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Interpreting the Battery Lifetime of the Itsy Version 2.4

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Abstract

Several previous studies have been performed which evaluate the power consumption of the Itsy pocket computer version 2, developed at Compaq Computer Corporation's *Western Research Laboratory (WRL)*. Attempts have been made by others to use the data from these studies to characterize the behavior of the Lithium-ion battery used for the Itsy. Although our previous studies correctly characterize the lifetime of the Itsy handheld under the various loads studied, they do not accurately characterize the lifetime of the battery, due to an artifact of the Itsy battery-fault sensing circuit. This technical note provides an additional study and then compares the results from that study to artificial load experiments performed directly on the Itsy battery. This new data is better suited to building a model of the battery lifetime.

Revision 1.1

Acknowledgements

The Itsy project was started and led by William R. Hamburgen. The hardware was designed jointly by William R. Hamburgen and Marc A. Viredaz, both of whose feedback greatly improved this document. The Linux operating system was ported to Itsy by Lawrence S. Brakmo, Carl A. Waldspurger, and the author (Deborah A. Wallach). Joel F. Bartlett and Timothy Mann have also made significant contributions to the operating system and the applications used for the present study. The Itsy project has also benefited from the work of many other researchers at the *Western Research Laboratory (WRL)* and the *System Research Center (SRC)*. Special thanks are due to Wayne Mack, for his help with the experimental setup. The author would also like to acknowledge the enthusiastic support of their management during this major project. Attempts to characterize the Itsy battery by Daler N. Rakhmatov and Sarma B.K. Vrudhula of the University of Arizona inspired this paper.

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1 Introduction

The *Itsy* pocket computer is a flexible research platform developed at Compaq Computer Corporation's *Western Research Laboratory (WRL)*. The goal of the *Itsy* project is to enable hardware and software research into pocket computing by developing a flexible research platform. Many early revisions of the Itsy were built, starting in 1997. The final major Itsy revision is Itsy v2.4; about 125 such systems have been manufactured. The Itsy v2 hardware and software have been described elsewhere [BBF^{+}00] and will not be presented in this document. A prior study was performed to accurately measure the battery lifetime of the Itsy v2.4 under different workloads while continuously monitoring the power consumption, and is described in [VW01b] (see also [VW01a]).

Many researchers are interested in defining accurate models of battery behavior. The data from our battery lifetime studies appears to be ideal input against which to test a battery model: each experiment starts with a fully-charged battery, runs with a well-characterized load, and then completes when the battery voltage cutoff level is reached. While a dedicated voltage sensor could have been used to detect cutoff voltage, as a practical expedient cutoff is defined on the Itsy when the voltage regulator supplying the audio circuit sends an "out of regulation" signal [ADP99]. Thus, the cutoff condition is a function of regulator current, and hence instantaneous audio output; with high audio output levels an experiment can be (and is, in the data from our previously reported experiments) considered to have halted prematurely.[1] To enable further research, we have rerun one set of battery lifetime studies with the audio output disabled; this data is reported here. Additionally, we report data from a series of artificial load experiments taken on a battery from the same manufactured lot as that used in earlier studies. Because the current set of studies is very closely based on the work reported in [VW01b], we have chosen not to repeat the background information which remained identical between the two studies, and as such this paper is not intended to be read as a standalone document but rather as an addendum to the previous ones.

The Itsy v2 system uses a 4.1 V prismatic Lithium-ion cell of nominal size $48\,\mathrm{mm} \times 30\,\mathrm{mm} \times 6\,\mathrm{mm}$, which is rated at $640\,\mathrm{mA} \cdot \mathrm{h}$ by the manufacturer.

2 Itsy study

This section describes the study which was performed on the Itsy.

The methodology for this experiment is identical to that of [VW01b], except for the calculation of the average power, which is as documented in [VW01a]. One of the same Itsy units that was used in the previous study (Itsy #35) was used for this study, to enable more direct comparison of the results. A subset of the benchmarks used in the original study were used in this one (all experiments which play audio were rerun, plus a few others), and the experiments were performed in a slightly different order (see Appendix C for the exact details). During all of the benchmarks, a headset plug was plugged into the audio output jack, which disconnects the Itsy internal speaker. Since the speaker is the main power sink on the audio regulator, no audio output means that very little power will need to be regulated, and thus the out-or-regulation signal on the regulator will be a good approximation to a voltage sensor. For greater precision in determining the

[1] Although this method of determining battery cutoff is entirely appropriate for a handheld system, where the software generally would be expected to reduce the system load well before the cutoff level was reached, this method is not accurate enough for modeling batteries.

