Li-ion Battery Degradation in Notebook Computers

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Executive summary

Lithium ion batteries have lower weight and higher energy compared to other battery chemistries (refer to Appendix A: Battery chemistry comparison), making them a good choice for powering devices ranging from electric vehicles to mobile phones and notebook computers. However, like all batteries Li-ion batteries suffer degradation in performance and the ability to maintain charge capacity over time due to major factors such as temperature, state of charge, and C-rate. In fact, according to some research, notebook computers can suffer up to a 50% degradation in usable battery capacity in the first year given certain usage patterns. This paper will examine major factors responsible for battery degradation and provide a simple to understand formula which the consumer can use to determine the level of battery degradation in a device such as a notebook computer.

How batteries work

According to Battery University, a battery is an “electrochemical cell, or cells, connected in series (some in parallel); composed of the anode (negative electrode), cathode (positive electrode), separator and electrolyte as catalyst”. (Battery Univerity Glossary, n.d.). The illustration below (Figure 1) also taken from Battery University shows how a Lithium ion battery operates. The anode stores the energy used to power the device when AC power is unavailable. When the power cable is unplugged, the negative Lithium ions flow from the anode to the cathode, discharging along the way and powering the device. The Lithium ions will continue to migrate from the anode to the cathode until the battery’s state of charge is exhausted and requires recharging or until the device is returned to AC power. When the device is plugged into an AC power source, the flow is reversed, and the positive ions migrate from the cathode to the anode where they are stored with negative charge until needed in the next discharge cycle.

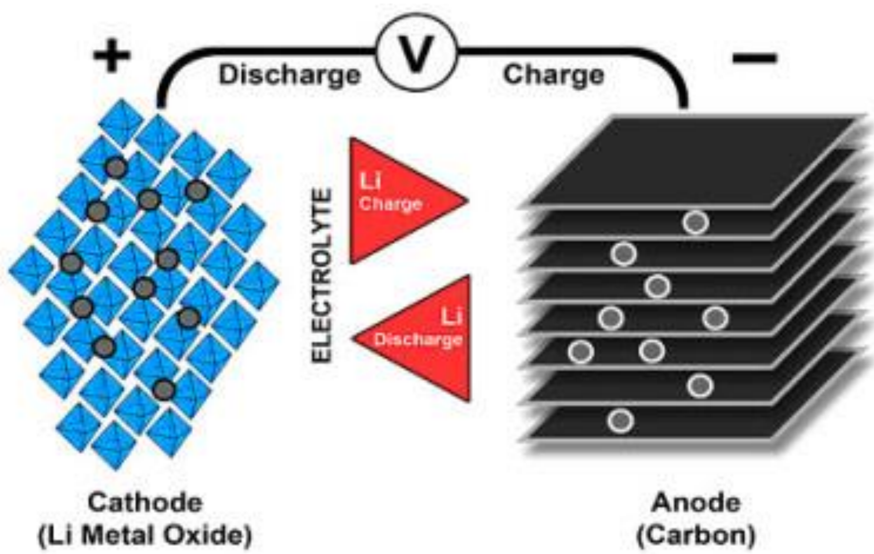


Figure 1: Diagram of a Lithium ion battery (How do lithium ion batteries work, n.d.)

Factors in battery degradation

Battery degradation occurs when one or more environmental factors interfere with the normal operation of the battery’s components. Over time, the cumulative effects of this interference cause the battery to gradually lose its ability to hold a charge.

The major factors contributing to battery degradation can be classified into three high-level groups: temperature, state of charge, and C-rate (rate of charge or discharge) (Woody, 2020). These factors may act individually or in any combination as they contribute to battery degradation. Therefore, it can be difficult to point to any one factor as the ultimate cause of the degradation of a specific battery.

Temperature

Exposure to heat stresses the components of a battery and contributes to its overall degradation. For example, a battery operating in an elevated temperature environment experiences more internal resistance and therefore has more difficulty in delivering its rated voltage to the device. Elevated temperatures can cause the SEI layer on the anode inside the battery to decompose, resulting in less storage area for the Lithium ions and a reduction in full charge capacity over time. (Woody, 2020).

