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On the Performance of Portable NiMH Batteries of General Use

Diego F. Quintero Pulido *, Catalin Felix Covrig and Matthias Bruchhausen

European Commission, Joint Research Centre (JRC), 1755 LE Petten, The Netherlands; catalin-felix.covrig@ec.europa.eu (C.F.C.); matthias.bruchhausen@ec.europa.eu (M.B.)
* Correspondence: diego.quintero-pulido@ec.europa.eu

Abstract: NiMH batteries are the most used technology of rechargeable batteries sold directly to consumers. Herein, we study the performance of the most common sizes of portable NiMH batteries (AA, AAA, D, C, and 9V). The performance and durability parameters—capacity, charge retention, charge recovery, and endurance in cycles—are measured for these types of batteries, according to the standard IEC 61951-2:2017 NiMH batteries. The purpose of this study is to create a basis for setting minimum performance requirements for the parameters in the European Regulation concerning batteries and waste batteries, EU 2023/1542, Annex III, Part B. Results show that the charging time of 16 h could be reduced to 8 h for verifying the rated capacity. The performance of commercial batteries with regard to charge retention, charge recovery, and endurance in cycles is often found to be 25–30% better than required in the relevant IEC standard. Furthermore, we present a short comparative analysis of an application test (IEC 60086-2:2021 "toy") for portable NiMH batteries with primary batteries. Such data allow comparing the performance of portable NiMH batteries compared to primary batteries in the application test "toy".

Keywords: NiMH battery; performance; portable batteries of general use; IEC standard; AA; AAA; C; D; 9V; battery regulation

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1. Introduction

The European Parliament and the Council adopted Regulation EU 2023/1542 concerning batteries and waste batteries in July 2023 [1]. It covers various categories of batteries, and one of its goals is to guarantee minimum performance and durability of batteries in the EU market to reduce environmental impacts. The Joint Research Centre (JRC) of the European Commission supports technical aspects for the regulation's implementation in the coming years.

One category of batteries covered by the regulation is "portable batteries of general use" (PBGUs), which refers to the most commonly used batteries directly sold to end-users with the common designations AAAA, AAA, AA, C, D, 4.5V, 9V, and A23. These batteries are found online, at supermarkets, and other retail businesses. In most cases, the batteries are used in domestic appliances (e.g., remote controls, clocks, radios, smoke detectors, toys). In the market a consumer may find common designation batteries with different chemistries. These batteries can be non-rechargeable batteries (also called 'primary' batteries), e.g., alkaline, zinc–carbon and lithium batteries, and rechargeable batteries (also called 'secondary' batteries). Nickel metal hydride (NiMH) is the most common chemistry, while nickel cadmium (NiCd) [2], nickel zinc (NiZn) [3], and lead acid [4] are used much less.

In this study, we analyze the performance and durability of commercial secondary NiMH batteries, focusing on their capacity, charge retention, charge recovery, and cycle endurance. By aligning our methodology with the IEC 61951-2 standard [5,6], we seek to establish a basis for future minimum performance requirements as mandated by the European batteries regulation in Article 9 [1]. Our findings will provide insights into both manufacturers and consumers, promoting the development of better battery technologies.

NiMH batteries contain valuable metals. At the positive electrode (cathode), nickel is present as a hydroxide compound. The negative electrode (anode) is composed of an intermetallic alloy with a combination of transition metals in a graphite substrate (nickel, cobalt, and manganese) and rare earth elements (lanthanum, cerium, neodymium, and praseodymium) that allow hydrogen storage [7]. The cathode and the anode are electrically separated by a polyolefin material, usually a non-woven polypropylene soaked in a concentrated aqueous solution of sodium hydroxide [8]. Research on improving the technology has been focused on the following: increasing cycle life [9], second life and reuse [10], recovery of rare metals from used batteries [11,12], and scaling up processes for battery recycling [13].

In terms of the energy storage market, the NiMH battery has gained attention for the different performance characteristics that it provides at the system and cell levels, such as a specific energy of 60–120 Wh/kg, an energy density of 140–300 Wh/L [14], an energy efficiency of 60–92%, a lifetime of 1800–2000 cycles, and its availability worldwide [15].

NiMH batteries have been commercially available since 1991, and in 2009, their production reached approximately 1 billion cells per year [16]. By 2022, the market was EUR 3 billion, and it is expected that by 2030 it will grow to EUR 4.1 billion [17]. Before the emergence of Li-ion batteries, NiMH batteries were the dominating technology in electric and hybrid vehicles, and they have received extensive investment from main manufacturers [18]. One important advantage of NiMH batteries is safety (in comparison with Li-ion batteries). To our knowledge, there have been no reports of fire accidents in the press mentioning NiMH batteries. Moreover, NiMH batteries are the preferred system for industrial and consumer applications for PBGUs due to their design flexibility and low maintenance and cost (as of 2018, 80 EUR/kWh to 250 EUR/kWh) [19], and it is expected that by 2040, NiMH batteries will still be used in hybrid and plug-in hybrid vehicles [20]. Due to the strong presence of NiMH batteries in the market, various IEC standards have been created to guarantee interoperability and compatibility between the many elements of a battery system (e.g., design, manufacturing [21], and testing of battery equipment [22]). Other considerations covered by standards are performance [5] and safety [23].

This research uses European and international standards for NiMH batteries, such as IEC 61951-2:2017+AMD1:2022 CSV [5,6], as references. These standards have been analyzed previously by our group at JRC [24–26].

The goal of this study is to present our research on analyzing the performance of NiMH batteries used as PBGUs. This is to create a base for setting minimum performance values listed in the batteries regulation Annex III [1]. The analysis is developed using the current standard IEC 61951-2 for portable NiMH batteries as a base for testing battery performance.

This research is organized as follows: In Section 2, the materials and methods are presented. In Section 3, we show the capacity analysis. In Section 4, the charge (capacity) retention is presented. In Section 5, charge (capacity) recovery is shown. In Section 6, the endurance in cycles is analyzed. Results are discussed in Section 7. In Section 8, the analysis of NiMH batteries in application test is shown. And lastly, Section 9 presents the conclusions.

2. Materials and Methods

This section presents the materials and methods used in this research. Two items are presented: the battery regulation link to NiMH batteries and the testing battery equipment used for this research.

2.1. The Batteries Regulation Concerning Portable Batteries of General Use

Table 1 lists the parameters from Regulation EU 2023/1542 Annex III part B applicable to rechargeable PBGUs, such as NiMH, for which minimum performance and durability requirements will be set. These definitions are based on those found in standard IEC 61951-1 [5].

Table 1. Performance parameters from the Battery regulation, Annex III, part B, rechargeable batteries.

Parameter	Definition
Rated capacity	Capacity value of a battery determined under specified conditions and declared by the manufacturer.
Charge (capacity) retention	Capacity that a battery can deliver after storage, at a specific temperature, for a specific time without subsequent recharge as a percentage of the rated capacity.
Charge (capacity) recovery	Capacity that a battery can deliver with subsequent recharge after storage, at a specific temperature, for a specific time, as the percentage of rated capacity.
Endurance in cycles	The number of charge and discharge cycles a battery can perform under specific conditions before the capacity drops below a specified fraction of the rated capacity.

The standard IEC 61951-2 is used for determining the parameters listed in Table 1. In Section 8, this research also uses the standard for primary batteries, IEC 60086 part 1 [27] and part 2 [28], together with the Nordic Ecolabel for primary batteries [29] and rechargeable batteries [30].

2.2. Samples and Battery Energy Storage Testing (BESTEST) Laboratory at JRC

The samples used in this research have been selected from the database on primary and secondary batteries created by the JRC since 2020 and that is in constant update. This database is not openly accessible for the time being but has been described in our previous research [25].

For the experimental analysis of the performance and durability, we use various brands of batteries commercially available in the European Union. Portable NiMH batteries and alkaline primary batteries (only in Section 8) of general use with the common designations AA, AAA, D, C, and 9V are used. A list of the selected batteries is presented in Table 2. All experiments are performed on pairs of batteries to check for repeatability. The differences in results between pairs of batteries were generally small; for all pairs used in this study, the difference was below 2%.

The testing of the batteries is performed at the BESTEST Lab (see Figure 1). The laboratory is in Petten, NL, and for this research, we used the following equipment:

- Three Maccor battery cyclers with the following capabilities:
  - ➢ Series 4000 with 32 channels rated 20 A @ −2/+8 V, and 32 T-Type thermocouple inputs.
  - ➢ Series 4000 M with 48 channels rated 5 A @ −2/+8 V, and 32 T-Type thermocouple inputs.
  - ➢ Series 4000 M with 16 channels rated 25 A @ 0–18 V, and 16 T-Type thermocouple inputs.
- Three BIA MTH 4.46 units (see Figure 1a), each composed of four independent and identical temperature chambers with a temperature control range between −40 °C and 85 °C. Each chamber has a volume of 46 l. The temperature deviation in the center

of the working space is ±0.5 °C, the temperature homogeneity in space relative to the set value is ± 1.5 °C.

