Battery Chargers and Energy Efficiency:

Summary of Findings and Recommendations

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Executive Summary

Portable products, such as laptop computers, cordless power tools and cell phones, are powered by batteries that require energy from the AC grid in order to be recharged. Hundreds of millions of these portable products are sold annually. These products likely consume the majority of their annual energy in low power modes when the battery is not being charged. The technology to reduce the power consumption in these low power modes is readily available and already employed in some products. If these low power losses were reduced on a national scale, this could be worth 4.5 billion kWh/year of reduced electricity use, end user electricity bill savings of 380 million dollars/year, and 3 million tons of CO_2 of avoided power plant emissions. Based on these and other findings in the full report, we recommend the following:

- Institute labeling programs to reduce low power mode consumption
- After low power mode consumption is reduced, establish programs to decrease unnecessary power losses during the charge cycle
- Establish clear and consistent indication of full battery condition on all battery chargers
- Conduct further research to establish reasonable duty cycles for battery charger products
- Establish recycling programs for nickel cadmium batteries, which are extremely toxic to the environment
- Encourage rechargeable batteries over throwaway batteries in order to reduce solid waste, simultaneously saving the consumer money.

Introduction

Portable technology is replacing many products that were once solely powered by an AC wall outlet. For example 20 years ago, a typical residential household utilized one phone powered by the landline. Now, a household can have multiple cordless phones as well as cell phones for the adults and the teenage children, all of which require batteries and battery chargers. Many other products mimic this trend: 1/5 of all computer sales are laptops, digital cameras are replacing film-based cameras, and PDAs are quickly becoming the preferred choice over paper organizers.

These recent trends in the marketplace towards electronic portability have important energy consequences. Although designers and engineers are extremely careful to save energy when portable products, such as laptops and PDAs, are running off of the battery, they often devote far less attention to how much energy is consumed when the product is connected to the grid and charging its battery. As a result, these products are often equipped with low efficiency power supplies (transformers) and inefficient charging circuitry. The result is that 10 to 16 times more energy is often drawn from an AC outlet in the charging process than can be retrieved from the charged batteries, indicating *active*[1] mode system efficiencies as low as 6 to 20% for AA battery chargers and cellular phones.

[1] *Active* mode is defined to be the mode in which the battery is being charged.

By contrast, the charging systems we have analyzed in laptop computers are highly energy efficient, with system charging efficiencies of up to 70%. However, even these chargers consume some power when the charger is plugged in and the battery is not being charged. There are two of these distinct low power modes for a battery charging system, *standby* and *idle*. *Standby* mode is defined to be when the charger is plugged in but there are no batteries in the charger. An example of this is when a portable telephone is not being used to make a call, but is off the base in another room with the user. Usually a little more power is consumed while in *idle*[2] mode, which is when no charging is taking place and there is full battery in the charger. Exact duty cycle data are not available for portable products, but it is likely that these chargers are plugged in either all the time (for example a cordless telephone) or most of the time (a household power tool charger).

A conservative estimate of the prospective energy savings resulting from the reduction of *standby* and *idle* energy losses in the residential sector is given in Table 1. We assume that household battery charging products currently have an average *standby* and *idle* power consumption of 3 watts.[3] Technical solutions exist to reduce this power consumption; we assume it is possible to achieve an average of 0.5 watts. If there are 4 battery chargers/household and *standby* and *idle* modes comprise 50% of the total annual duty cycle, then we estimate it is possible to save 4.5 billion kWh of energy annually. Overall *active* losses are difficult to estimate because duty cycles vary significantly from product to product, but it is likely that the sum of *standby* and *idle* losses are higher than *active* losses for most products. Please note that this estimation does not include losses from the commercial and industrial sectors.

Table 1- Estimated Savings Resulting from the Reduction of Standby and Idle Power in Residential Battery Charging Products

