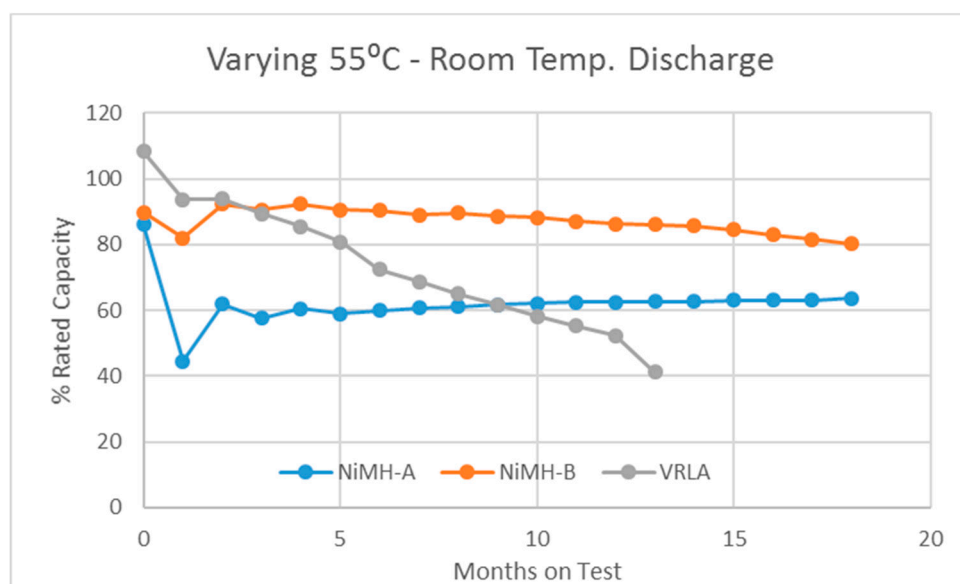
Ni/MH batteries in this test were supplied by FDK Corp (Tokyo, Japan) using the new type of superlattice metal hydride alloys [12–17]. This newly developed alloy family has a

higher storage capacity, an improved high-rate dischargeability, and a better cycle life when comparing to the conventional AB<sub>5</sub>-based metal hydride alloys [18–23]. These cylindrical cells (in long-A size) were assembled with pasted negative electrode, pasted Ni(OH)<sub>2</sub>-based positive electrode, polypropylene/polyethylene grafted separator, and a 30% KOH electrolyte. The cell design is targeted at a negative-to-positive ratio of 1.4 with a capacity of 3700 mAh.

### 3. Results and Discussion

#### 3.1. The Varying-55 °C Test

After 30 days' float (13.5 V per 12 V module) on the Varying-55 °C profile, batteries were cooled to room temperature (RT) and stabilized for 24 h, before being discharged at a C/8 rate. Figure 1 presents results from the monthly capacity check in a unit of percentage of the battery's nominal capacity.



**Figure 1.** Eight-hour discharge at room temperature (RT) following 30 days' float on the Varying-55 °C profile.

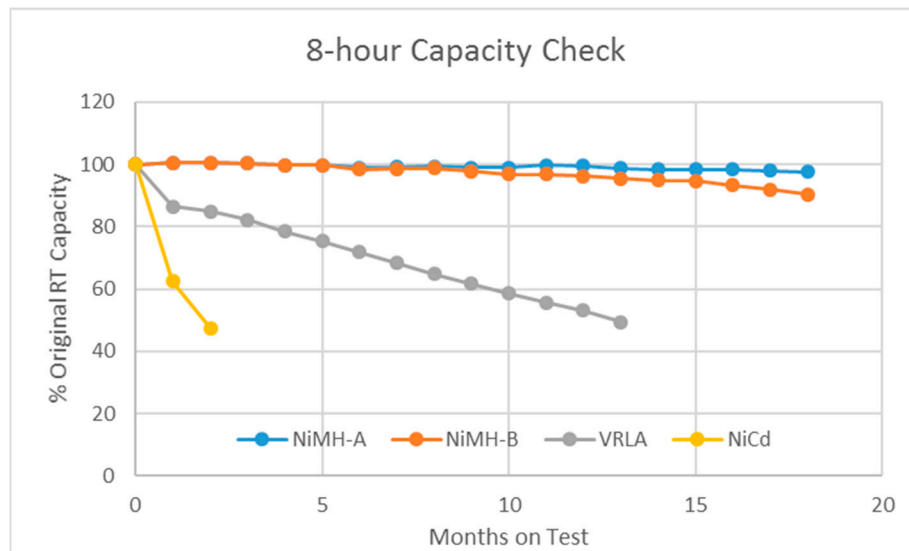
Specifications for the state-of-the-art Ni–Cd battery state operation in temperatures ranging from −20 to +50 °C and the capability of tolerating −50 to +70 °C for short durations [11]. Daily exposure of 9 h per day at 65 °C must have exceeded such “short duration” conditions as electrolyte leakage was observed on multiple Ni–Cd cells and the module was removed from the test.

