TEXAS INSTRUMENTS

*Application Report*
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# *Single-cell Battery Discharge Characteristics Using the TPS61070 Boost Converter*

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**ABSTRACT**

This application report presents practical single-cell battery discharge characteristics in real-world application, and primarily focuses on the varying internal impedance of a battery and how that affects the battery terminal voltage.

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# 1 Introduction

Regardless of battery chemistry—alkaline, nickel cadmium (NiCd), or nickel metal hydride (NiMH)—in single-cell applications the battery voltage can be drained as low as 0.8 V ~ 0.9 V when the battery is finally empty. Ideally, the dc/dc boost converter start-up/operating voltage range should be specified down to this voltage range. This is true of Texas Instruments' TPS6101x family of devices; the start-up voltage is specified as 0.9 V to alleviate potential issues regarding start-up in such a low-voltage condition. After the device is started, it can be operated down to 0.8 V.

Texas Instruments' TPS61070/1 devices have a typical start-up voltage specified as 1.1 V (with a worst case start-up voltage of 1.2 V). However, once started, these devices can operate at < 0.9 V. The typical specified battery voltage in data specifications for NiMH batteries is 1.2 V. The typical discharge curve of both nickel and alkaline batteries is a non-linear curve from 1.5 V down to 0.9 V (with some battery capacity remaining when the battery voltage is below 1.2 V). These battery voltage specifications, and the start-up specifications of the TPS61070/1, generated some questions as to whether it is suitable for single-cell battery applications. In both cases, device start-up and battery energy utilization, the TPS61070 works well in single-cell applications.

**Table 1. TPS61070 Data Sheet Excerpt Showing Start-up Voltage**

| DC/DC STAGE | | | | | | |
|---|---|---|---|---|---|---|
| PARAMETER | | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
| $V_I$ | Minimum input voltage range for start-up | $R_L = 270\ \Omega$ | | 1.1 | 1.2 | V |
| | Input voltage range, after start-up | | 0.9 | | 5.5 | |
| $V_O$ | TPS61070 output voltage range | | 1.8 | | 5.5 | V |

# 2 Battery Chemistry and Circuit Model

To address the differences between start-up voltage and operating voltage, it is necessary to understand the basic structure of the battery. A simple model is represented in Figure 1.

When the battery is not loaded, the terminal voltage is equal to the internal cell voltage, because there is no current flowing through the battery's internal series resistor. This is indicated by the solid blue line of Figure 1 and shows the actual cell voltage and the terminal voltage at no load.