- Two independent and identical Vötsch VCS3 7060-5 climate chambers (see Figure 1b), with a temperature control range between −55 °C and 155 °C and a humidity range of 10% to 98% RH. Each chamber has a volume of 600 l. The temperature deviation in the center of working space is ±0.5 °C.
- Hioki BT3562 battery testers for initial voltage and internal resistance measurements (3 mΩ to 3000 Ω/60 V DC).
- Nanotom S X-ray computed tomography system (GE Sensing & Inspection Technologies, phoenix X-ray, Wunstorf, Germany). X-ray tube with a maximum output power of 15 W and a maximum voltage of 180 kV, in combination with a 2D detector with a dynamic range of 850:1 which consists of 2304 × 2304 pixels

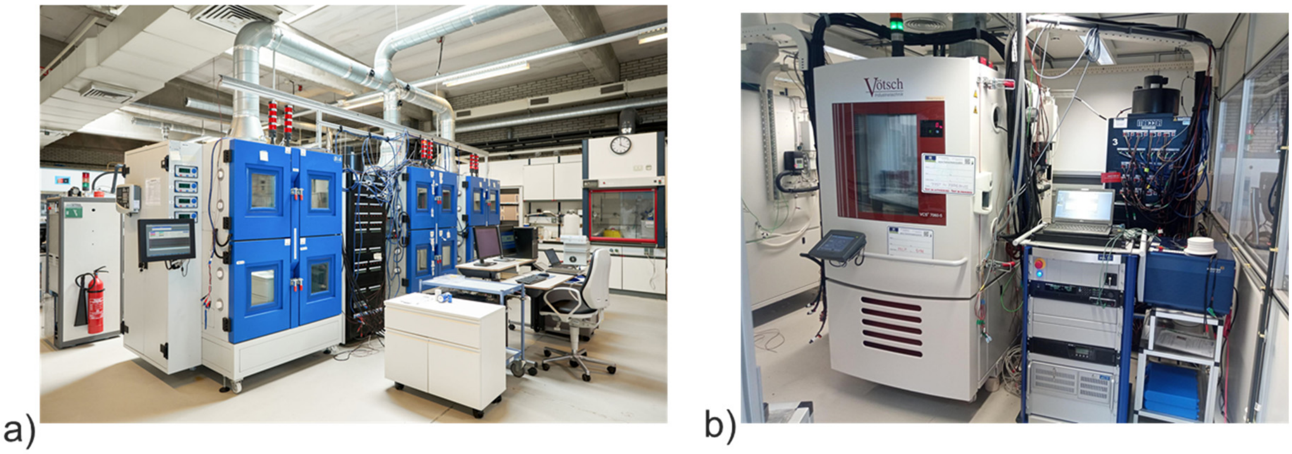

Figure 1. Experimental facilities at JRC Petten, The Netherlands: (**a**) Maccor battery cycler with BIA temperature chambers; (**b**) Maccor battery cycler with a Vötsch temperature chamber.

Table 2. Batteries from JRC database.

Manufacturer	Common Designation	Rated Capacity mAh	Type
Energyzer	AA	2500	NiMH
GP	AA	2100	NiMH
Duracell	AA	2500	NiMH
Soshine	AA	2700	NiMH
Duracell	AAA	900	NiMH
Tronic	AAA	1000	NiMH
GP	AAA	650	NiMH
Duracell	AAA	750	NiMH
Duracell	C	3000	NiMH
GP	C	3000	NiMH
Energizer	C	2500	NiMH
Energizer	D	2500	NiMH
Duracell	D	3000	NiMH
Phillips	D	3000	NiMH
Energizer	9V	175	NiMH
Agfaphoto	AA	2300	NiMH
Ansmann	C	4500	NiMH
RS pro	D	10000	NiMH
Agfaphoto	AAA	900	NiMH
Varta	C	3000	NiMH
GP	D	5700	NiMH

Table 2. *Cont.*

Manufacturer	Common Designation	Rated Capacity mAh	Type
Duracell	9V	170	NiMH
Energizer	AAA	700	NiMH
Energizer	AA	N/A	Alkaline primary
Duracell	9V	N/A	Alkaline primary
Varta	AAA	N/A	Alkaline primary
Duracell Plus	C	N/A	Alkaline primary
Energizer	D	N/A	Alkaline primary

3. Capacity Analysis of Portable NiMH Batteries

The analysis of the capacity is divided into three parts: first, an analysis of the charging profile; second, an analysis of discharge profile characteristics; and third, an analysis of the capacity protocols for portable NiMH batteries in IEC-61951-2.

3.1. Charge Analysis of Portable NiMH Batteries

There are three commonly used criteria for ending the charging of portable NiMH batteries denoted as temperature difference, time detection, and negative delta voltage [31]. These methods are applied by different manufacturers; however, in IEC-61951-2-2017-7.2.1, the method for charging portable NiMH batteries for verifying capacity is the time detection defined as 0.1 C for a charging time of 16 h (after discharging the battery to 1 V at 0.2 C). There is no definition of maximum cell voltage or maximum temperature. Furthermore, a fast-charging methodology for rated capacity tests is not included in this standard. Section 7 presents this in more detail.

Figure 2 presents the charge (a) and discharge (b) capacities of two AA NiMH batteries with a rated capacity of 2.5 Ah. The charging durations are varied between 8 h and 17 h. For one battery, the charging time increased between cycles (AS); for the other battery, it decreased (DS). Each battery has a twin battery to check repeatability. This is in order to exclude any effects that might be caused by cycle aging. The experiments are performed using a 0.1 C charge and 0.2 C discharge as specified in IEC-61951-2-2017-7.2.1 and 7.3.2.2.

We observed in Figure 2a that charging the AA NiMH battery for longer periods of 10 h does not affect the battery's discharge capacity of 2.5 Ah (see Figure 2b). In terms of efficiency, the highest columbic and energy efficiency is observed at 8 h for AS and DS experiments (see Figure 2c,d).

Having a similar discharge capacity at different charging periods may be an effect of the passivation of the negative electrode during charging of the NiMH battery, which can affect the cycle life of the battery [32]. The IEC 61951-2017 charging methodology (7.2.1) shows that a NiMH battery can have a columbic efficiency (charge–discharge) ranging from 62% (when charged for 16 h (see Figure 2d)) up to 99.1% (when charged for 8 h). Similarly, the energy efficiency varies between 55 and 90% with the same rated capacity (in this case, 2.5 Ah).

To further analyze the charging of portable NiMH batteries, we have selected different batteries available to consumers in Europe. These batteries are charged using the protocol in IEC 61951-2. The charge profiles for AAA, AA, C, and D batteries are shown in Figure 3. Portable NiMH batteries of different sizes have similar voltage profiles when charged at 0.1 C for 16 h (see Figure 3a–d). However, these batteries are from different manufacturers and have different rated capacities and sizes (see Figure 3e). The average charge voltage profile shows a start charging voltage of ~1.2 V rising for 8 h until a voltage of ~1.4 V, then a change phase is observed at 10 h during which the voltage rises quickly followed by a voltage plateau at 1.5 V with very little increase until 16 h (see Figure 3f).

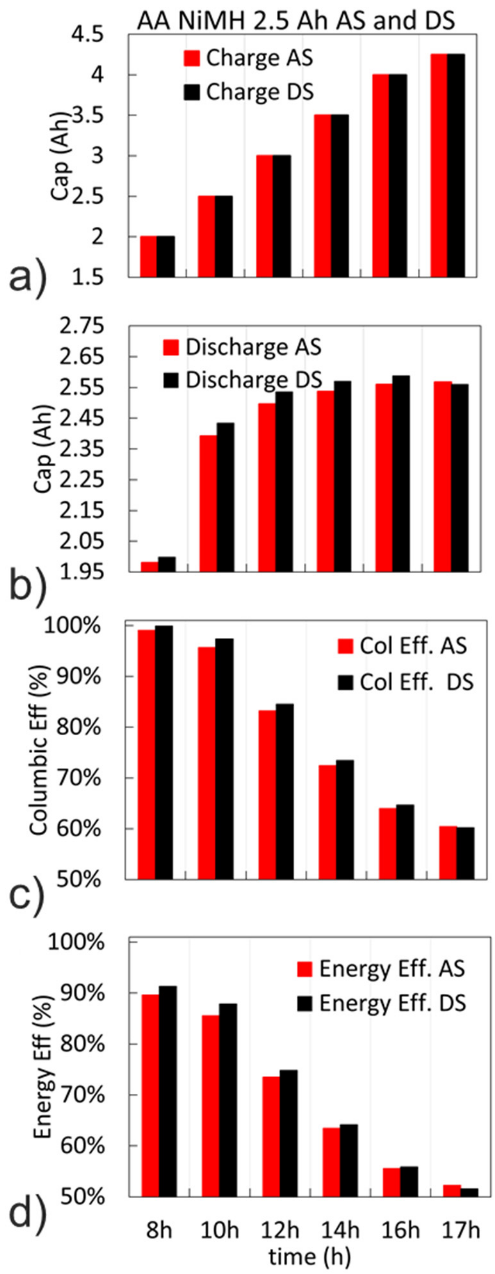

Figure 2. AA Energizer 2.5 Ah NiMH battery charge at 0.1 C and discharge at 0.2 C for different charging durations. AS = ascending charging duration; DS = descending charging duration with (**a**) charge capacity, (**b**) discharge capacity, (**c**) columbic efficiency, and (**d**) energy efficiency.