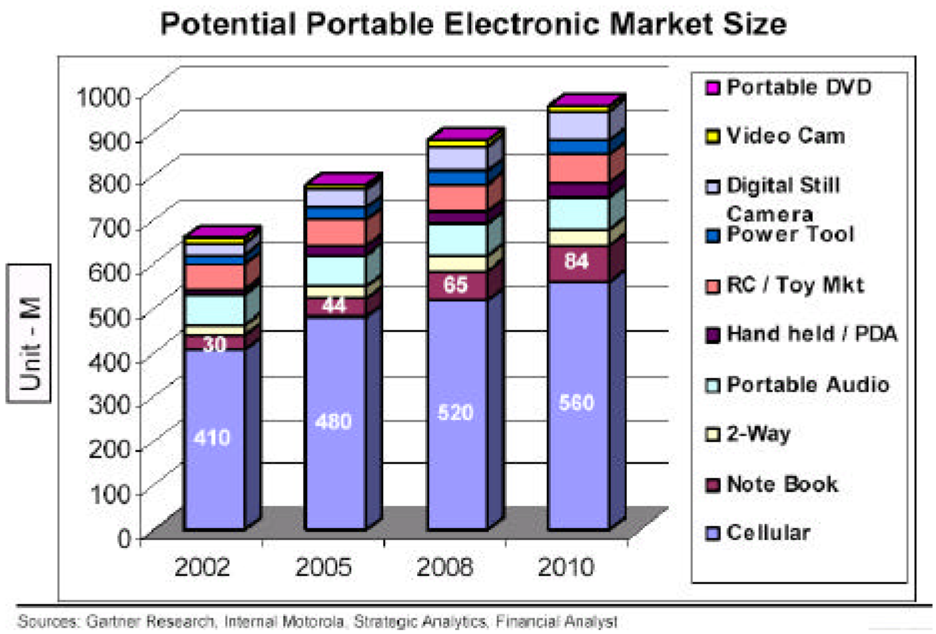
Estimated Annual Residential Savings for Battery Chargers: Standby and Idle Mode Improvements[4]	
Potential Energy Savings:	***4.5 billion kWh***
Potential Dollar Savings:	***380 million dollars***
Potential Emissions Savings:	***3 million tons CO_2***

While a single battery charging system consumes a relatively small amount of energy, there are a large number of these units currently in use, and this number is only expected to increase over time. Cell phones have by far the largest number of units sold worldwide: Nokia reported in July of 2003 that that the number of cell phone units sold in 2002 was 405 million, each of which is sold with a battery charging system consisting of

[2] An example of *idle* would be the following. A laptop computer is turned off and left plugged into the AC wall outlet overnight so that the battery may charge. In the morning, some power still being drawn even though the battery is full. This state of power consumption is considered *idle* mode.
[3] This estimate is derived from data gathered in Ecos Consulting's lab. Ecos measured the *standby* and *idle* power consumption of over 60 battery-charging products. Idle power ranges from approximately 0W (digital camera) to 26W (power tool). Standby power ranged from 0W (PDA) to 7W (portable phone).
[4] Improvement scenario detailed in above text.

an external power supply and rechargeable battery. Motorola confirms that estimation in Figure 1 below as well, while also providing a sense of how the how the market size of cell phones compares to other rechargeable products.

Figure 1- Market Size of Portable Electronic Products Typically Containing Rechargeable Batteries[5]



Technical Summary

Batteries store energy chemically; this chemical energy is converted to electrical energy to run a telephone, computer, or power tool. A battery is often comprised of a number of cells of the same chemistry linked together to give the proper electrical configuration for a device. Consequently, batteries are sometimes referred to as cells. There are 4 major types of rechargeable battery chemistries in widespread use today. NiCd, or nickel cadmium, is the oldest of the technologies, has a relatively low energy density (extractable energy per unit weight), and has many environmental drawbacks because of the heavy metals contained in the cells. These types of batteries are most often found in power tools, toys, cordless phones, and cordless toothbrushes.

Nickel metal-hydride (NiMH) has a higher energy density than NiCd and requires more sophisticated circuitry to prevent overcharge, but it is not as toxic as NiCd. NiMH batteries are found primarily in high-end cordless tools, cell phones, and older digital cameras and laptops.

[5] Doug Morris, Motorola Systems Energy Group, in a presentation entitled “State of the Battery Industry and Future of Energy Systems Market,” given at Advancements in Battery Charging, Conditioning, monitoring, and Testing Conference in Denver, Colorado, June, 2003.

Lithium ion (Li-Ion) is most often found in the newest cell phones, digital cameras, laptop computers, and PDAs. It has a higher energy density than the other two chemistries, but it must be charged carefully to prevent damage to the battery. Lithium Polymer, the forth type of chemistry, is just beginning to find use in portable devices like PDAs. It is not yet in widespread use in higher power applications, but that may change as the market for portable devices continues to expand.

The recharge process is the opposite of the discharge process: electrical energy (from an AC outlet) is transformed into stored chemical energy. The charging system, which facilitates this energy conversion process, has three basic components. 1) the power supply 2) the charging circuitry (sometimes located on a PC board) and 3) the housing of the charger, which has on its surface external contact areas that allow a connection to the battery itself. An example of these three parts in the context of a typical cell phone is given in Figure 2.