Experiment	Audio output enabled			Audio output disabled		
	P_{avg} [mW]	V_{cutoff} [V]	t_{cutoff} [h]	P_{avg} [mW]	V_{cutoff} [V]	t_{cutoff} [h]
*Sleep	7.46	2.83	302.97	7.57	3.00	298.98
*Idle, 59, LV	57.0	3.02	38.77	57.5	3.01	38.69
*Idle, 59	72.9	3.02	30.27	73.7	3.01	30.15
*Idle, 133	86.6	3.02	25.41	87.4	3.03	25.35
*Idle, 206	105	3.02	20.82	106	3.01	20.92
WAV, 59	283	3.21	7.46	155	3.08	14.17
WAV, 206	316	3.22	6.63	186	3.10	11.73
DECtalk, 74, LV	356	3.19	5.94	328	3.07	6.61
DECtalk, 74	403	3.20	5.18	375	3.07	5.75
DECtalk, 206	406	3.23	5.10	377	3.13	5.69
*Dictation, DC, 206	767	3.11	2.58	764	3.06	2.66
MPEG-1, 206	835	3.33	2.33	706	3.12	2.95

Table 1: Comparison of battery cutoff data between an Itsy running with the audio output enabled vs. disabled.

cutoff time, a five-second acquisition time ($t_{\text{acq},\,a}$) was used instead of the thirty-second time used in the previous studies. The number of integrations was empirically selected as $N = 700$ to achieve this result. As in our previous documents, all physical quantities (power, time, etc.) reported have been rounded to the closest least-significant shown digit. On the other hand, errors have been rounded to the next highest such digit.

Table 1 compares the average power P_{avg}, the cutoff voltage V_{cutoff}, and the time at which the cutoff voltage was reached t_{cutoff} for the original set of Itsy experiments (audio output enabled) with the new set (audio output disabled). Experiments which produce no audio output are indicated by an asterisk. In addition to the data presented in this table, all of the quantities and errors reported in the previous paper were collected for this set of experiments as well, and are reported in Appendix C.

We define V_{cutoff} to be the minimum average voltage that the battery reached over a single acquisition period ($\min_a(V_{\text{avg},\,a} + V_{R\,\text{avg},\,a})$). Although this condition could happen at any time, it usually occurs in the time period during or directly before the one in which the out-of-regulation signal is sent. Note that for the audio output enabled experiment, an acquisition length was 30 seconds whereas for the disabled experiment, it was only 5 seconds. t_{cutoff}, is defined as the time at which this measurement was taken (halfway between the start and the end of the acquisition period). Although this time does not always exactly match that reported for the battery lifetime t_{batt}, it is always within $\varepsilon_{t_{\text{batt}}}$ (the error reported on t_{batt}).

There are several effects that can be noticed by examining just the data from the experiments done with the audio output enabled. First, the cutoff voltage varies from 2.83 V to 3.33 V, depending on the experiment. Ignoring the sleep experiment, the voltage varies from 3.02 V to 3.11 V for the experiments which produce no audio output, and from 3.19 V to 3.33 V for the ones which do; clearly the use of the audio circuit voltage regulator to define battery cutoff has a substantial impact. For the sleep experiment, the cutoff voltage is not a meaningful measure, because the StrongARM processor ignores the battery fault signal while it is in sleep mode and it only wakes up once an hour. The cutoff voltage measured one hour earlier than t_{cutoff} in this case was 3.06 V.

For the audio output disabled set of experiments, on the other hand, the cutoff voltage V_{cutoff} is close to being constant, and is in the range of 3.00 V to 3.13 V for all of the experiments. For an upper bound as to how significant this difference may be, consider the MPEG benchmark. The difference between the time that the MPEG battery voltage for the no audio output case reached 3.33 V (the audio output enabled cutoff value) and the time that it reached 3.12 V (where it actually cut off), is five minutes, which is 3% of the total run time (of either the audio-output enabled or disabled experiment). Although this difference is an upper bound, since the audio output enabled MPEG uses more power and thus would run for less time between these two battery voltage levels, it still demonstrates that the previously published data might not be accurate enough to build highly precise battery models from.