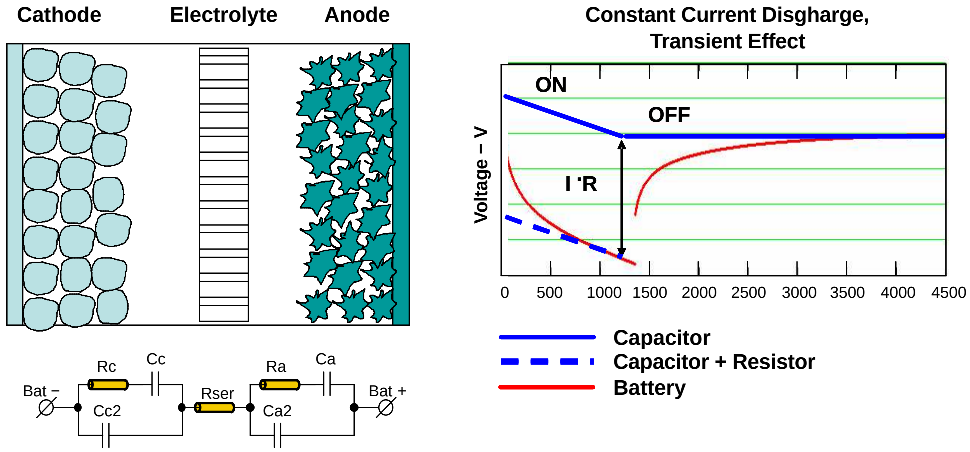


**Figure 1. Battery Structure, Basic Circuit Model, and Discharge Characteristics**

Once a load is applied to the battery, current flowing through the cells induces a voltage drop (**I** × **R**) across the internal series resistor (or sometimes referred to as the internal impedance of the battery), resulting in a lower terminal voltage versus the cell voltage. In steady-state conditions this **I** × **R** voltage is directly proportional to the load current multiplied with the internal resistance, as shown in Figure 2. However, during transient load conditions, due to the internal equivalent capacitance between the electrode, electrolyte, and separator, the actual terminal voltage is non-linear and does not represent a direct relationship with the **I** × **R** drop. At the initial condition of the load, due to this internal battery capacitance, the terminal voltage drops slightly slower due to the discharge of the equivalent capacitance voltage. After removal of the load, the terminal voltage does not recover to the cell voltage immediately. Rather, it takes several tens to hundreds of seconds for the terminal voltage to recover back to the cell voltage as shown in Figure 1.

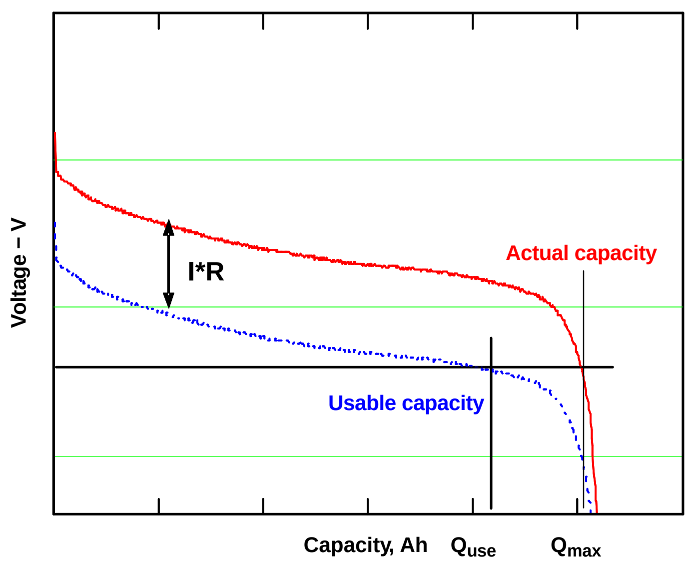


**Figure 2. Discharge Curve of Single-Cell Battery Under Different Load Conditions**

## 3 Battery Terminal Voltage vs Internal Cell Voltage

A commonly misunderstood concept of battery voltage is that the specified discharge voltage curve in the data sheet indicates the voltage under a specified load condition. The data sheet fails to mention the cell voltage internal to the battery, hence, misleading the engineer into thinking that the terminal voltage at no load is the same as the terminal voltage under a load condition. This case only exists if the load on the battery is so small that it does not generate noticeable voltage drop across the battery's internal resistance. This leads to discussion on whether the TPS61070/1 may not start up using an almost-depleted battery, and subsequently, not fully use the battery's capacity. The following experiment shows that in an actual application of a few tens of milliWatts, almost all energy in the battery is used and the device readily starts up.

Figure 3 shows the test results of a AA-size alkaline battery under a constant power discharge of 330 mW with TPS61070 output voltage of 3.3 V. As evident from the two curves, when the terminal voltage is discharged to < 0.9 V, almost all of the battery's usable energy is depleted. However, sometime after the load is removed, the terminal voltage recovers to nearly 1.2 V although the battery energy is still almost empty.