Figure 2 – Electrical Flow in a Typical Cell Phone

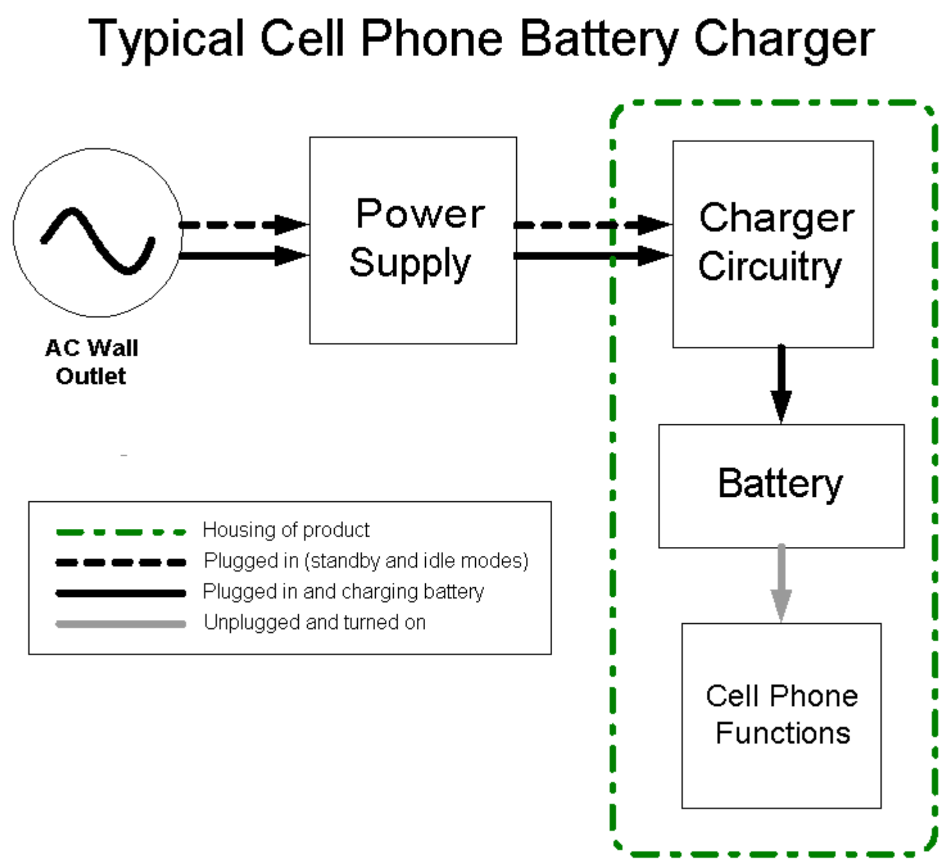


Figure 2 – In the case of the cell phone, the power supply is located in a separate housing external to the phone itself, but the battery and battery charging circuitry are integrated into the same housing as the phone. Notice all power that gets to the charger circuitry must first pass though the power supply. In this way the power supply affects the efficiency in all power modes. This type of schematic would be different in the case of the typical cordless drill, where the charger is located in a housing separate from the tool itself.

The power supply converts the type of power that comes from an AC outlet, which is high voltage alternating current, to the type of power required to run battery-charging circuitry. This power conversion process affects the energy efficiency of a battery charger in all power modes. Therefore, it is possible increase the overall efficiency of the device by simply incorporating a more efficient power supply.[6]

The charging circuitry, which runs off of the power supply, dictates how the battery is recharged. Charging circuitry varies widely from product to product and depends on the specific design parameters as well as the chemistry of the battery. Some charging circuitry charges the battery quickly while monitoring the charge levels and temperature of the battery, adjusting its rate as the battery is charged. Other circuitry has no monitoring capability and just continuously charges the battery at some slow rate, degrading the life of the battery as it is overcharged.

Because Ecos and NRDC have done previous work that reveals how the power supply affects overall efficiency, this section will focus on the second component of the battery charging system, the charging circuitry that is fed by the power supply. We spoke with designers and engineers in the industry who are most familiar with the current technology associated with the field. From these conversations, we were able to identify a number of concepts that could be used to increase the efficiency of designs.

A number of different circuit designs are found in portable products. They range in efficiency as follows:

- *Basic Charger* - This charger applies a relatively low and constant current to the battery indefinitely regardless of state of charge. These types of battery charger units are only found in the most inexpensive of products. This circuitry is primarily implemented with NiCd batteries, because this chemistry tolerates overcharging and does not require any special safety circuitry. The user is required to unplug or remove the battery from the charger to stop charging. Because there is no control of the energy consumption, this design has the potential to waste the most energy: the charger is always trying to store more charge in the battery, whether or not the battery can accept the charge. Ecos has measured cordless tools of this type that consume approximately 7 watts of AC power at all times, regardless of the state of charge of the battery (Figure 3).