In the monthly test, the VRLA module showed a steadily decreasing capacity due to the prolonged exposure to elevated temperature. The two Ni/MH modules returned relatively stable, but with vastly different capacities. This apparent capacity inconsistency of Ni/MH modules will be explained later. It is interesting to note that the Ni–Cd battery did not achieve any recordable discharge capacity in this test.

At the end of each discharge, battery modules were recharged at RT for 24 h and discharged again at a C/8 rate. Although this procedure is not part of the GR-3168 test protocol, it still provides a valuable capacity verification. The results of the monthly capacity check are shown in Figure 2.

After recharging at RT, the VRLA results were unaffected. The module reached 50% of its original capacity and was removed from the test after 13 months. In contrast, a significant change was observed for the Ni/MH modules—both types showed almost identical results of nearly full capacity after recharge at RT after more than one year on test. The very different result comparing to Figure 1 was not surprising as it has been documented that the standard Ni/MH (like module Type A) does not

charge well at temperatures higher than 50 °C [3]. The Ni/MH module Type B used an advanced cathode material [24] with a higher charging efficiency at an elevated temperature and thus did not display the same behavior as the standard Type A Ni/MH module. We reported before the failure mode of superlattice MH alloy at elevated temperature to be the continuous pulverization and surface oxidation [25]. Testing of both Ni/MH modules continues. It is interesting to note that, unlike the results in Figure 1, some discharge capacity was observed for the Ni–Cd module when charged at RT.



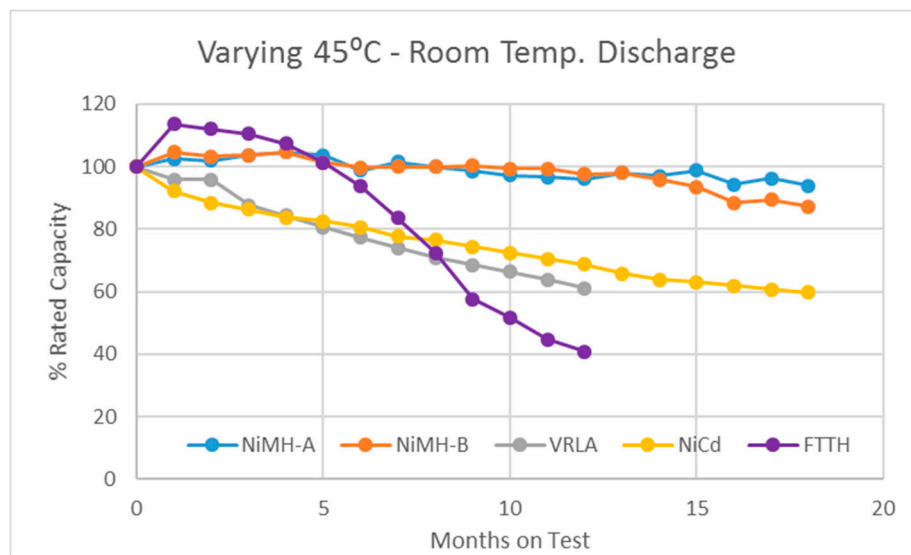
**Figure 2.** Varying-55 °C test; capacity check following recharge at room temperature (RT).