The selected portable NiMH batteries exhibit different internal resistances ranging from 2 mΩ up to 130 mΩ (see Figure 4). Increasing the size of the batteries tends to correlate with lower internal resistance. A "D" NiMH battery has a larger cell construction than a "AAA" battery (diameter of "AAA" 10 mm and "D" 33 mm); thus, the D battery has a greater electrode contact area with the electrolyte, reducing the internal resistance [33]. While the internal resistance is lower in bigger NiMH batteries (C and D designations), the specific energy density of the NiMH batteries is larger in AA and AAA batteries (see Figure 4). In all cases, there are differences between the rated capacity (Wh/kg declared label) and the tested capacity (Wh/kg JRC test). In most cases, the capacity declared by the manufacturer is larger than the capacity measured in this study. These differences could be related to the manufacturer's date of production, testing equipment, changes in the cell during transportation and distribution, to name a few.

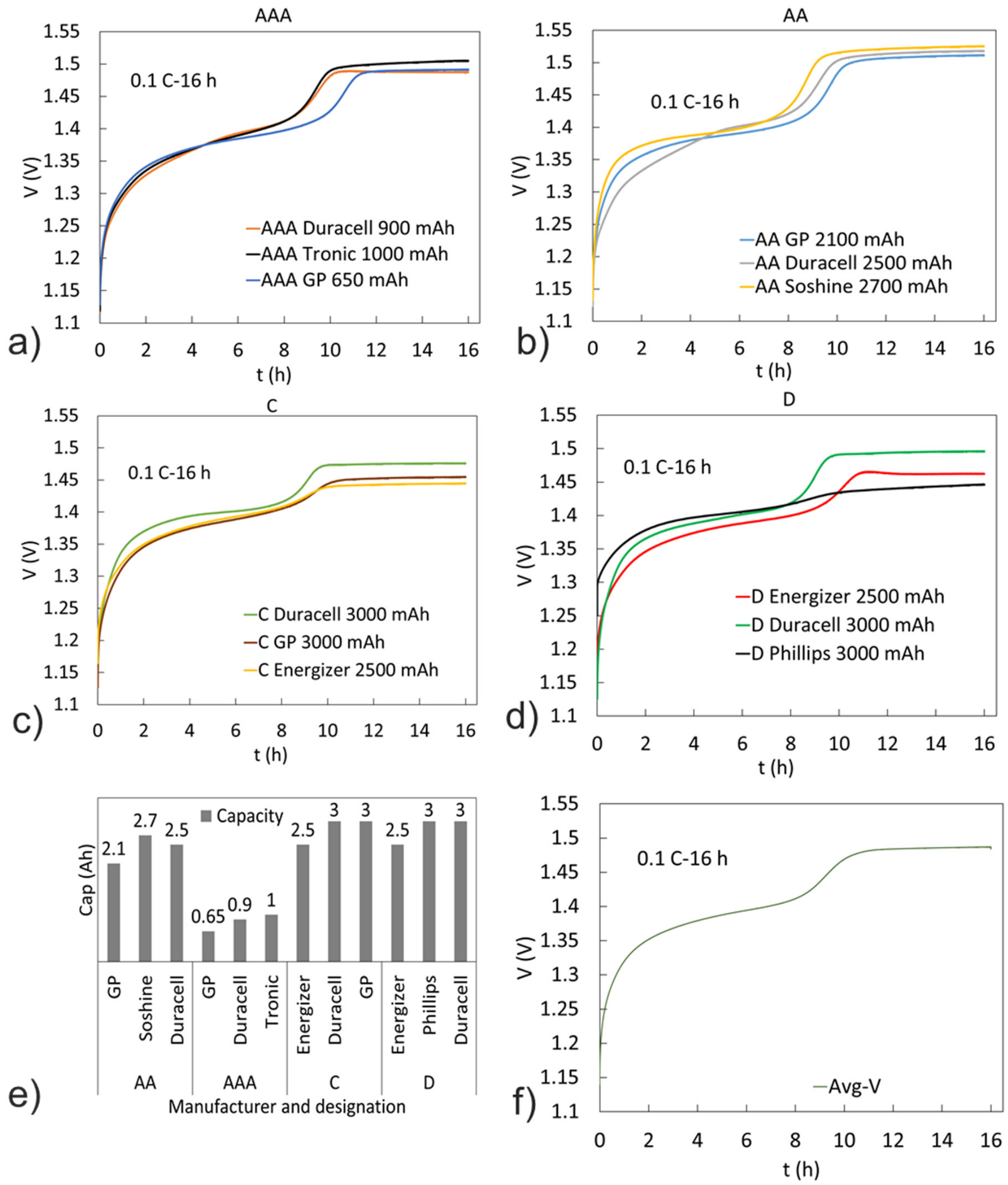

Figure 3. NiMH battery charge profile at 0.1 C and 16 h of different battery manufacturers of (**a**) AAA, (**b**) AA, (**c**) C, (**d**) D, (**e**) rated capacity, manufacturer, size, and (**f**) average charging voltage profile.

The difference in resistance and specific energy of batteries of the same size can also be related to the internal construction of the batteries. Figure 5 shows the X-ray tomography scan of the cross-sectional view of two AAA NiMH batteries with different rated capacities (see Figure 5a NiMH 900 mAh and Figure 5b NiMH 1000 mAh). The reconstructed CT data are evaluated by the VGSTUDIO MAX 3.4 software.

There are different design approaches for NiMH batteries depending on the manufacturer and application. In the case of the AAA NiMH of 900 mAh (see Figure 5a), the thickness of the electrode ensemble is small (0.1–0.2 mm); this allows for a high number of windings inside the battery casing (23 turns). The high number of windings is considered a method to increase both cell mechanical stability and cycle life [34]. In the other case, the AAA NiMH of 1000 mAh (see Figure 5b), the ensemble of separator and electrodes has a thickness of 0.5–0.7 mm and is wound four times. The electrodes with higher thickness in this case are of the felt structure type, with an increase in surface area that could increase the capacity of a battery [35].

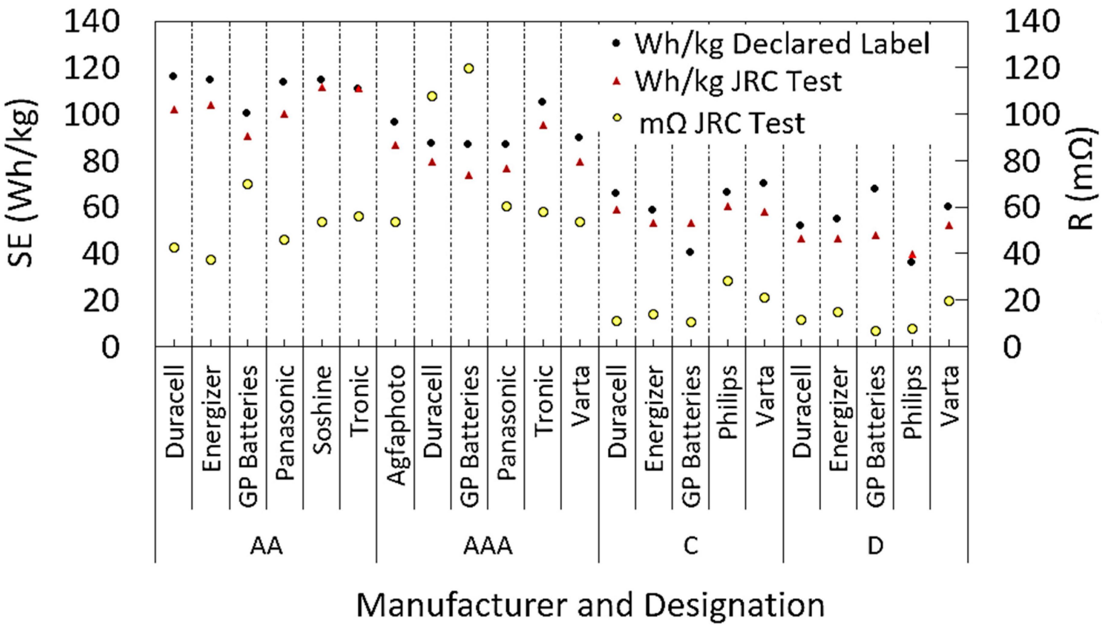

Figure 4. Portable NiMH batteries specific energy and internal resistance with manufacturers and designation.