3 Artificial load experiments

In order to further characterize the battery behavior, two more sets of experiments were performed, both using a programmable power supply/load (the Agilent 6634B). The goal of these studies was to compare the lifetime resulting from a real load applied to a battery (such as that from running a benchmark on the Itsy) to that resulting from the average value of that load artificially applied to a battery. Note that a real system load changes over time in several different ways. First, as an application runs, it uses different amounts of current (and thus power) to perform different operations; obviously an average current (or power) does not capture the variation inherent in the application behavior. Second, as the battery voltage decreases, more current is required to supply the same amount of power to the system. Finally, since buck-type switching regulators are more efficient at reduced input voltage, the overall power used by the system decreases with the battery voltage. In an attempt to model a real workload, one could use constant current (e.g., [PCD+01]), constant power (e.g., [SBGDM00]), or attempt to vary the power as the as the battery decreases.

We decided to perform both constant power and traditional constant current experiments. For each benchmark, we chose a value for a constant power load test which matched the measured average power in the original experiment performed on Itsy #35 (see Table 1). For the constant current tests, the obvious analogue would have been to use the measured average current from the same set of experiments to determine a constant current load. However, in order to compare our work to that done by other researchers, we used a different method of calculation: we took the average power for the benchmark as measured on Itsy #35 (the target power) and divided it by the effective battery voltage of 3.75 V [VW01a]. The difference between the values calculated by these two methods is less than 2.5% in all cases, with the majority of the differences being less than 0.6%. For the lowest power benchmarks, the average current is slightly lower than the constant load we chose and for the highest power benchmarks, the average current is slightly higher; the intermediate values have the smallest differences.

Table 2 shows the results of both the constant power and constant current experiments. The first column shows the benchmark that the artificial load was intended to model. This set of experiments was intended to model a system with audio output; the second and third columns are thus input to the experiment, taken directly from the data collected on Itsy #35 and previously reported in [VW01a]. The second column shows the target average power for each artificial load benchmark and the third is the cutoff voltage used to determine when to declare the experiment finished.

Columns 4–7 show the results of the constant current experiment, and 8–10 the constant power one.

Experiment	Original P_{avg} [mW]	V_{cutoff} [V]	Constant Current Load [mA]	Constant Current P_{avg} [mW]	Constant Current t_{cutoff} [h]	Constant Current Extra Time [%]	Constant Power P_{avg} [mW]	Constant Power t_{cutoff} [h]	Constant Power Extra Time [%]
Idle, 59	72.9	3.02	19.5	73.9	30.66	1.30	72.8	31.48	3.99
Idle, 206	105	3.02	28.0	106	21.40	2.77	105	21.83	4.85
WAV, 59	283	3.21	75.5	284	7.79	4.52	283	7.89	5.85
WAV, 206	316	3.22	84.3	317	6.93	4.54	316	7.03	6.04
DECtalk, 74, LV	356	3.19	94.9	356	6.18	4.13	356	6.28	5.79
DECtalk, 74	403	3.20	107.5	403	5.40	4.38	403	5.51	6.49
DECtalk, 206	406	3.23	108.3	406	5.35	4.78	406	5.45	6.71
Dictation, DC, 206	767	3.11	204.5	752	2.80	8.71	767	2.79	8.28
MPEG-1, 206	835	3.33	222.7	821	2.51	7.41	835	2.54	8.70

Table 2: Comparison of constant current and constant power loads to actual load.

The fourth column shows the constant current load, calculated as described above. The fifth column reports the measured average power over the entire experiment, which shows how close the constant current load actually came to achieving the target average power. The sixth column shows how long the battery "lasted" from full to the cutoff for that particular experiment, and the seventh column shows how much longer the artificial load lasted than the real load as a percentage of the real cutoff time. The three columns of data shown for the constant power experiment are exactly analogous to those of the constant current experiment. During this experiment, the power was calculated once a second and adjusted upwards or downwards as necessary.

Both sets of constant load benchmarks were performed with a fresh battery, and run in the same order as they were for the Itsy *no audio output* experiments (see Appendix C)[2]. Before each experiment, the battery was charged at a maximum current of 500 mA until it approached 4.1 V, and then was charged at a constant voltage of 4.1 V until it took no more than X mA of current at three consecutive five-minute intervals. X was 0.6 mA for the Itsy experiments and the constant power experiments, and 1 mA for the constant current experiments. Hopefully the difference between these two states is minuscule, but it has not been quantified. Our charging method results in more time spent charging than usual industrial reporting practice, but was retained for more direct comparison with the Itsy experiments. The battery was actually drained all the way down to 2.8 V before each experiment was stopped, in order to collect as much data as possible, but we only report results up to the cutoff point of the actual load being simulated. Benchmarks not listed in Table 2 were not run.