### 3.2. The Varying-45 °C Test

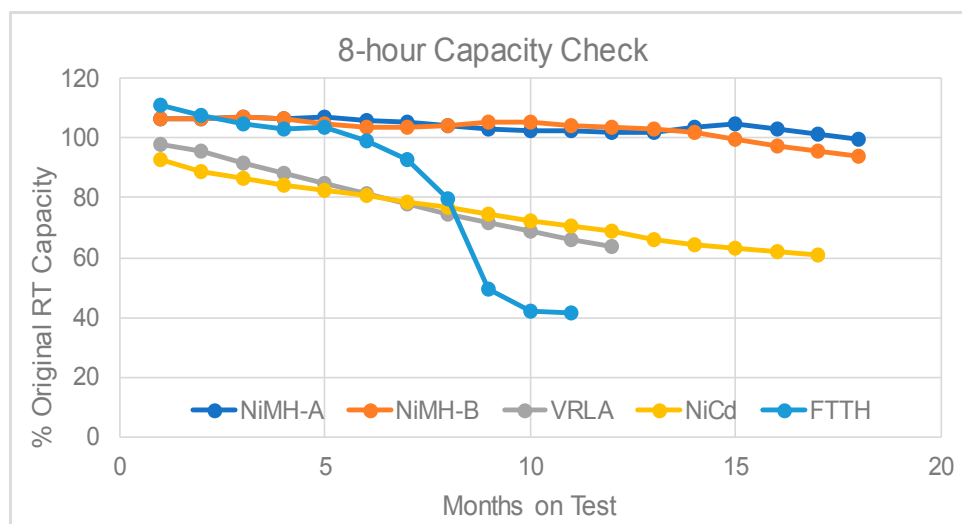
The Varying-45 °C aging test was conducted in a similar manner using the same types of batteries as in the Varying-55 °C test plus one additional VRLA module; a 12 V, 8 Ah monobloc module of the type commonly used in a fiber-to-the-home (FTTH) equipment [26].

Results of this ongoing testing are summarized in Figure 3. Following a significant initial jump in capacity, the 8 Ah FTTH battery began losing capacity at an increasing rate, falling below 60% of its nominal capacity after 9 months. The larger VRLA module displayed a slower, but steady capacity loss of about 3–4% with each monthly discharge. The capacity of the Ni–Cd battery showed similar behavior, losing about 2–3% per month. Capacities for both Ni/MH modules remained fairly steady, showing less than 5% reduction from their initial discharge capacity after 14 months at this elevated temperature profile.

Following each discharge, all batteries were recharged at room temperature (RT) and subsequently discharged at the C/8 rate. The results of this capacity verification are summarized in Figure 4. Similar to the results as shown in Figure 2, the standard Ni/MH battery (NiMH-A) recovered to a full capacity following recharge at RT. Since 80% of rated capacity indicates the end of life condition under which telecom batteries are replaced in the field, both VRLA modules and the Ni–Cd battery were removed from the test. Meanwhile, both Ni/MH batteries continue to return capacities above 90% and will remain on test for the foreseeable future.



**Figure 3.** Eight-hour discharge at room temperature (RT) following 30 days' float on the Varying-45 °C profile.



**Figure 4.** Varying-45 °C test; capacity check following recharge at room temperature (RT).

#### 4. Conclusions

Battery modules of various chemistries were tested according to simulated telecom outdoor power cabinet temperature profiles. Among the three chemistries tested, nickel/metal hydride showed the most durable results in both Varying-45 and -55 °C aging tests. Longer operating life and superior capacity retention at elevated temperatures are important considerations for stationary battery users since many applications require operation at high temperature. While this paper focuses on high ambient temperature environments, high heat can result from a number of other conditions including rapid cycling, high discharge rates, and fast charging. Nickel/metal hydride, therefore, can be considered a superior alternative to valve-regulated lead-acid and nickel-cadmium batteries for a wide range of applications.

Nickel/metal hydride battery technology offers a great number of additional benefits as an advanced alternative to conventional valve-regulated lead-acid and nickel-cadmium batteries, including proven safety and reliability in more than 12 million hybrid electric vehicles, high power

and energy density, and long cycle life. While small stationary Ni/MH battery products have begun to appear on the market, the development of large-format Ni/MH batteries is creating new business opportunities for substation-scale energy storage and other industrial battery applications. Examples of stationary Ni/MH batteries for specific applications are discussed in the Supplemental Materials accompanying this paper.