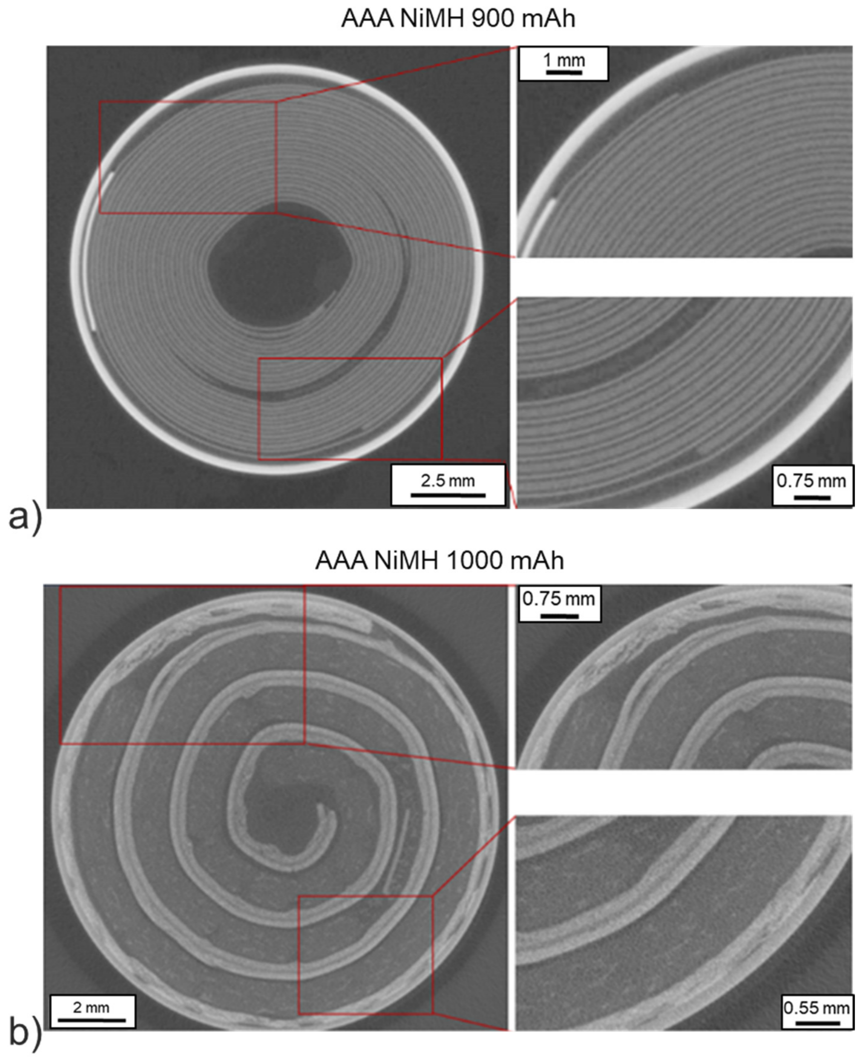

Figure 5. X-ray tomography scan cross-sectional view of AAA NiMH battery: (**a**) GP 900 mAh and (**b**) Tronic 1000 mAh rated capacity.

3.2. Discharge Analysis of Portable NiMH Batteries

The discharge is performed by following the procedure in standard IEC 61951-2. Figure 6 shows the discharge profile of different sizes of portable NiMH batteries. The batteries are discharged at a rate of 0.2 C until a cut-off voltage of 1 V (no resting period between charging and discharging is used). The discharge voltage profiles of the different NiMH batteries with sizes AAA, AA, C, and D are similar (see Figure 6a–d). The starting discharge voltage is between 1.38 V and 1.45 V, depending on the brand and battery size. The voltages drop until reaching a voltage of ~1.25 V after approximately 1 h. This is followed by a plateau where the discharge voltage is relatively stable. After 4.5–5.5 h, the voltage drop accelerates again until the cut-off voltage of 1 V is reached. The batteries have different final cut-off times (from 4.5 h to 5.8 h) depending on the manufacturer and size. It should be noted that the capacity declared by the manufacturer and not the actual capacity was used to determine the C rate (Figure 4); this can influence discharge duration.

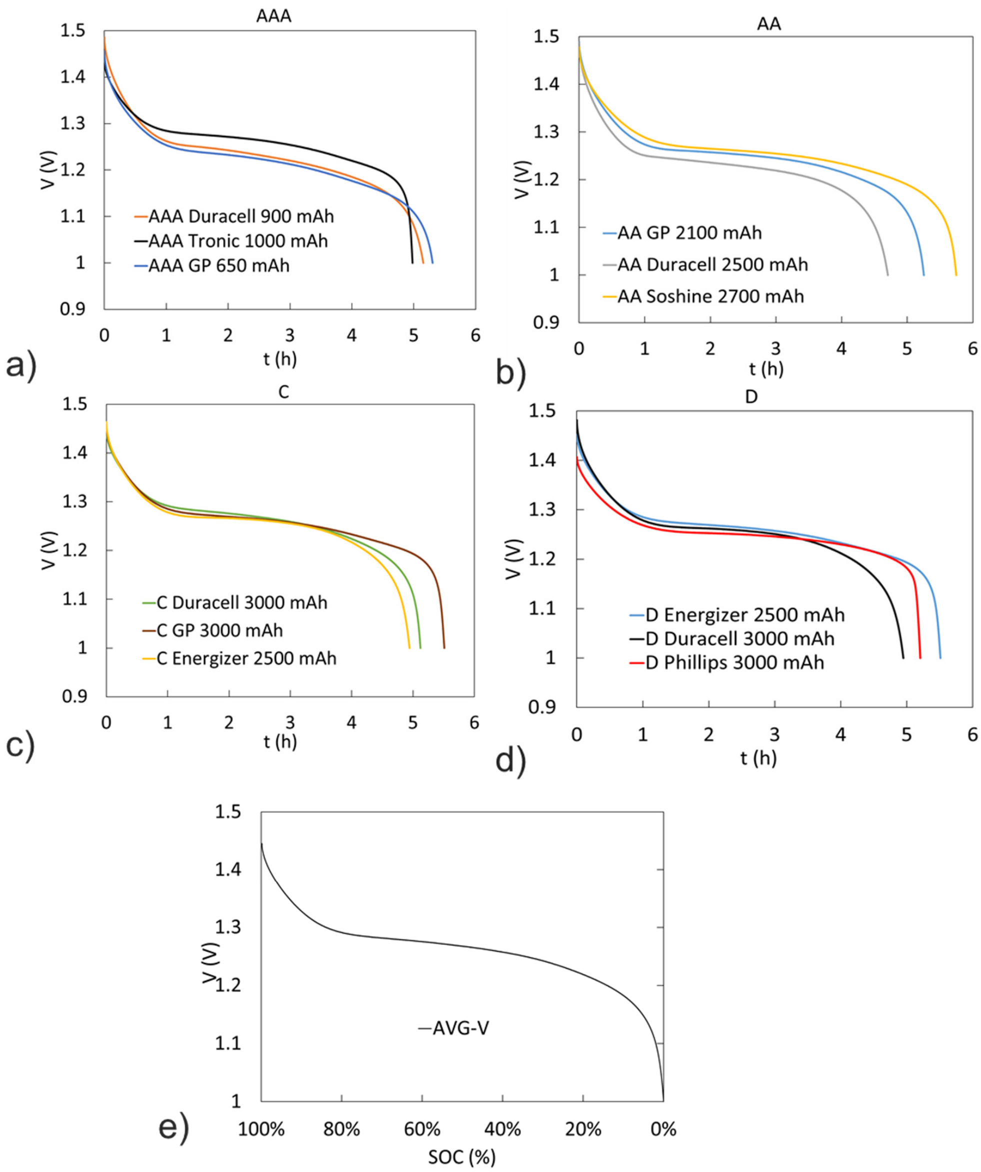

Figure 6. NiMH battery discharge profiles at 0.2 C and a cut-off of 1.0 V for different battery manufacturers of (**a**) AA, (**b**) AAA, (**c**) C, (**d**) D, and (**e**) average SOC.

Figure 6e shows the average voltage profile as a function of SOC. The starting average voltage at 100% SOC is 1.45 V. During the discharge, the voltage decreases quickly to 1.28 V, which corresponds to 80% SOC. Then the voltage drops more slowly while the discharge continues until ca. 1.2 V (20% SOC). Finally, there is another quick voltage drop until 1 V, determining the 0% SOC.

The test of the (rated) capacity is performed using the procedure in standard IEC 61951-2 clause 7.3.2. For this test, batteries are discharged at 0.2 C to a cut-off voltage of 1 V (7 V for the 9V battery). Then, they are charged at 0.1 C for 16 h and discharged at 0.2 C until the cut-off voltage of 1 V. The experiment is finished when the battery can reach the declared capacity by the manufacturer (the battery discharge time needs to be higher than 5 h in order to comply with IEC 61951-2 Table 6 [5]); if the battery fails to reach the capacity value, the experiment can be repeated up to five times. Figure 7 presents the results of testing different sizes of NiMH batteries.