State of charge (SoC)

State of charge describes the amount of energy stored in a battery at a given point in time. A high state of charge indicates the battery is at or near its full charge capacity, while a low state of charge describes a battery with little charge remaining. (Woody, 2020). Batteries repeatedly exposed to extremes in their state of charge will show signs of degradation related to accelerated wear on the battery's internal components due to swelling and exposure to heat during discharge and recharge events. Although state of charge can contribute battery degradation on its own, it is often present along side the other major factors of temperature and C-rate. A battery in a low state of charge requires recharging, and since the charging event introduces swelling and exposure to heat some minor degradation is bound to occur with each charging event.

C-rate (current)

C-rate is the rate which a battery charges or discharges. For example, battery which has a capacity of 2000 mAh, and is rated at 1C; will deliver 2000mAh of current for one hour when discharging. If the same battery were to discharge 2000 mAh of current in 30 minutes, it would be rated at 2C. Batteries are designed to discharge a constant C-rate. An abnormal C-rate, where the battery is discharging faster than intended can outpace the speed of lithium transfer from anode to cathode inside the battery. The incomplete transfer promotes dendrite growth which consumes lithium and contributes to capacity fade (Woody, 2020).

Woody concludes that for notebook computers, the battery's built in BMS (Battery Management System) circuity helps to mitigate the negative effects of temperature, SoC and current, but that that individual usage patterns may still accelerate a battery's decline. He recommends that notebook users follow the recommendations for battery longevity typically found at the manufacturer's web site. By following these suggestions, users can benefit from longer battery life between charges, as well as extending the useful life of the notebook itself.

Calendar aging and cycle aging

In devices such as notebook computers, battery degradation also varies with the usage pattern. Research from Hewlett-Packard examined the impact of usage patterns, calendar aging, and cycle aging on notebook computer battery life (Hewlett-Packard, 2004). Calendar aging is the *"...battery's inherent degradation over time, the rate of which is affected by the temperature and the state of charge of the battery"*. Cycle aging refers *"…the life lost each time the battery cycles between charging and discharging"* (Xu, Oudalov, Ulbig, Andersson, & Kirschen, 2016). Hewlett-Packard modeled the effect of calendar aging and cycle aging on notebook batteries as shown in Figure 2. HP describes this degradation model as *"typical users who completely cycle the battery each working day by running low to medium power applications (word processing, e-mail, and spreadsheets) in wired or wireless modes"* (Hewlett-Packard, 2004).

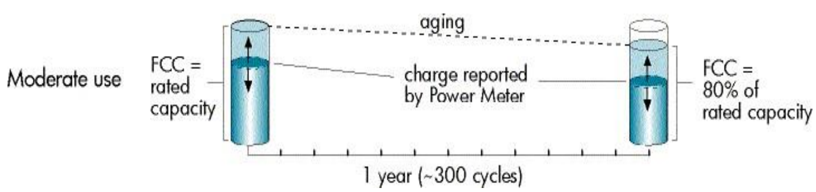


Figure 2: Full charge capacity loss over one year. (Hewlett-Packard, 2004)

HP concludes that notebook battery degradation will increase with increased cycle aging, temperature, and resource intensive activity. More details on HP's finding are in the table below.

Power load (applications)	**Full charge capacity (% of initial capacity) after one year**	
	Mobile user **Battery cycled daily (25ºC, 77ºF)**	**Stationary user (with docking station) Battery cycled weekly (>35ºC, 95ºF)**
Low (word processing, Internet, e-mail)	>80%	80%
Moderate (wireless, spreadsheets, database management)	80%	70%
High* (CAD, 3D games, DVDs, high LCD brightness)	60%	50%

Full charge capacity projections after one year of use
**High power applications may also reduce the battery cycle life by as much as 25%*
(Hewlett-Packard, 2004)

Calculating battery degradation

As detailed above, multiple factors contribute to battery degradation. Creating a predictive model of battery degradation which accounts for these factors is a complex task as described in the linked research paper "[Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment]" (Xu, Oudalov, Ulbig, Andersson, & Kirschen, 2016). Users who are interested in determining the current state of battery degradation in their notebook computer can refer to the formula presented below which uses the values of design capacity and full charge capacity.