**Supplementary Materials:** The following are available online at [www.mdpi.com/2313-0105/4/1/1/s1](http://www.mdpi.com/2313-0105/4/1/1/s1), Figure S1: A 600 W Small Cell Power System (left) and its integrated battery module with Ni/MH cells and battery management system (right). Photos are courtesy of Alpha Technologies Ltd. (Burnaby, British Columbia, Canada) and FDK Corp. (Tokyo, Japan), Figure S2: Bi-polar cell design/construction in KHI GigaCell, Figure S3: High-rate charge and discharge capability of KHI GigaCell. 5.0C equals 750 amps, Table S1: Specific energy and power for commercial large format battery modules of four different chemistries. (Ni/MH and Li-ion include integrated electronic components), Figure S4: Illustration of a wayside railroad BPS installation, Figure S5: Single day charge/discharge profile for a wayside railroad BPS installation, Figure S6: Solar farm and Ni/MH BPS near Osaka, Japan.

**Acknowledgments:** The authors would like to thank the following individuals: Sui-ling Chen, Cheryl Setterington, Anthony Wilde, and Nathan English from BASF.

**Author Contributions:** Michael A. Zelinsky and Kwo-Hsiung Young prepared the manuscript. John M. Koch performed the experiment and analyzed the data.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

Telecom	telecommunications
VRLA	valve-regulated lead acid
Ni-Cd	nickel cadmium
Ni/MH	nickel/metal hydride
HEV	hybrid electric vehicle
MH	metal hydride
RT	room temperature
FTTH	fiber-to-the-home
BPS	battery power system

## References

1. Zelinsky, M. Heat Tolerant Ni/MH Batteries for Stationary Power. In Proceedings of the Battcon 2010 International Stationary Battery Conference, Hollywood, FL, USA, 17–19 May 2017.
2. Fetcenko, M. Battery Materials for E-Mobility. In Proceedings of the 33rd International Battery Seminar & Exhibit, Fort Lauderdale, FL, USA, 21–24 March 2016.
3. Zelinsky, M. Batteries and Heat—A Recipe for Success? In Proceedings of the Battcon 2013 International Stationary Battery Conference, Orlando, FL, USA, 6–8 May 2013.
4. Alpha Technologies Ltd. Celect™ 600 Product Data Sheet. Available online: <https://atl.app.box.com/v/celelect-600-48v-dc> (accessed on 31 July 2017).
5. Palu, J. Design considerations for data-storage memory back-up. Available online: [https://www.electronicproducts.com/Power\\_Products/Batteries\\_and\\_Fuel\\_Cells/Design\\_considerations\\_for\\_data-storage\\_memory\\_back-up.aspx](https://www.electronicproducts.com/Power_Products/Batteries_and_Fuel_Cells/Design_considerations_for_data-storage_memory_back-up.aspx) (accessed on 22 December 2017).
6. WMATA Energy Storage Demonstration Project, Federal Transit Administration Final Report. June 2015. Available online: [https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA\\_Report\\_No.\\_0086.pdf](https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA_Report_No._0086.pdf) (accessed on 31 July 2017).
7. Nishimura, K.; Takasaki, T.; Sakai, T. Introduction of large-sized nickel-metal hydride battery GIGACELL for industrial applications. *J. Alloy. Compd.* **2013**, *580*, S353–S358. [CrossRef]
8. Bai, W. The Current Status and Future Trends of Domestic and Foreign NiMH Battery Market. Available online: <http://cbea.com/u/cms/www/201406/06163842rc0l.pdf> (accessed on 31 August 2017).