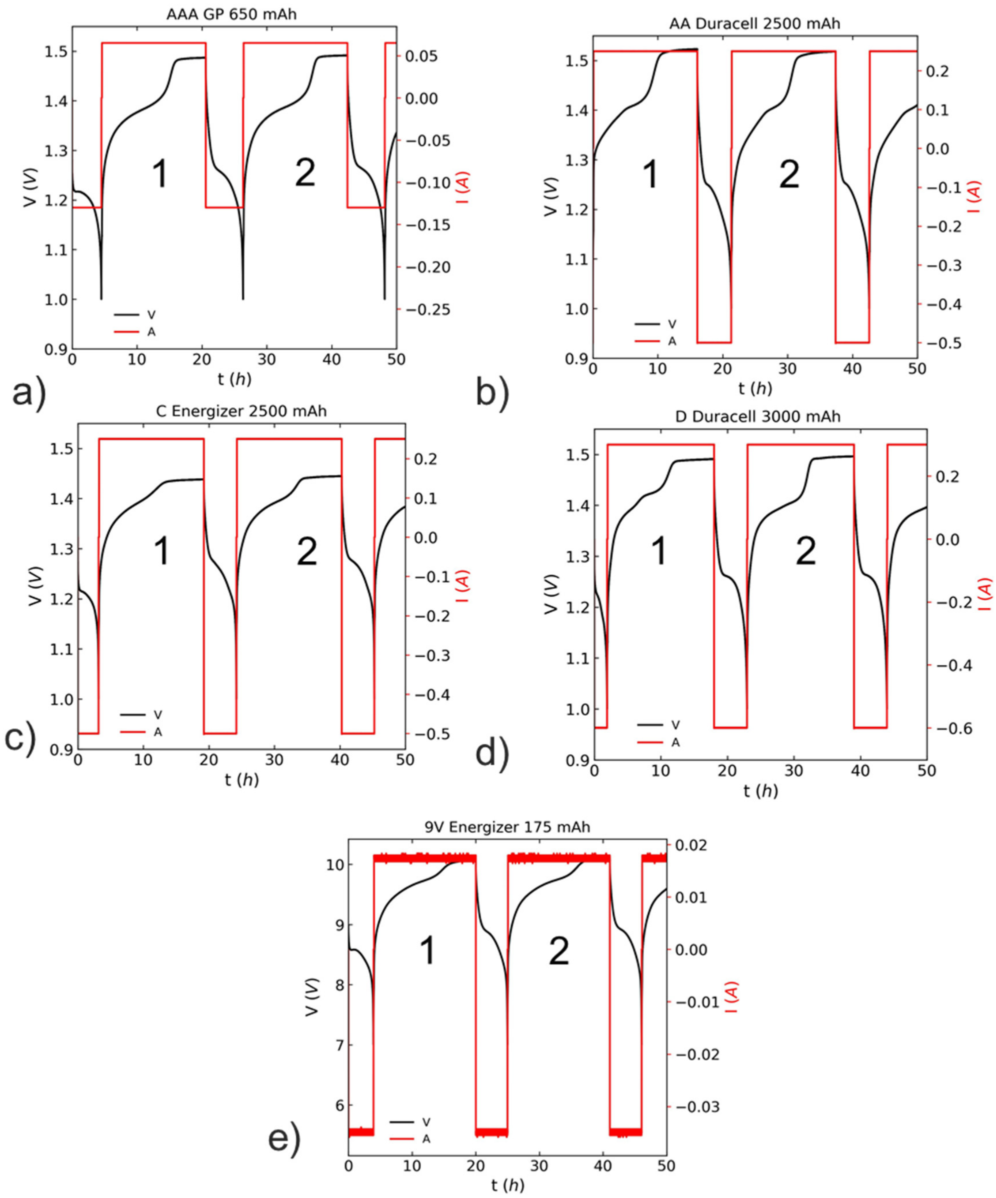

Figure 7. NiMH voltage and current profiles for rated capacity analysis according to IEC 619512, for (**a**) AAA GP, (**b**) AA Duracell, (**c**) C Energizer, (**d**) D Duracell and (**e**) 9V Energizer battery.

The AAA and AA NiMH battery voltage and current profiles are presented in Figure 7a,b. As expected, the AAA and AA batteries have similar voltage and current shape profiles. In both cases, the batteries do not reach the manufacturer’s rated capacity in the first cycle. However, in the second cycle, both batteries reached the rated capacity of

650 mAh for AAA and 2500 mAh for AA, with a discharge time longer than 5 h (thus meeting the requirement in IEC 61951-2). Similar behavior is observed for the C and D NiMH batteries (see Figure 7c,d). Also in this case, both batteries reached the manufacturer-rated capacity after the second cycle. The 9V battery consists of 7 cells connected in series. The voltage profile rises continuously during charging from 7 V to 10 V (Figure 7e); during discharge, the battery reaches the rated capacity in the second charge/discharge cycle. It is observed that the charging and discharging currents tend to have small changes in the 9V battery; this may be due to the connections between the cells that create resistance for the current to be fully constant. However, the fluctuation of the current is 1% to 3%, which, to our knowledge, does not affect the outcome of the experiment.

4. Charge Retention of Portable NiMH Batteries

The charge retention test of portable NiMH batteries is performed by following the procedure in standard IEC 61951-2 clause 7.4. The results are presented in Figure 8. The test protocol consists of the following:

1. The battery is first discharged to 1 V at 0.2 C.
2. The battery is then charged for 16 h at 0.1 C.
3. After charging, the battery is stored for 28 days in a temperature-controlled chamber at 21 °C ± 2 °C
4. Following the storage period, the battery is discharged at a 0.2 C until 1 V, and the discharge duration is measured to determine the remaining capacity.

A battery is considered to pass the IEC test if the discharge lasts for longer than 3 h before reaching the cut-off voltage. This means that the battery still held at least 60% of its initial charge after the 28-day storage period.

Figure 8a,b shows the discharge of AAA and AA batteries after 28 days of storage, with their corresponding initial discharge and charging steps. The AAA and AA batteries have similar voltage profiles. However, as expected, the capacity of AAA and AA is different, with 646 mAh and 2101 mAh, respectively. The voltage and current profiles in the C and D portable NiMH batteries are shown in Figure 8c,d. The C battery has a capacity of 4319 mAh, and the D battery has a capacity of 7477 mAh. In the case of the 9V (Figure 8e), the battery shows a discharge voltage curve like the one observed in the other NiMH battery sizes, but at an average voltage of 8.4 V. Furthermore, all NiMH batteries tested during the charge retention experiment show a discharge current curve longer than 3 h (minimum for IEC 61951-2 clause 7.4), and in terms of columbic efficiency, the highest observed value is 70% for the D size and the lowest observed value is 58% for the 9V battery. Further discussion of these results is presented in Section 7.