Design capacity

The design capacity of a battery indicates the maximum amount of energy the battery can store when new. It is a fixed value typically expressed in units such as milliwatt hours (mWh) or milliamp hours (mAh). Physical characteristics such as the number of cells, size of the components, and spatial constraints are all factors in determining the design capacity of a battery pack. For example, large form factor "desktop replacement" notebooks can accommodate bigger battery packs with a higher design capacity. By contrast, an ultra-portable form factor must be thin and light. Therefore, such designs are restricted to smaller, lighter, battery packs with a lower design capacity.

Full charge capacity

Although design capacity communicates the maximum energy level a battery can store, full charge capacity is more apparent to the end user. Full charge capacity is the amount of energy the battery can store when the state of charge is 100%. When a battery is new and unused, the full charge capacity value equal to the design capacity value. Occasionally, a new battery may report a full charge capacity which is greater than the design capacity value. In these cases, the battery may require a few charge cycles for the OS to report the correct values. However, in all cases, design capacity is a static value that does not change, full charge capacity decreases over time as the damage to the battery accumulates.

Battery degradation formula

A notebook installed with Microsoft Windows 10 is used in this example, however, the formula works for any battery if the values for design capacity and full charge capacity are known.

On a Windows 10 notebook, find the values for the battery's design capacity and full charge capacity by opening a PowerShell prompt in admin mode and running the following command generate a battery report.

```
PS C:\Windows\system32> Powercfg.exe /BATTERYREPORT /OUTPUT c:\battery.report.html
```

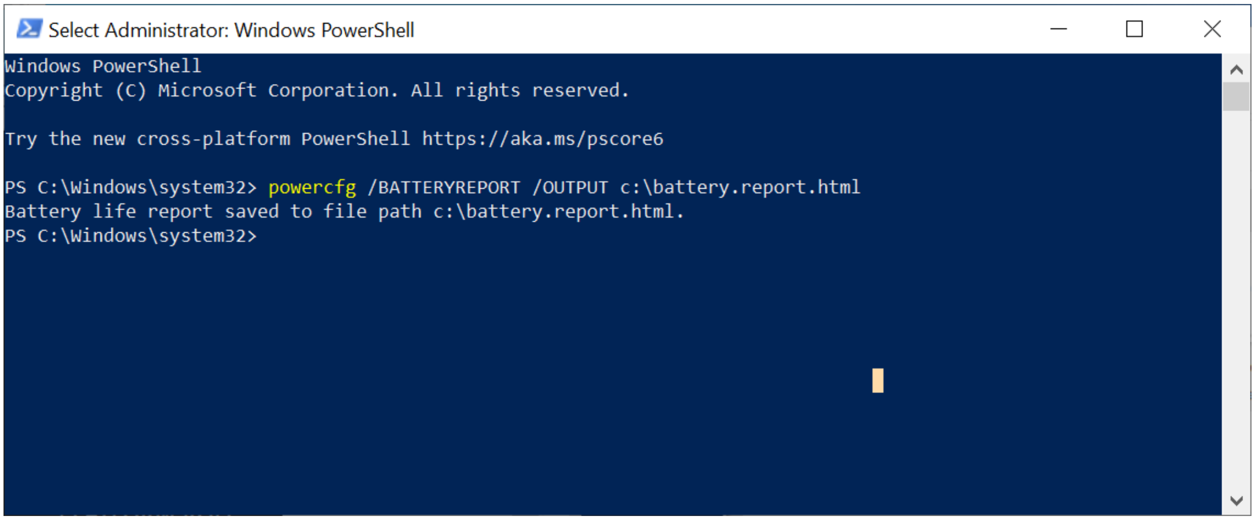


Figure 3: Generate battery report with PowerShell

In Windows File Explorer, navigate to the location where the battery report is saved and open the file in a web browser.