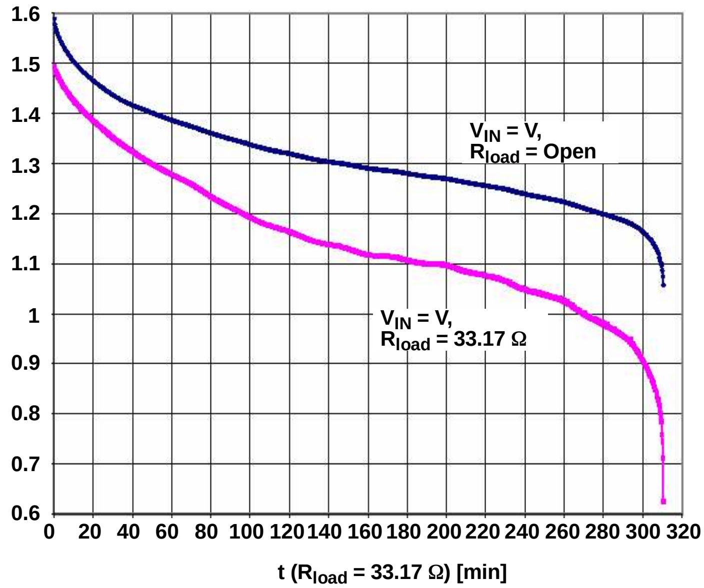


**Figure 3. A Typical AA-Size Alkaline Battery Voltage at No Load Versus at 330-mW Discharge**

## 4 Internal Resistance of a Battery vs Battery Energy State

An important parameter that usually is not well specified in a battery specification is the internal resistance of the battery throughout the discharge cycle. When a battery discharges, its internal resistance increases as its energy capacity decreases. Table 2 compares the specification of a typical AAA-size alkaline battery and NiMH battery side-by-side. Note the change in internal resistance at different capacities of the NiMH battery. This should also be specified for alkaline batteries.

**Table 2. Specifications for an Alkaline and NiMH Battery.**

| | | | |
|---|---|---|---|
| **Chemical System:** | Alkaline<br>Zinc-Manganese Dioxide (Zn/$MnO_2$)<br>(No Added Mercury or Cadmium) | **Description:**<br>**Chemical System:** | Rechargeable 1.2 V<br>Nickel-Metal Hydride (NiMH) |
| **Designation:** | ANSI-24A, IEC-LR03 | **Designation:** | ANSI-1.2H1 |
| **Battery Voltage:** | 1.5 Volts | **Battery Voltage:** | 1.2 Volts |
| **Internal Resistance:**<br>**Operating Temp:** | 205 milliohms (Fresh)<br>–18°C to 55°C (0°F to 130°F) | **Average Capacity:** | 850 mAh ( to 1.0 volts)<br>(Based on 170 mA (0.2C) discharge rate) |
| **Average Capacity:** | 1,250 mAh (to 0.8 volts<br>(Rated capacity at 25 mA continuous drain) | **Average Weight:**<br>**Volume:** | 12.0 grams (0.4 oz)<br>3.8 cubic centimeters )0.2 cubic inch) |
| **Average Weight:**<br>**Volume:** | 11.5 grams (0.4 oz)<br>3.8 cubic centimeters (0.2 cubic inch) | **Jacket:** | Plastic Label |
| **Cell:** | One No. 3-312 (size AAA) | | |
| **Jacket:** | Plastic Label | | |
| **Shelf Life:** | 7 years (80% of rated capacity) | | |
| | | **Internal Resistance** | |
| | | The internal resistance of the cell varies with state of charge, as follows: | |
| | | **Cell Charged** | **Cell 1/2 Discharged** |
| | | 100 milliohms | 1200 milliohms |
| | | (tolerance of 20% applies to above values) | |

How this parameter affects the start-up voltage and usable capacity of the battery in reality can be seen in the following experiments. The TPS61070 EVM boosts the battery output voltage to 1.8 V while loaded at 40 mA (constant power discharge of 72 mW at the output equates to about 85 mW discharge from the battery because of ~85% efficiency at this Vin). All waveforms are captured from an almost fully discharged battery; the upper (yellow) waveform indicates the battery terminal voltage and the lower (blue) waveform indicates the output load current of 40-mA peak

## 5 Alkaline Battery Testing

Figure 4 and Figure 5 show screen captures of the loading voltage waveform of a AAA-size alkaline battery at different stages of battery discharge. The left image of Figure 4 shows that the open-load battery voltage of 1.4 V drops to 1.28 V when it is loaded at 85 mW. The right image shows that when the battery is further discharged down to open-load battery voltage of 1.3 V the battery voltage drops to 1.14 V, when it is loaded at 85 mW.