[6] The effects of power supply efficiency are more completely addressed in an NRDC report authored by Chris Calwell and Travis Reeder of Ecos Consulting, "Power Supplies: A Hidden Opportunity for Energy Savings," available on the web at http://www.nrdc.org/air/energy/appliance/app2.pdf .

Figure 3 –*Basic Charger* Charge Curve

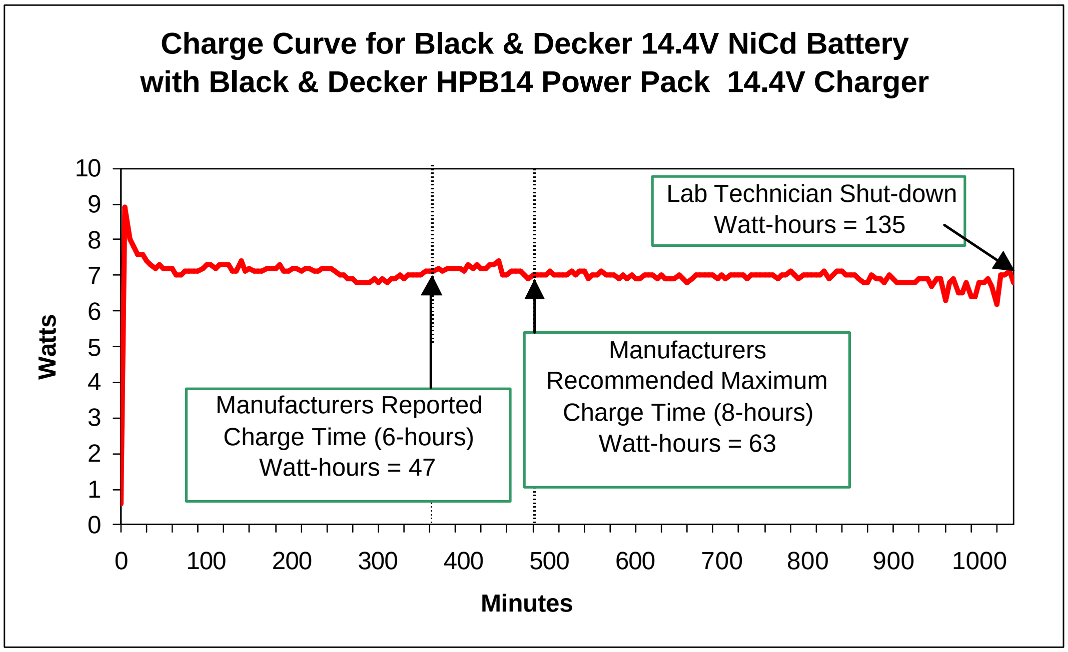


Figure 3 – The charger, packaged with a power tool, requires the consumer to remove the battery in order to have the charger drop into a lower power mode. Users are unlikely to remove the battery exactly at the recommended charge time, leaving the charger to operate for long periods of time in the *active* mode, continuing to consume 7W of power until unplugged.

- *Basic Charger with Timer* - Similar to the *Basic Charger*, this charger applies a low constant current regardless of state of charge, but rather than charging indefinitely, shuts off after a certain amount of time has passed, dropping down to a *idle* mode. This set amount of time is the amount of time that would normally require the charger to fully charge the battery if it were completely drained. This solution does not protect against overcharging, but does prevent high *idle* mode losses that are associated with the *Basic Charger*. This type of charge circuitry is typically used with NiCd batteries.

- *Charger with State of Charge Monitoring* – Slightly more sophisticated than the previous timed charger, this charger monitors voltage across the battery terminals while applying a charge. When the charger senses that the battery voltage reaches some maximum, it can switch to the next period in the charge function or terminate the charge. This charge function can be more complex than a constant current function. An example is a typical Li-Ion charge function that utilizes a period of constant current, a period of constant voltage, and then terminates. This type of charger solution prevents overcharging and allows a low *idle* mode. This solution is primarily used with NiMH and Li-Ion batteries (Figure 4).