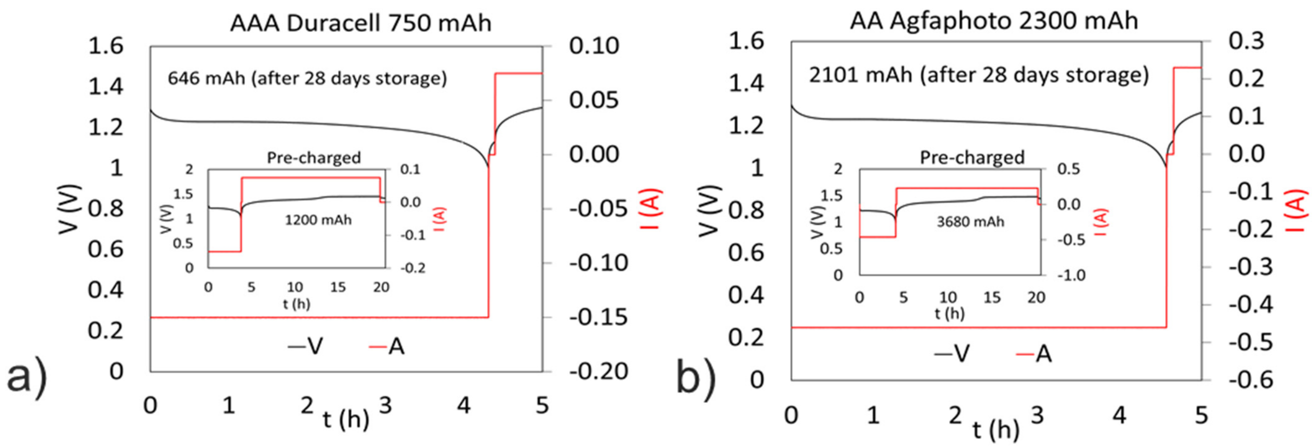

Figure 8. *Cont.*

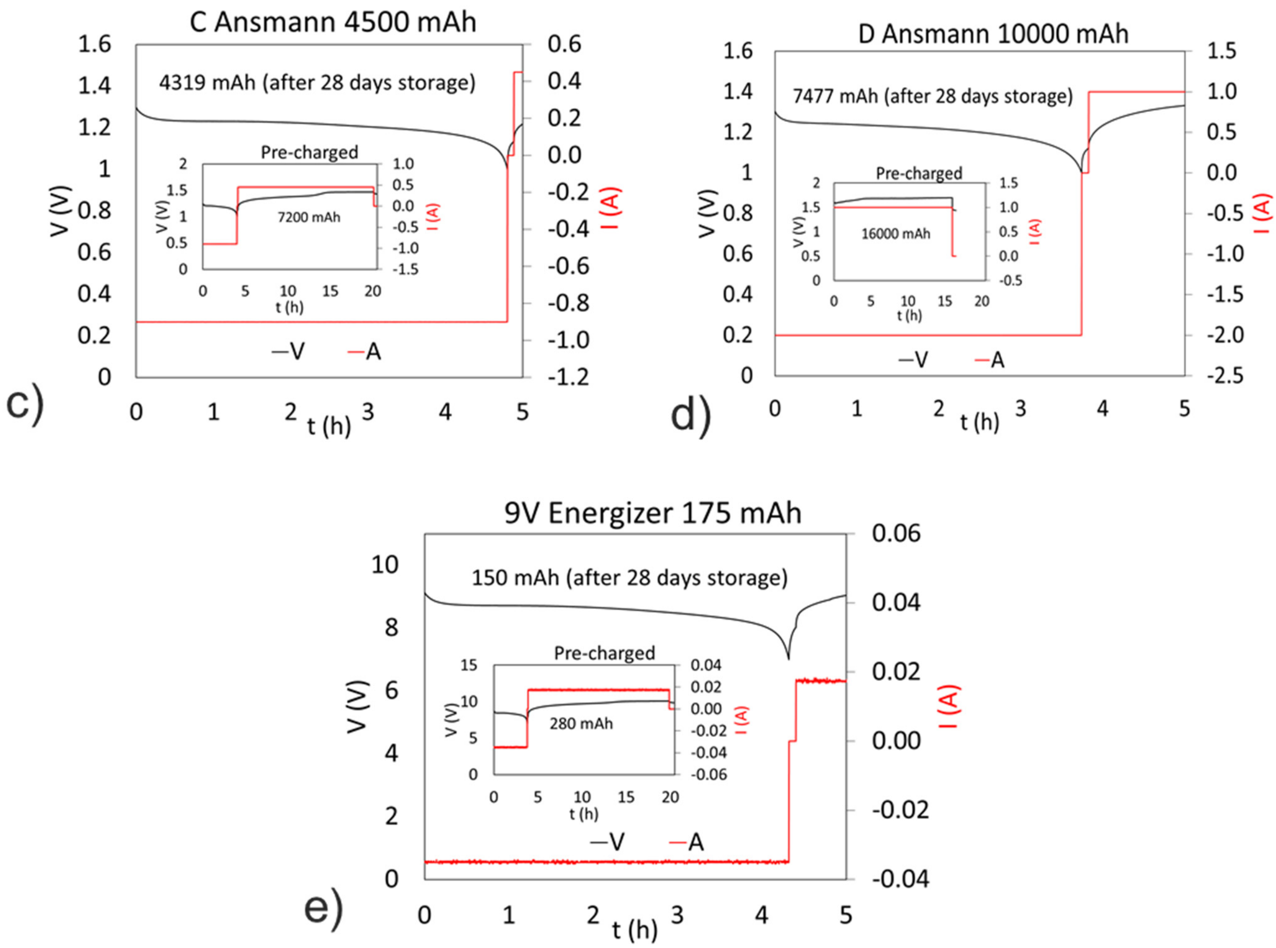

Figure 8. NiMH charge (capacity) retention analysis according to IEC 61951-2 with the pre-charged test for (**a**) AAA Duracell, (**b**) AA Agfaphoto, (**c**) C Ansmann, (**d**) D Ansmann, and (**e**) 9V Energizer batteries.

5. Charge (Capacity) Recovery of Portable NiMH Batteries

The charge recovery test is assessed following the procedure in standard IEC 61951-2, clause 7.10. Prior to testing, the NiMH batteries are stored for 8 months in their original package in a temperature chamber at 21 °C ± 2 °C before doing the following test:

1. The batteries are discharged at a 0.2 C rate until they reach a cut-off voltage of 1 V.
2. The batteries are then charged for 16 h at a 0.1 C rate.
3. Finally, the batteries are discharged again at a 0.2 C rate, and the duration of this discharge was measured.

A battery is considered to pass the test if the discharge is longer than 4 h before reaching the cut-off voltage, i.e., if they have at least 80% of their initial capacity left after storage.

Figure 9a,b show the discharge profiles of AAA and AA NiMH batteries after 8 months of storage. The AAA and AA batteries have similar voltage profiles. However, as expected, the current values are different. This results in different capacity values of 912 mAh for AAA and 2095 mAh for AA. Furthermore, the corresponding current curves for C and D batteries are presented in Figure 9c,d. In this case, the C battery reaches a capacity of 3249 mAh and the D battery a capacity of 7117 mAh. In the case of the 9V NiMH (Figure 9e), the battery shows a discharge capacity of 260 mAh after the storage period of 8 months.

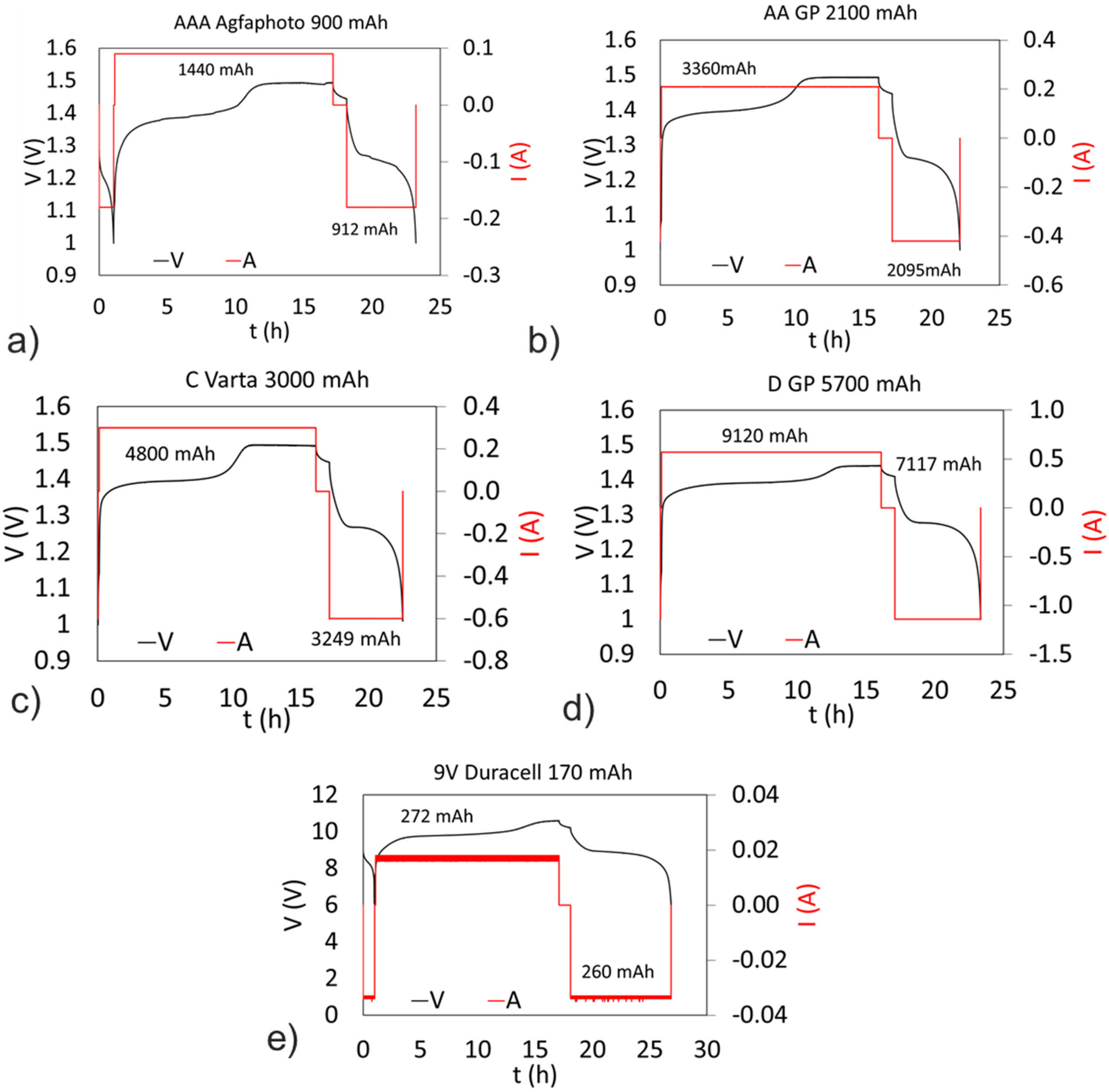

Figure 9. NiMH charge (capacity) recovery analysis according to IEC 61951-2 of (**a**) AAA Agfaphoto, (**b**) AA GP, (**c**) C Varta, (**d**) D GP, and (**e**) 9V Duracell batteries.

Furthermore, all portable NiMH batteries tested during the recovery experiment show a discharge duration longer than 4 h, and in terms of columbic efficiency, the highest observed value is 78% for the D size and the smallest value is 62% for the 9V battery.