When the battery is discharged even further to almost empty, the internal resistance continues to increase, and the left image of Figure 5 shows the open-load battery voltage of 1.25 V, which drops to 1 V when it is loaded at 85 mW. The right image shows open-load battery voltage of 1.22 V, which drops to 0.9 V when it is loaded at 85 mW.

Notice the increasing voltage drop from the initial test results of 112 mV (with open-load battery voltage of 1.4 V) to 320 mV (with open-load battery voltage of 1.22 V). The internal resistance increases more than twofold.

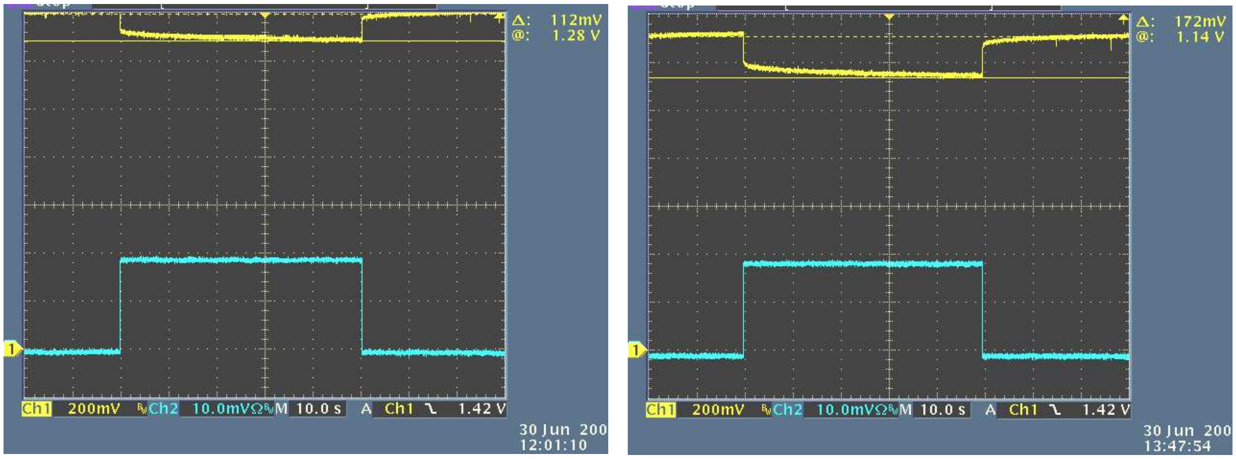


**Figure 4. Open Load and 85-mW Step Load of Alkaline Battery with Terminal Voltage of 1.4 V (Left) and 1.3 V (Right)**

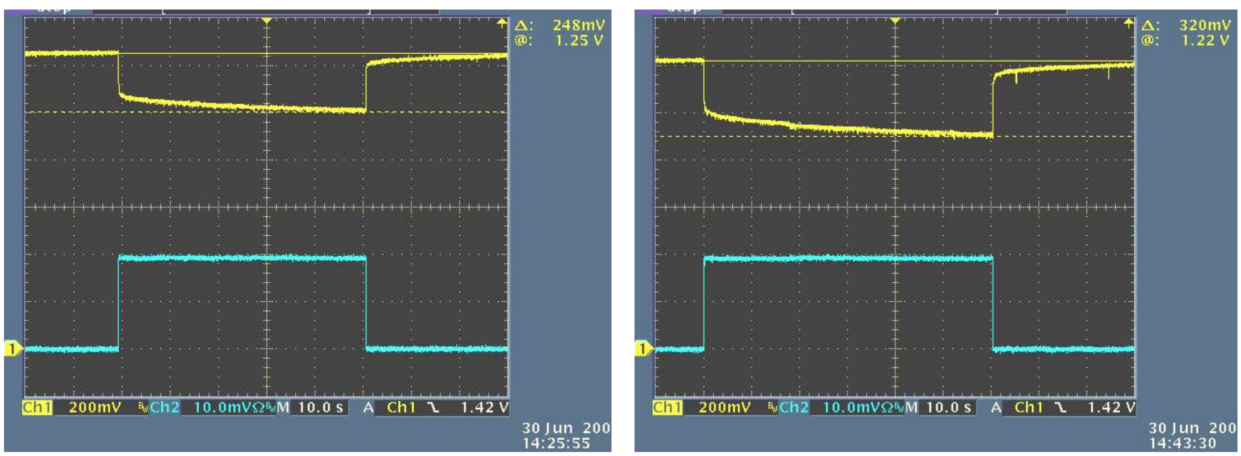


**Figure 5. Open Load and 85-mW Step Load of Alkaline Battery with Terminal Voltage of 1.25 V (Left) and 1.22 V (Right)**