In all cases, the battery lasted longer with the constant loads than it did with the real load. Also, the percentage error is roughly correlated with the load. This may be due to the real loads reaching the cutoff value during a current spike, which obviously could not be the case for a constant artificial load. Except for the case of Dictation, the constant power experiments all lasted longer than the constant current ones, even though the highest load constant current ones used nearly 2% less power than their constant power

[2]Due to an error in the scripts, the order of the first two constant current experiments were swapped, and the MPEG-1 benchmark was run after the DECtalk, 59, LV experiment. This error did not occur in the constant power benchmark run.

counterparts due to the method we used to determine the value for the average current load.

Another set of experiments that can be useful to characterize a battery is constant discharge data taken at the loads typically supplied by cell manufacturers. For the convenience of those interested in building a model, we measured this data as well; it is reported in Appendix D.

4 Conclusion

This document provided additional data that could be used to build improved models of the Itsy battery. Data from three sets of experiments were reported. The first set was from the Itsy itself, running a set of benchmarks which were designed not to trigger a variable and artificially high battery cutoff value. The second and third sets were a group of constant load benchmarks, chosen to match the average current or average power of the Itsy benchmarks but run with a programmable load. These sets showed the effect of a constant load versus a varying load, plus the potential differences between constant power and constant current. The appendix also includes basic data on the Itsy battery performance for a variety of standard industry loads.

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A List of symbols

a	Acquisition index.
N	Number of multimeter integrations per acquisition.
P_{avg}, P^x_{avg}	Average battery power during an experiment, and during the experiment x.
$P_{\text{avg},\,a}$	Average battery power during the acquisition a.
$P_{\text{low bnd}}$	Lower bound on the battery power during an experiment.
$P_{\text{up bnd}}$	Upper bound on the battery power during an experiment.
$t_{\text{acq},\,a}$	Duration of the acquisition a (until the start of the acquisition $a+1$).
t_{batt}, t^x_{batt}	Battery lifetime for an experiment, and for the experiment x.
V	Battery voltage.
$V_{\text{avg},\,a}$	Average battery voltage during the acquisition a.
V_R	Voltage drop across the sense resistor.
$V_{R\,\text{avg},\,a}$	Average voltage drop across the sense resistor during the acquisition a.
$\varepsilon_{\mathbf{X}}$	Relative error on symbol **X** (e.g., V, P_{avg}, t_{batt}).
V_{cutoff}	Voltage at which the battery is considered exhausted.
t_{cutoff}	Time required for the battery to reach V_{cutoff}.

B Multimeter configuration

The following listings are the commands used to configure the HP 34401A multimeters [HP96]. The initial number selects the multimeter (0 for V and 1 for V_R). The rest of the line is the actual command sent to the instrument, in *Standard Commands for Programmable Instruments (SCPI)* format. Commands are sent in listing order. The *initialization* section is sent once at the beginning of the experiment, while the *acquisition* section is sent for each acquisition.

Initialization

```
0 SYSTEM:REMOTE
1 SYSTEM:REMOTE
0 *RST
1 *RST
0 *CLS
1 *CLS
0 DISPLAY:TEXT "ITSY TEST: V"
1 DISPLAY:TEXT "ITSY TEST: I"
0 SYSTEM:BEEPER:STATE OFF
1 SYSTEM:BEEPER:STATE OFF
0 *IDN?
1 *IDN?
0 SYSTEM:VERSION?
0 FUNCTION "VOLTAGE:DC"
1 SYSTEM:VERSION?
1 FUNCTION "VOLTAGE:DC"
0 VOLTAGE:DC:RANGE:AUTO ON
1 VOLTAGE:DC:RANGE:AUTO ON
0 VOLTAGE:DC:NPLCYCLES 0.2
1 VOLTAGE:DC:NPLCYCLES 0.2
0 ZERO:AUTO ON
1 ZERO:AUTO ON
0 INPUT:IMPEDANCE:AUTO ON
1 INPUT:IMPEDANCE:AUTO ON
0 CALCULATE:FUNCTION AVERAGE
1 CALCULATE:FUNCTION AVERAGE
0 DATA:FEED RDG_STORE, ""
1 DATA:FEED RDG_STORE, ""
0 TRIGGER:SOURCE IMMEDIATE
1 TRIGGER:SOURCE IMMEDIATE
0 TRIGGER:DELAY MINIMUM
1 TRIGGER:DELAY MINIMUM
0 TRIGGER:COUNT 1
1 TRIGGER:COUNT 1
0 SAMPLE:COUNT 700
1 SAMPLE:COUNT 700
```