9. Available online: <http://telecom-info.telcordia.com/site-cgi/ido/docs.cgi?ID=SEARCH&DOCUMENT=GR-3168&> (accessed on 31 August 2017).
10. EnerSys PowerSafe SBS 100 Technical Specifications. Available online: [http://www.enersys.com/Asia/PowerSafe\\_SBS\\_Batteries.aspx?langType=1033](http://www.enersys.com/Asia/PowerSafe_SBS_Batteries.aspx?langType=1033) (accessed on 31 July 2017).
11. Saft Tel.X Ni–Cd Batteries for Telecom Networks Technical Manual. Available online: [http://www.npstelecom.com/resources/products/fcm/\\_10q11wyx4nw9122mr4nbh87x1066kfv8z6smqm9djyh8pn584.pdf](http://www.npstelecom.com/resources/products/fcm/_10q11wyx4nw9122mr4nbh87x1066kfv8z6smqm9djyh8pn584.pdf) (accessed on 31 July 2017).
12. Yasuoka, S.; Magari, Y.; Murata, T.; Tanaka, T.; Ishida, J.; Nakamura, H.; Nohma, T.; Kihara, M.; Baba, Y.; Teraoka, H. Development of high-capacity nickel-metal hydride batteries using superlattice hydrogen-absorbing alloys. *J. Power Sources* **2006**, *156*, 662–666. [CrossRef]
13. Teraoka, H. Development of Low Self-Discharge Nickel-Metal Hydride Battery. Available online: <http://www.scribd.com/doc/9704685/Teraoka-Article-En> (accessed on 9 April 2016).
14. Kai, T.; Ishida, J.; Yasuoka, S.; Takeno, K. The effect of nickel-metal hydride battery's characteristics with structure of the alloy. In Proceedings of the 54th Battery Symposium, Osaka, Japan, 7–9 October 2013; p. 210.
15. Teraoka, H. Development of Ni-MH EThSS with Lifetime and Performance Estimation Technology. In Proceedings of the 34th International Battery Seminar & Exhibit, Fort Lauderdale, FL, USA, 20–23 March 2017.
16. Teraoka, H. Ni-MH Stationary Energy Storage: Extreme Temperature & Long Life Developments. In Proceedings of the 33th International Battery Seminar & Exhibit, Fort Lauderdale, FL, USA, 21–24 March 2016.
17. Teraoka, H. Development of Highly Durable and Long Life Ni-MH Batteries for Energy Storage Systems. In Proceedings of the 32th International Battery Seminar & Exhibit, Fort Lauderdale, FL, USA, 9–12 March 2015.
18. Young, K.; Yasuoka, S. Past, present, and future of metal hydride alloys in nickel-metal hydride batteries. In Proceedings of the 14th International Symposium on Metal-Hydrogen Systems, Manchester, UK, 21–25 July 2014.
19. Young, K.; Chang, S.; Lin, X. C14 Laves phase metal hydride alloys for Ni/MH batteries applications. *Batteries* **2017**, *3*, 27. [CrossRef]
20. Young, K.; Wong, D.F.; Wang, L.; Nei, J.; Ouchi, T.; Yasuoka, S. Mn in misch-metal based superlattice metal hydride alloy—Part 1 Structural, hydrogen storage and electrochemical properties. *J. Power Sources* **2015**, *277*, 426–432. [CrossRef]
21. Young, K.; Wong, D.F.; Wang, L.; Nei, J.; Ouchi, T.; Yasuoka, S. Mn in misch-metal based superlattice metal hydride alloy—Part 2 Ni/MH battery performance and failure mechanism. *J. Power Sources* **2015**, *277*, 433–442. [CrossRef]
22. Wang, L.; Young, K.; Meng, T.; Ouchi, T.; Yasuoka, S. Partial substitution of cobalt for nickel in mixed rare earth metal based superlattice hydrogen absorbing alloy—Part 1 Structural, hydrogen storage and electrochemical properties. *J. Alloy. Compd.* **2016**, *660*, 407–415. [CrossRef]
23. Wang, L.; Young, K.; Meng, T.; English, N.; Yasuoka, S. Partial substitution of cobalt for nickel in mixed rare earth metal based superlattice hydrogen absorbing alloy—Part 2 Battery performance and failure mechanism. *J. Alloy. Compd.* **2016**, *664*, 417–427. [CrossRef]
24. Fierro, C.; Zallen, A.; Koch, J.; Fetcenko, M.A. The influence of nickel-hydroxide composition and microstructure on the high-temperature performance of nickel metal hydride batteries. *J. Electrochem. Soc.* **2006**, *153*, A492–A496. [CrossRef]
25. Meng, T.; Young, K.; Koch, J.; Ouchi, T.; Yasuoka, S. Batteries with cobalt-substituted superlattice hydrogen-absorbing alloy anodes at 50 °C. *Batteries* **2016**, *2*, 20. [CrossRef]
26. GS Yuasa GoldTop Technical Specifications. Available online: <http://www.gsbattery.com/fiber-home-batteries-ftth> (accessed on 31 July 2017).