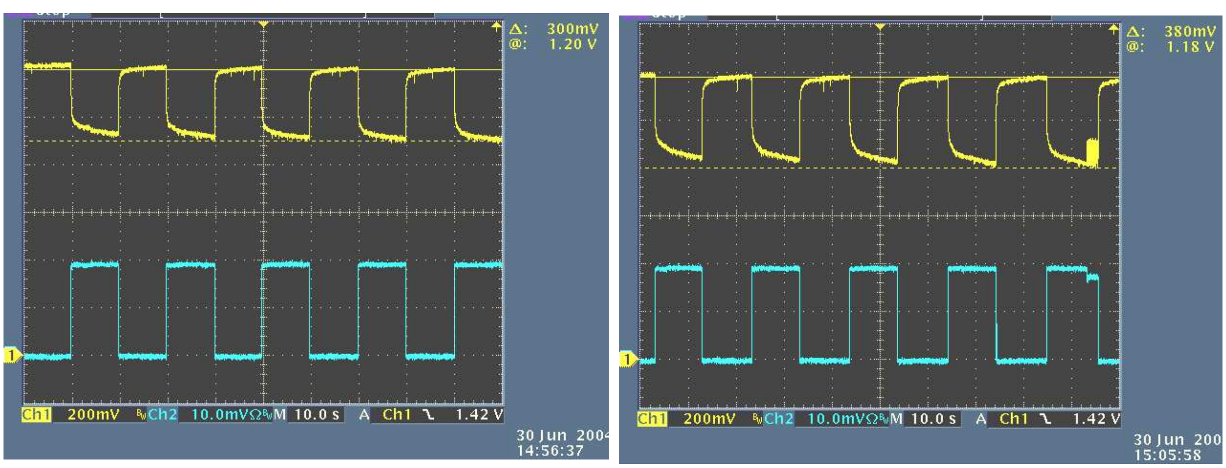


**Figure 6. Pulse Load of 10-sec Duration Showing the Battery Open Load Voltage (Left) and Loaded Voltage Until Device Shutdown (Right)**

Figure 6 shows battery voltage under pulse load of 10-seconds-on / 10-seconds-off. Note the drop of battery voltage below 0.9 V when the battery is practically empty and the open-load battery voltage recovers to 1.15 V when unloaded.

These results show that in most applications the TPS61070 (with specified start-up voltage of 1.1 V) does not exhibit start-up issues, because the open-load battery voltage of an almost empty alkaline cell is around 1.1 V. With a worst case start-up voltage of 1.2 V, the capacity losses due to this higher start-up voltage is less than 5% of the battery capacity which should not be prohibitive in most applications. Remember that once the device is started, it readily operates down to < 0.9 V.

## 6 NiMH Battery Testing

The same testing was also carried out using rechargeable NiMH batteries (tested in AAA-size with 800-mAH and 550-mAH battery capacity).

Figure 7 and Figure 8 show screen captures of the loading voltage waveform for a AAA-size 800-mAH new NiMH battery at different stages of discharge. The left image of Figure 7 shows the open-load battery voltage of 1.34 V when the battery is almost full, which drops to 1.29 V when it is loaded at 85 mW. The right image shows the voltage waveform of the battery when it is discharged to about half its capacity. The open-load battery voltage is about 1.23 V and then drops to 1.18 V when it is loaded at 85 mW. Figure 8 shows the voltage waveform of the battery when it is discharged to about 1/4 its capacity (left image); the open-load battery voltage is about 1.17 V and then drops to 1.11 V when it is loaded at 85 mW. Subsequently, the right image of Figure 8 shows the same voltage characteristics when the battery is discharged to about 1/10 the capacity; the open-load battery voltage is about 1.16 V and then drops to 1.10 V when it is loaded at 85 mW.