Acquisition

```
0 CALCULATE:STATE ON
1 CALCULATE:STATE ON
0 INITIATE ; CALCULATE:AVERAGE:AVERAGE?
1 INITIATE ; CALCULATE:AVERAGE:AVERAGE?
0 CALCULATE:AVERAGE:MINIMUM?
0 CALCULATE:AVERAGE:MAXIMUM?
0 CALCULATE:STATE OFF
1 CALCULATE:AVERAGE:MINIMUM?
1 CALCULATE:AVERAGE:MAXIMUM?
1 CALCULATE:STATE OFF
```

C Complete results

This appendix presents the average power P_{avg}, its lower and upper bounds $P_{\text{low bnd}}$ and $P_{\text{up bnd}}$, and the battery lifetime t_{batt} for all experiments. The product $P_{\text{avg}} \cdot t_{\text{batt}}$, representing the battery capacity, is also shown. This value is comparable to the manufacturer's rating of $640\,\text{mA} \cdot \text{h}$. The experiments that were performed with the audio output disabled are indicated with an asterisk in the tables; the ones without an asterisk were performed with the audio output enabled, and were previously reported in [VW01a]. For the no-audio and constant load experiments described in this paper, the benchmarks were executed in the following order unless otherwise noted:

1. MPEG-1, 206.4 MHz.
2. DECtalk, 73.7 MHz, low voltage (LV).
3. DECtalk, 73.7 MHz.
4. DECtalk, 206.4 MHz.
5. WAV, 59.0 MHz.
6. WAV, 206.4 MHz.
7. Idle, 59.0 MHz, low voltage (LV).
8. Idle, 59.0 MHz.
9. Idle, 132.7 MHz.
10. Idle, 206.4 MHz.
11. Sleep.
12. Dictation, daughter-card (DC), 206.4 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	7.46	3.0 %	5.20	217	302.5	0.24 %	2.26
35*	75	7.57	2.9 %	5.92	217	298.5	0.25 %	2.26

Table 3: Benchmark results: sleep.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	57.0	2.0 %	52.4	396	38.8	0.45 %	2.21
35*	75	57.5	1.7 %	53.3	377	38.6	0.45 %	2.22

Table 4: Benchmark results: idle, 59.0 MHz, low voltage (LV).

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	72.9	1.8 %	67.3	419	30.3	0.46 %	2.21
35*	75	73.7	1.5 %	68.8	416	30.1	0.46 %	2.22

Table 5: Benchmark results: idle, 59.0 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	86.6	1.8 %	80.1	612	25.4	0.49 %	2.20
35*	75	87.4	1.5 %	82.3	603	25.3	0.49 %	2.21

Table 6: Benchmark results: idle, 132.7 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	105	1.8 %	98	718	20.8	0.53 %	2.19
35*	75	106	1.4 %	100	711	20.9	0.53 %	2.21

Table 7: Benchmark results: idle, 206.4 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{avg}}$	$P_{low\,bnd}$ [mW]	$P_{up\,bnd}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{batt}}$	$P_{avg} \cdot t_{batt}$ [W · h]
35	17	283	1.9 %	149	674	7.47	0.58 %	2.12
35*	75	155	1.6 %	142	480	14.14	0.46 %	2.19

Table 8: Benchmark results: WAV, 59.0 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	316	2.6 %	180	996	6.62	0.63 %	2.09
35*	75	186	2.2 %	170	786	11.73	0.47 %	2.19

Table 9: Benchmark results: WAV, 206.4 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	356	1.9 %	53.3	640	5.97	0.57 %	2.12
35*	75	328	1.4 %	55.0	531	6.62	0.54 %	2.17

Table 10: Benchmark results: DECtalk, 73.7 MHz, low voltage (LV).