6. Endurance of Portable NiMH Batteries

The analysis of endurance, measured in cycles, is performed using the method described by IEC 61951-2, clause 7.5.1.4. Figure 10 shows the cycling profiles of an AAA NiMH battery. The test procedure is as follows:

1. The battery is first discharged at a rate of 0.2 C until it reaches the cut-off voltage of 1 V.
2. The battery is then charged for 2 h at a 0.5 C rate. The charge termination criterion is either a ΔV of 5 mV to 10 mV (this criterion refers to a decline of voltage during charge after a certain time) or a maximum charge time of 132 min.

3. Immediately after charging, the battery is discharged at a 0.5 C rate until it reaches the cut-off voltage of 1 V.

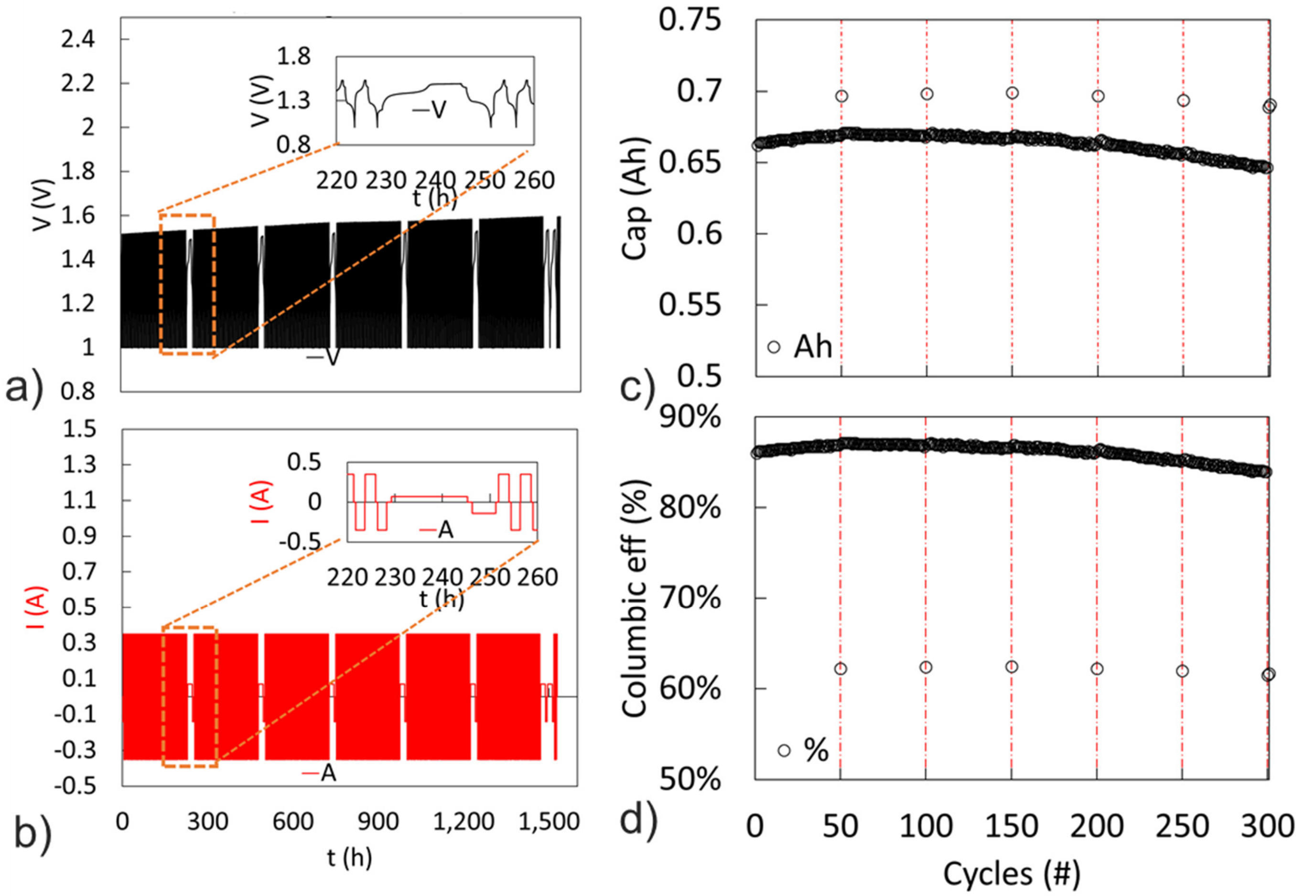

Figure 10. NiMH endurance in cycles analysis according to IEC 61951-2 for an AAA Energizer 700 mAh battery (**a**) voltage profile, (**b**) current profile, (**c**) capacity, and d) columbic efficiency vs. cycle number. The vertical red lines in (**c**,**d**) indicate checkup cycles.

If the discharge duration is less than 72 min, the experiment is terminated.

Moreover, every 50 cycles a checkup cycle is performed using the standard conditions for capacity rate calculation (charge 0.1 C for 16 h and discharge 0.2 C until 1 V); the experiment stops when the discharge time is less than 3 h. However, it is possible to perform a second capacity test, and if the discharge capacity is less than 3 h, the experiment is terminated. A battery has passed the test if the number of cycles is equal to or exceeds 200 (in the case of an AAA NiMH battery).

The voltage and current profiles of an AAA battery are presented in Figures 10a and 10b, respectively. The charge termination voltage tends to increase from 1.49 V in the first cycle to 1.59 V at the end of cycle 300; this effect in voltage can be related to an increase in resistance in the cell after cycling and possible side reactions, e.g., gas formation [36]. Furthermore, the average capacity of the AAA NiMH battery during cycling is 660 mAh, and during the checkup cycle, a capacity of 698 mAh is observed (see Figure 10c). Additionally, the columbic efficiency of the AAA NiMH battery varies from 86% to 82% during the cycles and ~62% during the checkup cycle (see Figure 10d). This is consistent with the kinetics of the cathode ($Ni(OH)_2$) and anode (MH), leading to higher capacity with lower C rates, which we have presented in Section 3.

7. Discussion

Portable NiMH batteries are tested for different parameters that are included in the European Regulation EU 2023/1542 (see Table 1). The procedures for measuring these parameters will be laid down in harmonized standards currently under development in CENELEC/TC 21X/WG 08 [37]. In this work, these parameters are evaluated using IEC 61951-2:2017 [5], the standard used as a basis for the ongoing work in WG 08.

It is observed that the performance of the tested commercial portable NiMH batteries generally complies with the performance and durability requirements in the current IEC 61951-2 standard.

The capacity test is developed to charge batteries for long periods, sacrificing columbic and energy efficiency. This method is looking at the maximum discharge output that a battery can provide under a constant load. However, as suggested in Figure 2, NiMH batteries can be charged for shorter periods (e.g., 8 h charge) to increase the electrical efficiency of the system (e.g., to >90% columbic efficiency), thus reducing electrical energy consumption. However, it is possible that reducing battery charging time may affect the rated capacity of the battery. This requires further analysis.

In terms of the analysis of capacity, we observed that for the analyzed batteries, using two cycles is sufficient to reach the rated capacity of the battery (see Figure 7), whereas IEC 61951-2 allows cycling up to 5 times for checking the declared capacity of the battery. Nevertheless, it is not possible to guarantee that any NiMH battery can pass the rate capacity test with two or five cycles; based on our observations, one cycle is not enough to pass the rated capacity test. Capacity increases after the first cycle may be related to the easier access of NaOH to the electrode's surface after the first cycle. Initially the NaOH is not able to reach all areas inside the cell, and this can show less capacity.

In the case of the charge (capacity) retention of portable NiMH batteries, it is observed that the batteries can provide up to 90% of the declared capacity (see Figure 8), and in all cases, the discharge time is longer than 4 h (above the IEC requirement of 3 h). This increase could be achieved thanks to new materials (e.g., better AB composites) and better construction of NiMH batteries that can provide less self-discharge [38]. It is important to note that the standard refers to this as a "charge (capacity) retention" test, but this terminology can be misleading. What is actually being measured is the amount of charge still available after storage, rather than the battery's ability to retain its full initial capacity.

For the capacity (charge) recovery of NiMH batteries, it is observed that batteries can be stored at 21 °C for 8 months without affecting the declared capacity, and in all cases, batteries can be discharged for periods of 5 h (the standard requires 3 h). Also, the test name "charge (capacity) recovery" in IEC 61951-2. This can be considered misleading since the battery is charged before the test, and its ability to store electric charge is measured, i.e., the state of health, SOH.

In the endurance testing of portable NiMH batteries, we observed that there are extra parameters that can be considered for the testing protocols in IEC61951-2., e.g., charge end voltage is included in the test for endurance cycles when batteries are charged at 0.5 C (this in contrast with the charging procedure in IEC 61951-2 that only foresees charging with 0.1 C for 16 h). When batteries are constantly cycled, the capacity measured in cycle 50 reached the declared capacity in the first cycle (the standard allows for two cycles to reach the declared capacity). Furthermore, the tested AAA battery reached 300 cycles, and the IEC requirement is 200 (see Figure 10). Recent studies on NiMH batteries show that they can perform up to 1000 charge/discharge cycles before losing 40% capacity [39], the threshold for the endurance test in this study. This suggests that the number of cycles for pass/fail for portable NiMH batteries can be increased significantly.