Figure 9 shows the battery voltage with a pulse load of 10-seconds-on / 10-seconds-off. The screen capture on the right shows the battery voltage dropping to a level which shuts down the TPS61070. Note the drop of battery voltage below 0.9 V when the battery is practically depleted. However, the open-load battery voltage recovered back to > 1.08 V within 1 minute and eventually back to about 1.15 V after 30 minutes.

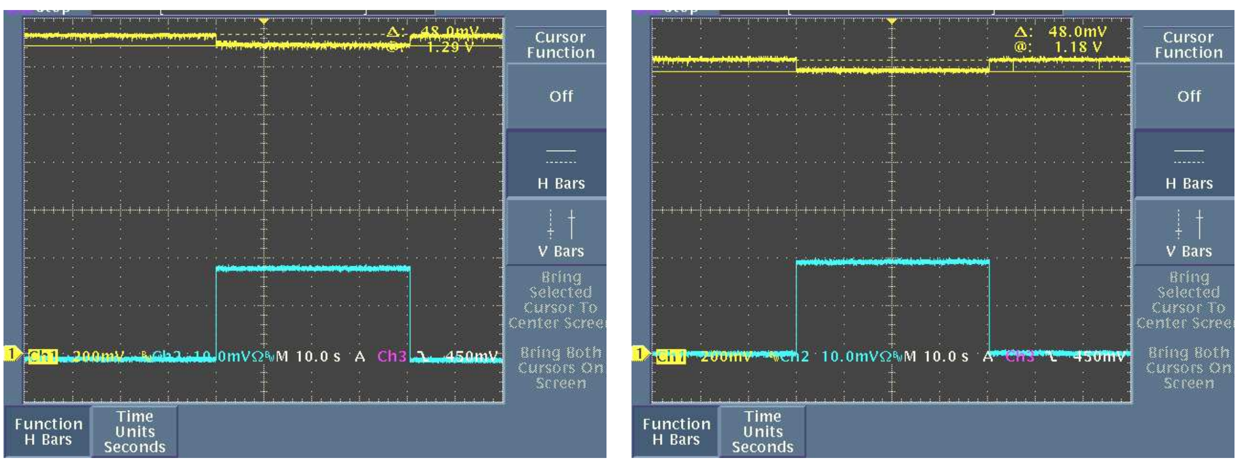


**Figure 7. Open and Step Load of NiMH Battery at Almost-Full Energy Capacity of 800 mAH (Left)—Open and Step Load of NiMH Battery at 1/2-Full Energy Capacity of 800 mAH (Right)**