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	403	1.7 %	70.2	637	5.20	0.63 %	2.10
35*	75	375	1.3 %	71.8	571	5.75	0.58 %	2.16

Table 11: Benchmark results: DECtalk, 73.7 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	406	3.2 %	97	973	5.13	0.63 %	2.08
35*	75	377	2.5 %	100	881	5.67	0.59 %	2.14

Table 12: Benchmark results: DECtalk, 206.4 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	767	3.3 %	107	1260	2.61	0.65 %	2.00
35*	75	764	2.0 %	109	1240	2.66	0.64 %	2.03

Table 13: Benchmark results: dictation, daughter-card (DC), 206.4 MHz.

Itsy no.	Batt. no.	P_{avg} [mW]	$\varepsilon_{P_{\text{avg}}}$	$P_{\text{low bnd}}$ [mW]	$P_{\text{up bnd}}$ [mW]	t_{batt} [h]	$\varepsilon_{t_{\text{batt}}}$	$P_{\text{avg}} \cdot t_{\text{batt}}$ [W · h]
35	17	835	4.1 %	230	1410	2.35	0.64 %	1.96
35*	75	706	3.0 %	179	1200	2.95	0.55 %	2.08

Table 14: Benchmark results: MPEG-1, 206.4 MHz.

D Discharge data for the Itsy battery

A set of experiments that can be useful to characterize a battery is constant discharge data taken at the loads typically supplied by cell manufacturers. For the convenience of those interested in building a model, we measured this data as well. In order to do so, we repeatedly drained a fresh battery at five different constant current discharge rates in order to see how long the battery could last at a given discharge rate and in order to see the effect of multiple charge-discharge cycles on the battery performance. After every discharge (to 2.8 V), the battery was recharged in an identical manner to that which was used for the constant current load experiments of Section 3.

Table 15 shows the results of this experiment. Although the experiments were performed in an interleaved fashion, the results are grouped by load. The actual order that the experiments were performed in is documented by the first column. The loads were chosen based on the nominal cell capacity C, per usual industry practice. Column four reports the number of seconds it took to drain the battery from full to 3.0 V, also per usual industry practice. The fifth column shows the percentage difference between the total time for the current iteration and that of the previous iteration at that load; the sixth column compares the current iteration to the the first iteration for that load. The seventh column shows the average power over the life of the experiment. The eighth column shows the capacity in W · h, as calculated by the average power multiplied by the run time, and for convenience the capacity in mA · h is reported in the ninth column.

Except for a small, unexplained capacity increase for the second test, battery capacity decreases monotonically with cycling. It appears that high load behavior is the most affected by how fresh a battery is. Figure 1, which is just a graph of the eighth column of Table 15, shows these trends especially well.

The full discharge data is shown in Figure 2. As expected, most of the time spent in the discharge occurs when the voltage is fairly high, and then a sharp drop-off occurs at approximately 3.55 to 3.65 volts.

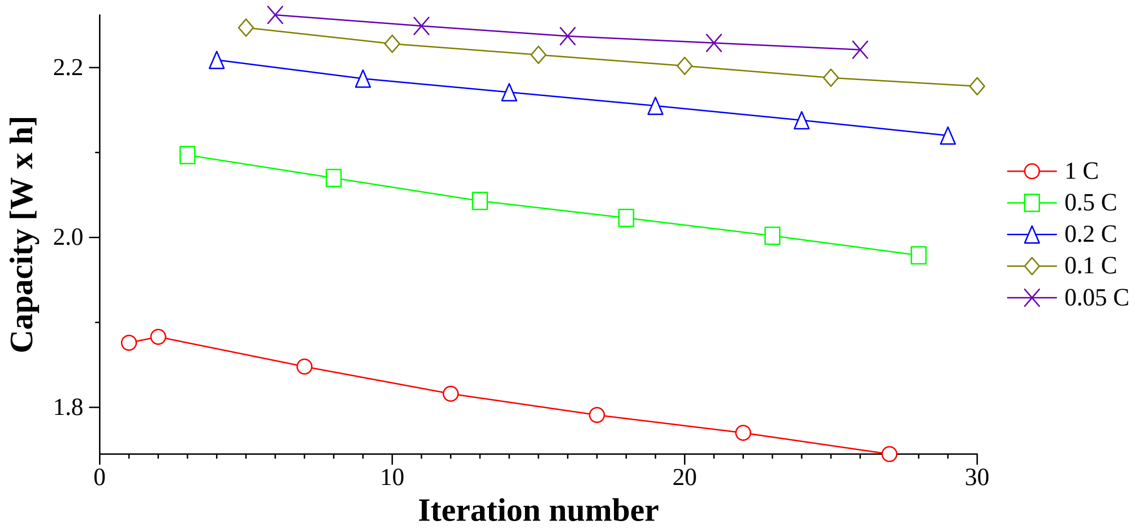

Figure 1: Capacity.