IEC 61951-2 defines performance and durability tests for portable NiMH batteries with constant currents for charging/discharging. In practice, batteries are used for different applications, with different requirements. IEC 61951-2 considers NiMH batteries interchangeable with primary batteries with the same common designations, but it is not presented if NiMH can perform the same application test that primary batteries required. In Section 8, we characterize portable NiMH batteries with application tests from IEC 60086-2 and Nordic swam Eco labelling for primary batteries [29].

8. Analysis of NiMH in 'Toy' Application Test

In this part of the study, primary and NiMH batteries of different sizes (AAA, AA, C, D, and 9V) are compared using the application test "toy" according to IEC 60086-2. The "toy" test is selected because it is one of the most common applications of PBGUs. While this application test is not intended for secondary batteries, it is still applied for facilitating the comparison of the performance of primary and NiMH secondary batteries. It is also chosen not to recharge the NiMH batteries for this test. In the case of NiMH batteries, the standard charging method in IEC 61951-2 is used (16 h, 0.1 C). The application test "toy" requires a battery to be discharged over a constant resistance for 1 h per day until a cut-off voltage of 0.8 V is reached for AA, AAA, C, and D size batteries and to 5.4 V for 9V batteries. A battery is considered to pass the test in IEC 60086-2 if the duration is higher than the minimum average duration (MAD) values in Table 3.

Table 3. Parameters for the toy test per common designation in IEC 60086-2.

Common Designation	Toy Test Ω	Nordic Swan MAD (min)	IEC 60086-2 MAD (min)
AAA	5.1	190	120
AA	3.9	450	300
C	3.9	1260	840
D	2.2	1440	960
9V	270	1260	420

Figure 11 presents the voltage and current profiles of both primary and secondary batteries using the "toy" application test. Figure 11a,b show the comparison of portable NiMH batteries with primary batteries for the "toy" application test for the common designations AA and AAA, respectively. Both the AA and AAA portable NiMH can pass the "toy" application test (as well as the primary batteries) even without recharging. The difference between the primary and the secondary AA and AAA batteries is 56 min (4.37% capacity difference) and 54 min (8.76% capacity difference), respectively. In the case of the C (see Figure 11c) and D (see Figure 11d) and 9V (see Figure 11e) NiMH batteries, they cannot meet the duration requirement for the application test "toy" without recharging. The difference between the C and D primary and secondary batteries is smaller than in the case of the 9V battery (C = 608 min (44.8% capacity difference), D = 787.9 min (49% capacity difference), and 9V = 179 min (400% capacity difference)).

Based on these results, although they cannot reach the pass value of the application test "toy", it is expected that the 9V, C, and D NiMH batteries can pass the test in the fourth charge/discharge cycle for the 9V NiMH battery and the second cycle for the C and D (as manufacturers declared a minimum of 400 cycles). For the AA and AAA batteries, the results show that the NiMH can fulfill the application test without recharging and that the gap between primary and secondary batteries for this specific test might depend on the battery size. Moreover, we observed that the application test from primary batteries (measured in duration) could have a direct relation with the NiMH battery (measured in capacity). Furthermore, conversion values for duration and capacity can be calculated, e.g., AAA 850 mAh NiMH can have a duration of 221 min, and AA 2100 mAh NiMH can have a duration of 419 min for the "toy" application test. These values might provide a realistic picture of the use of portable NiMH batteries in specific applications as observed in the toy test for primary batteries.

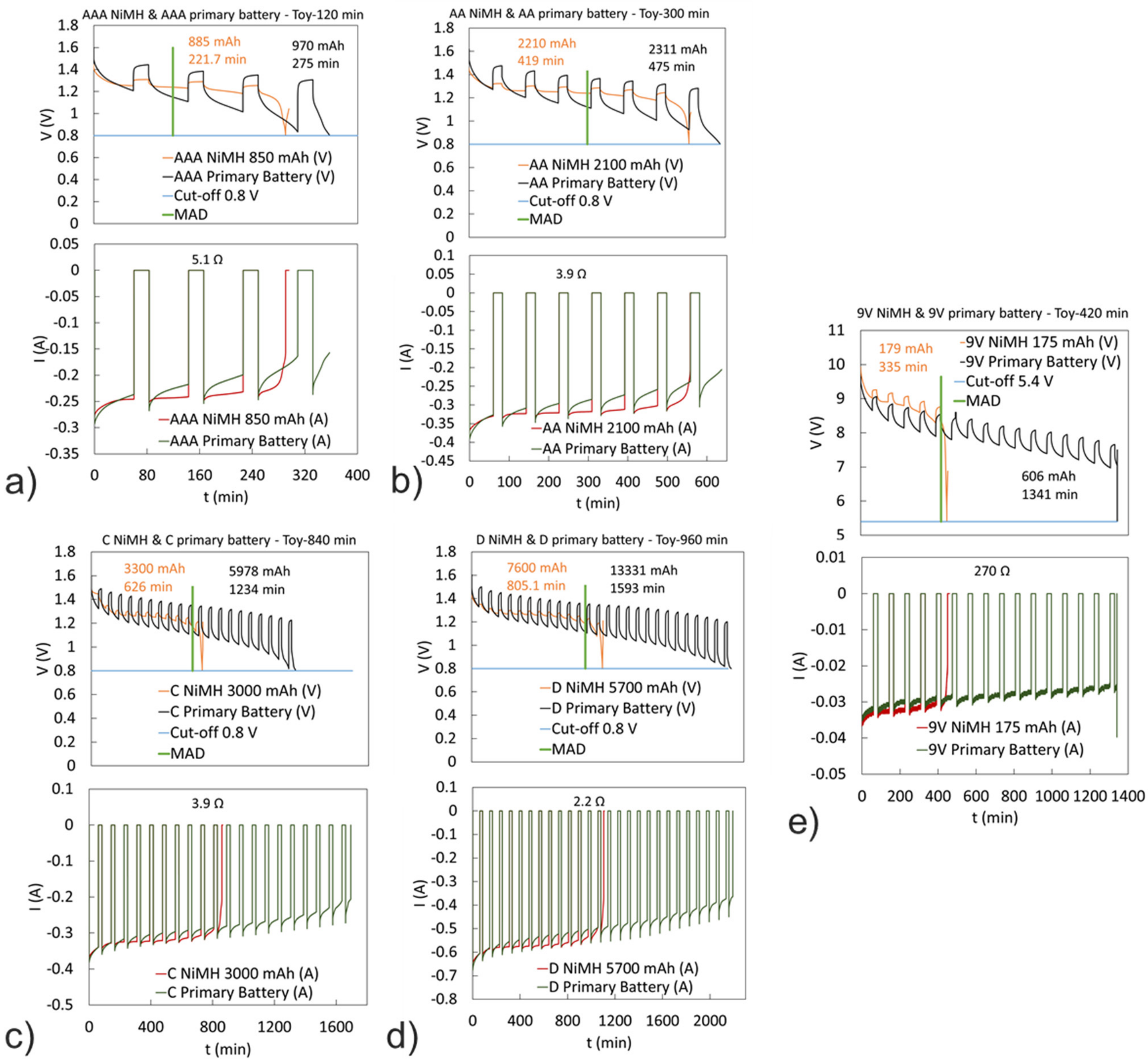

Figure 11. Comparison of portable NiMH batteries with primary batteries (alkaline) using the "toy" application test from IEC 60086-2, including the minimum average duration value, average duration, and measured capacity for (**a**) AAA, (**b**) AA, (**c**) C, (**d**) D, and (**e**) 9V batteries.

9. Conclusions

Portable NiMH batteries of general use are an important technology and require specific performance testing. The performance and durability parameters—rated capacity, charge retention, capacity recovery, and endurance in cycles—are measured in this study according to the applicable standard IEC 61951-2:2017/AMD1:2022.

Our findings show that better energy efficiency is achieved by reducing charging times (e.g., 8 h), as compared to 16 h defined for charging of NiMH batteries at 0.1 C in this standard. However, reducing charging time must be analyzed in more detail to observe if this change does not affect the battery's capacity.

Furthermore, the charge retention tests show that batteries lose 5% to 10% capacity after the 28-day storage period. This suggests that the minimum discharge time in IEC 61951 can be modified from 3 h to 4 h for these batteries. For the charge recovery, our results suggest that stored batteries after 8 months can pass the performance test of IEC 61951-2 and that the required discharge time could be increased from 4 h to, e.g., 5 h.

In addition, the endurance test shows that a maximum charge voltage may be added as an end-of-charge criterion to reduce the charging time, and the minimum number of cycles could be increased to be more in line with manufacturer-declared values; however, this needs to be analyzed more in detail to evaluate a realistic value for battery cycles per size.

Lastly, the application test shows that portable NiMH batteries in general can perform the "toy" test intended for primary batteries (IEC 60086-2); our results suggest that NiMH batteries can be used for this specific application as portable primary batteries.

Results confirm the common experience that NiMH batteries can replace primary batteries in a toy application. While a primary typically lasts longer than a NiMH battery on a single charge, a NiMH battery can be recharged.

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