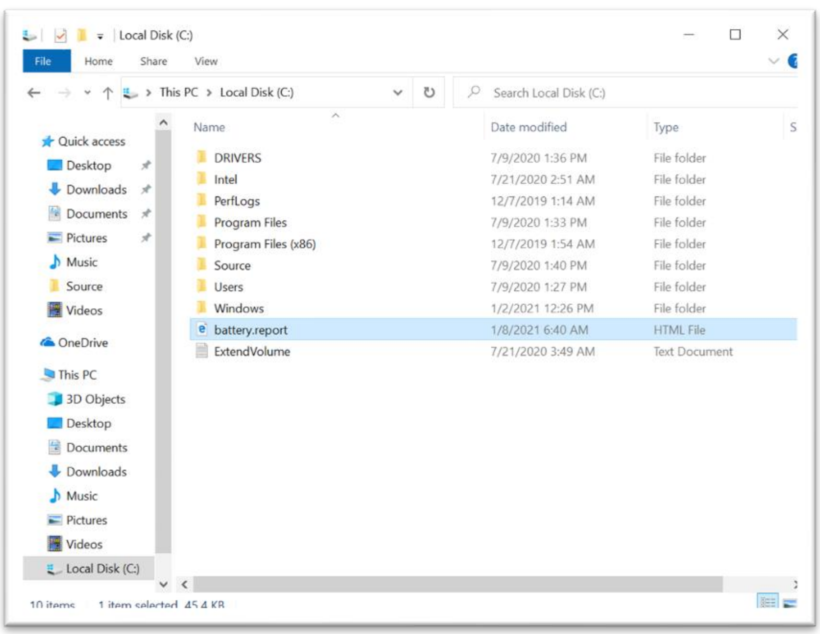
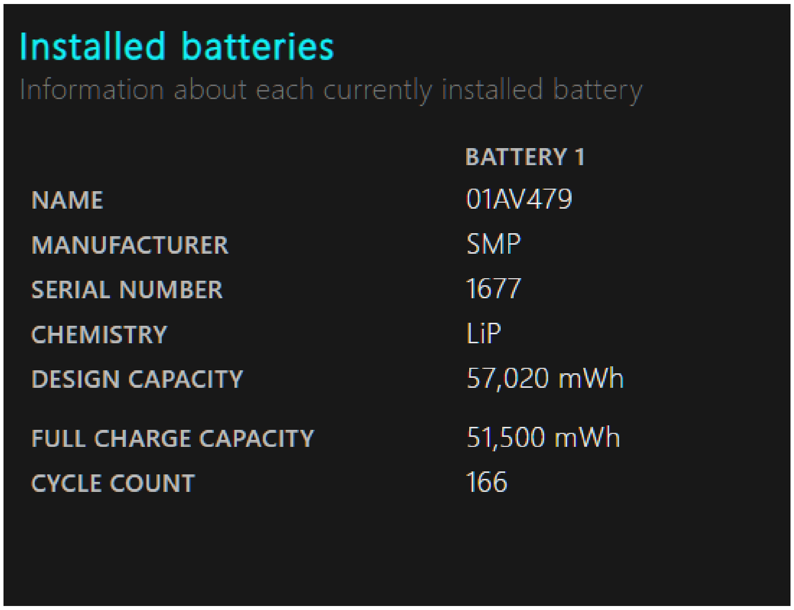


Figure 4: Find the battery report and open in a web browser

Scroll to the “Installed batteries” section and record the values for design capacity and full charge capacity. If there are multiple batteries installed in the computer, they will also be listed in this section. Record the design capacity and full charge capacity for any additional batteries, if desired.



Installed batteries

Information about each currently installed battery

	BATTERY 1
NAME	01AV479
MANUFACTURER	SMP
SERIAL NUMBER	1677
CHEMISTRY	LiP
DESIGN CAPACITY	57,020 mWh
FULL CHARGE CAPACITY	51,500 mWh
CYCLE COUNT	166

Figure 5: The installed batteries section portion of the Windows 10 battery report

Calculate the current level of battery degradation by plugging the values for design capacity and full charge capacity into the equation below.