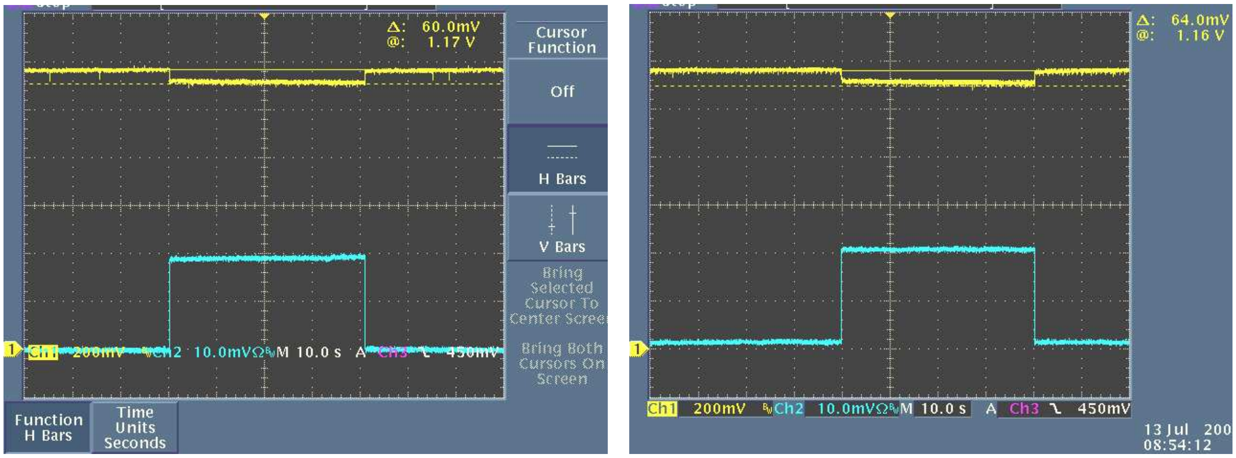


**Figure 8. Open and Step Load of NiMH Battery at 1/4-Full Energy Capacity of 800 mAH (Left)—Open and Step Load of NiMH Battery at 1/10-Full Energy Capacity of 800 mAH (Right)**

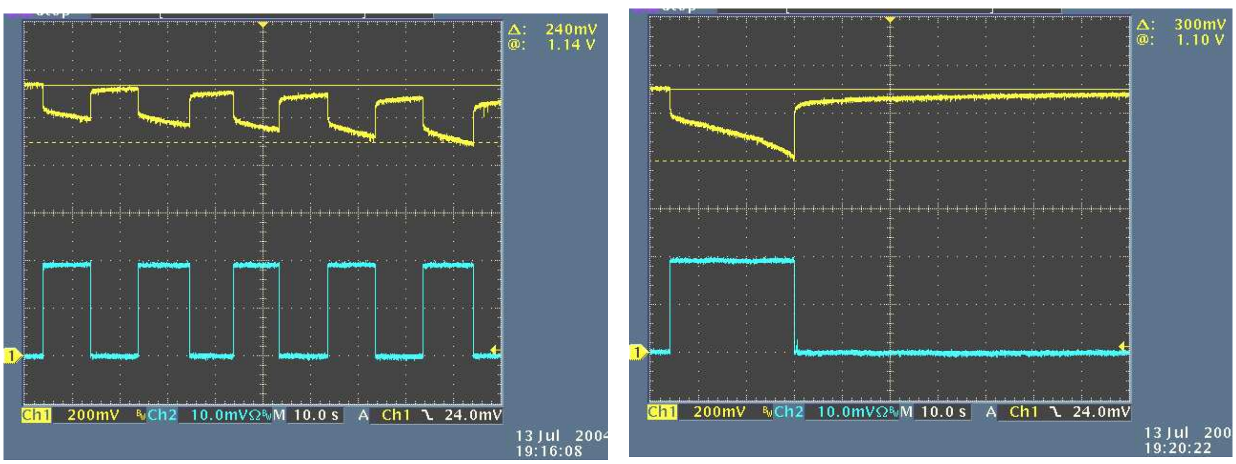


**Figure 9. Pulse Load of 10-sec Duration Showing the Battery Open-Load Voltage (Left) and Loaded Voltage Until Device Shutdown (Right)**