Iter.	Drain value	Load [mA]	Time [s]	Loss vs. previous	Total loss	Power [mW]	Capacity [W · h]	Capacity [mA · h]
1	1 C	640	3046	–	–	2216	1.88	542
2			3054	-0.3 %	-0.3 %	2218	1.88	543
7			3001	1.8 %	1.5 %	2216	1.85	534
12			2952	1.6 %	3.1 %	2214	1.82	525
17			2917	1.2 %	4.2 %	2210	1.79	519
22			2883	1.2 %	5.3 %	2209	1.77	513
27			2846	1.3 %	6.5 %	2206	1.75	506
3	0.5 C	320	6497	–	–	1161	2.10	578
8			6416	1.3 %	1.3 %	1161	2.07	570
13			6336	1.2 %	2.5 %	1160	2.04	563
18			6280	0.9 %	3.3 %	1159	2.02	558
23			6219	1.0 %	4.3 %	1158	2.00	553
28			6151	1.1 %	5.3 %	1157	1.98	547
4	0.2 C	128	16641	–	–	477	2.21	592
9			16479	1.0 %	1.0 %	477	2.19	586
14			16365	0.7 %	1.7 %	477	2.17	582
19			16253	0.7 %	2.3 %	477	2.15	578
24			16130	0.8 %	3.1 %	477	2.14	574
29			16002	0.8 %	3.8 %	476	2.12	569
5	0.1 C	64	33533	–	–	241	2.25	596
10			33266	0.8 %	0.8 %	241	2.23	591
15			33089	0.5 %	1.3 %	241	2.21	588
20			32894	0.6 %	1.9 %	240	2.20	585
25			32695	0.6 %	2.5 %	240	2.19	581
30			32565	0.4 %	2.9 %	240	2.18	579
6	0.05 C	32	67217	–	–	121	2.26	597
11			66836	0.6 %	0.6 %	121	2.25	594
16			66498	0.5 %	1.1 %	121	2.24	591
21			66270	0.3 %	1.4 %	121	2.23	589
26			66032	0.4 %	1.8 %	121	2.22	587

Table 15: Battery discharge curve data.

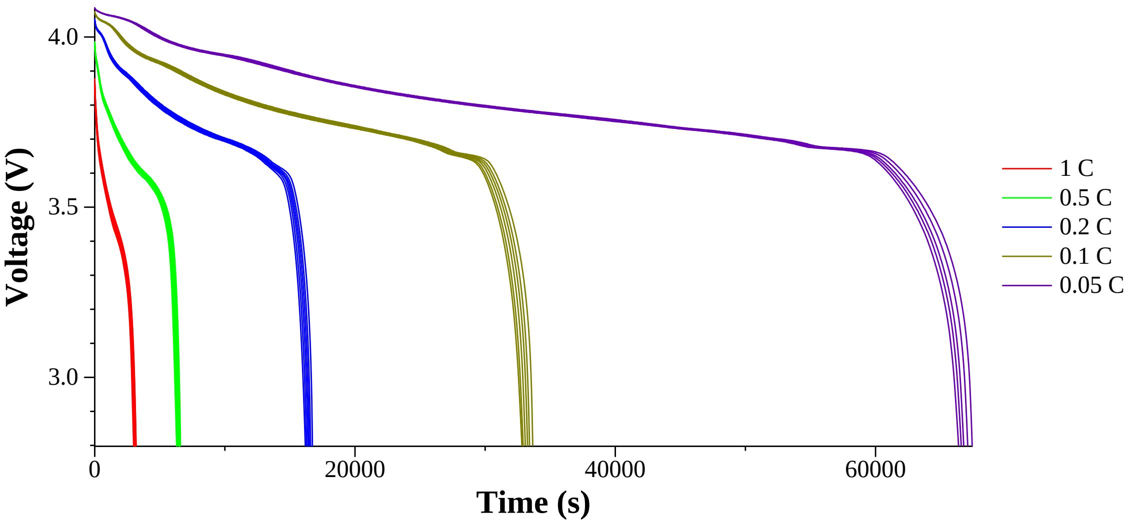

Figure 2: Battery voltage during constant current discharges.