Formula:

$$Degradation \ = \left(\frac{Design\ Capacity - Full\ Charge\ Capacity}{Design\ Capacity}\right) * 100$$

Example:
A battery with a design capacity of 57,020 mWh, and a current full charge capacity of 51,500 mWh.

$$9.68\% \ = \left(\frac{57020 mWh - 51500\ mWh}{57020\ mWh}\right) * 100$$

The battery in this example has experienced nearly 10% loss in its full charge capacity over the course of 166 charge cycles. Although the formula detailed above does not allow for a predictive model of battery degradation, it can be used to track degradation over the service life of the battery.

Conclusion

In conclusion, lithium ion batteries offer superior performance vs other battery chemistries, which makes them a good choice for notebook computers. Still, Lithium ion batteries will suffer from battery degradation over time due to multiple factors, such as usage pattern, temperature, charge cycle aging and calendar aging. Hewlett-Packard found that in some use cases, battery capacity loss may be as high as 50% after one year in service. Users interested tracking battery degradation in their notebooks can use the formula described above, and plot the results over time. For an predictive model of battery degradation, refer to "Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment" (Xu, Oudalov, Ulbig, Andersson, & Kirschen, 2016). Finally, while a loss of full charge capacity is inevitable for any device equipped with a battery, the rate of degradation can be mitigated by following the device manufacturers' recommended strategies for battery health and longevity.

Glossary

Design capacity: The amount of energy a battery is designed to store when fully charged.

State of Charge: Current charge level of a battery at any given time, for example, 90%.

Full charge capacity: The amount of energy the battery is capable of storing in when at 100% state of charge.

Charge cycle: One complete charge and discharge of the battery.

Charge cycle count: The number of times a battery is fully charged and discharged

Depth of Discharge: The level of battery discharge. For example, a battery with 5% state of charge remaining would be at a high depth of discharge.

Bibliography

Battery Univerity Glossary. (n.d.). Retrieved from Battery University: https://batteryuniversity.com/learn/article/bu_1101_glossary

Hewlett-Packard. (2004). *Lithium-ion battery technology: Getting the most from smart batteries.*

How do lithium ion batteries work. (n.d.). Retrieved from Battery University: https://batteryuniversity.com/index.php/learn/article/lithium_based_batteries

What's the best battery. (2017, 03 21). Retrieved from Battery University: https://batteryuniversity.com/learn/archive/whats_the_best_battery

Woody, M. (2020). *Strategies to limit degradation and maximize Li-ion battery service lifetime - critical review.* Master's Thesis, Unversity of Michigan.

Xu, B., Oudalov, A., Ulbig, A., Andersson, G., & Kirschen, D. S. (2016, 6). Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment. *IEEE Transactions on Smart Grid, 99*, 1-1. doi:10.1109/TSG.2016.2578950

Appendix A: Battery chemistry comparison

From Battery University: (What's the best battery, 2017)

Nickel Cadmium (NiCd) — mature and well understood but relatively low in energy density. The NiCd is used where long life, high discharge rate and economical price are important. Main applications are two-way radios, biomedical equipment, professional video cameras and power tools. The NiCd contains toxic metals and is environmentally unfriendly. Suffers from the memory effect and requires periodic cycling for conditioning.

Nickel-Metal Hydride (NiMH) — has a higher energy density compared to the NiCd at the expense of reduced cycle life. NiMH contains no toxic metals. Applications include mobile phones and laptop computers. Also suffers from the memory effect, but to a lesser degree than NiCd batteries.

Lead Acid — most economical for larger power applications where weight is of little concern. The lead acid battery is the preferred choice for hospital equipment, wheelchairs, emergency lighting and UPS systems.

Lithium Ion (Li-ion) — fastest growing battery system. Li-ion is used where high-energy density and lightweight is of prime importance. The technology is fragile, and a protection circuit is required to assure safety. Applications include notebook computers and cellular phones. Li-ion batteries do not suffer from the memory effect, and are low maintenance

Lithium Ion Polymer (Li-ion polymer) — offers the attributes of the Li-ion in ultra-slim geometry and simplified, flexible packaging. Main applications are mobile phones. Improved safety over standard Li-ion batteries.