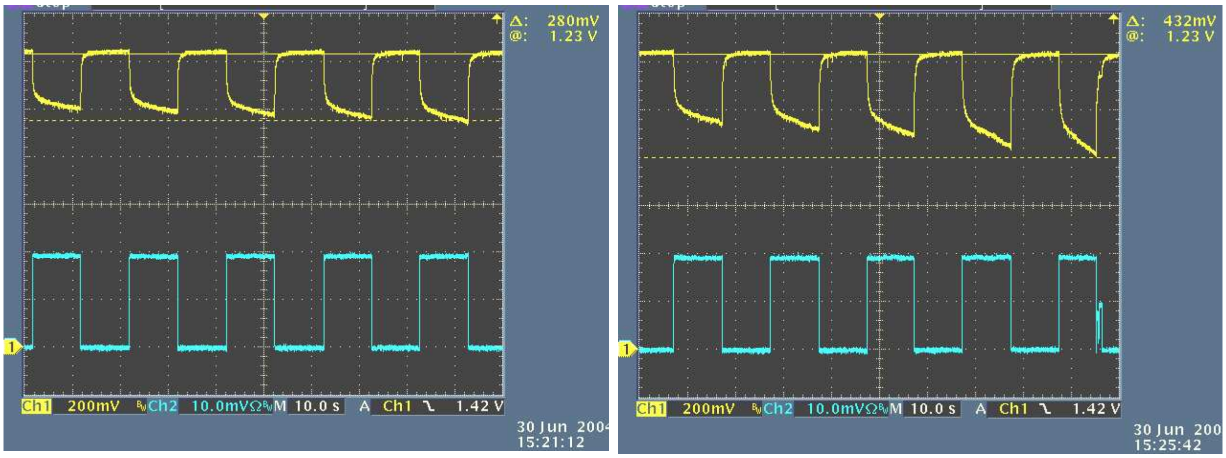


**Figure 10. Pulse Load of 10-sec Duration Showing the AAA-Size NiMH Battery Open Load Voltage (Left) and Loaded Voltage Until Device Shutdown (Right)—550 mAH Capacity**

Figure 10 shows the battery voltage with a pulse load of 10-seconds-on / 10-seconds-off with a 550-mAH NiMH battery after a few hundred cycles of usage. Notice the sharp drop in battery terminal voltage down to < 0.9 V, and the recovery voltage up to > 1.15 V when the load is removed due to increased battery resistance after cyclic usage of the NiMH battery.

## 7 Device Start-up vs Temperature

Figure 11 shows the start-up voltage versus temperature using the TPS61070 EVM with resistive load connected at the 1.8-V output.

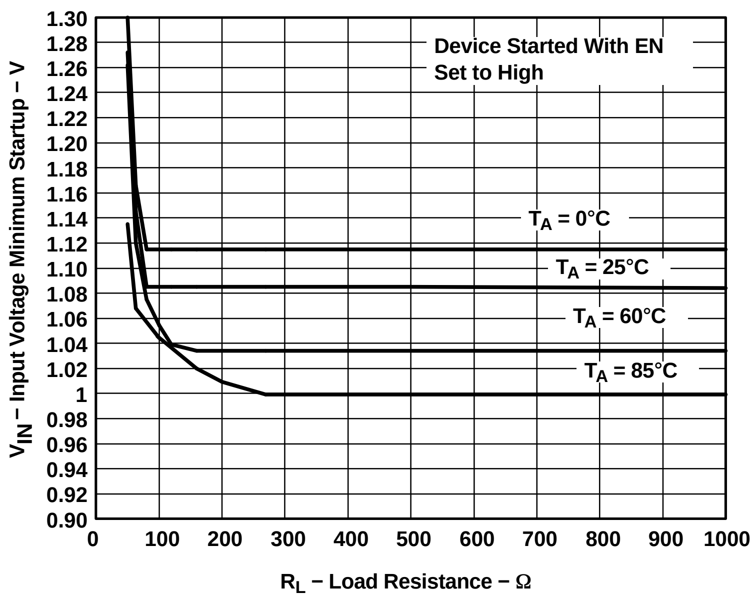


**Figure 11. TPS61070 Start-up Voltage vs $R_L$ at Different Temperatures**

## 8 Summary

This application report presents practical single-cell battery discharge characteristics in real-world application, and primarily focuses on the varying internal impedance of a battery and how that affects the battery terminal voltage.

The TPS61070/1 devices work well in most single-cell boost applications. Though in some cases the discharging battery terminal voltage could be lower than the start-up voltage of the device, the battery voltage readily recovers above 1.1 V once the load is disconnected. Therefore, the TPS61070 does not have difficulty starting up again even when the battery energy capacity is minimal at these terminal voltages.

On a final note, the discharging of the battery in an actual application exhibits constant power discharge rather than a constant current discharge. This shortens battery lifetime at lower voltages when nearing its end of discharge, further reducing the battery voltage (during constant power discharge, the discharge current increases as terminal voltage decreases to supply the same power to the load). However, once the load is disconnected, or the device is shut down, the battery voltage recovers to a higher voltage (typically above 1.1 V).

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