Figure 4 – Example of *Charger with State of Charge Monitoring*

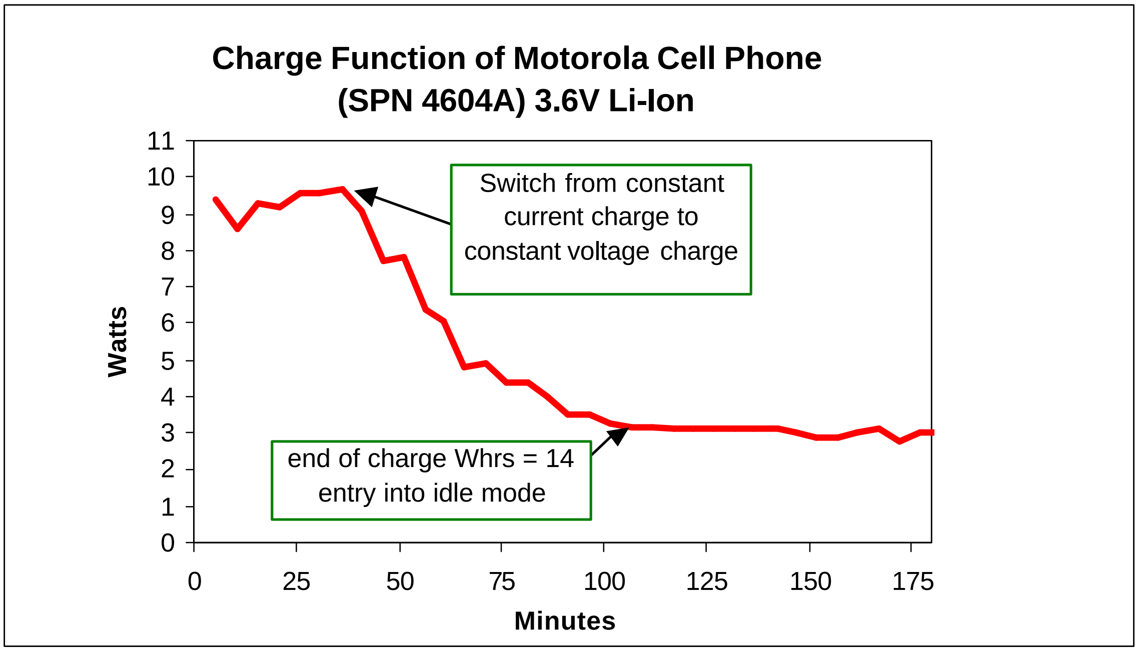


Figure 4 – The state of charge monitoring allows this cell phone battery to be charged in two stages: a constant current stage and a constant voltage stage. This battery charger drops down to an *idle* mode that is lower than the maximum charge value.

- *Smart Charge System* - Monitoring the battery's state of charge (SOC) and state of health (SOH) allows this system to give the battery exactly the kind of charge it needs. The charge function, controlled by a small computer chip, is capable of adapting to the number of cycles the battery has experienced and the battery's depth of discharge. It monitors the battery by logging the way voltage, impedance, and temperature change in time, sometimes within the individual cells of the battery itself. Sometimes the computer chip and associated controller circuits are located in the charger. Other times the chip is located within the housing of the battery itself. These circuits are primarily used for NiMH and Li-Ion cells. This is the most sophisticated solution that allows the combination of fast charging of batteries, and better cycle-life (the number of cycles before the battery is unusable). There is potential for poorer *active* efficiency with fast charging battery units, but this solution also allows for a low *idle* mode.

The ideal charging system would be able to charge a battery efficiently in *active* mode and then drop down to a low power level in *idle* mode after the battery is fully charged. The most sophisticated charging technology (*smart charging*) is not always the best solution for every product; there are many solutions that would offer an efficiency improvement in battery chargers in *standby, idle, and active* modes.

Differences in *idle* power are more often determined by the power supply that converts AC to DC rather than the charging circuitry itself. To illustrate how the charging circuitry and power supply efficiency interact to give an overall product efficiency, reflect on the following hypothetical example of two products with identical batteries. The first product incorporates a *smart charger* with a power supply that is inefficient at low power loads. This charger efficiently charges a battery in the high-powered *active* mode and then falls into *idle* mode with AC power of 5W. Most of this 5W is consumed because the power supply is inefficient at low loads; little power is reaching the circuitry itself. The second product has a *basic charger with timer* and a power supply that is efficient at all loads. This charger would likely take more energy to charge the battery even with the efficient power supply because there is no detailed monitoring of the battery. Yet, when the product falls into an *idle* mode, only 2W of AC power are consumed because it utilizes a more efficient power supply.

If these products spend a large amount of time in *idle* mode, the second product, which has the *basic charger with timer* circuitry and is less efficient in the active mode, will likely consume less power over the course of the product's life than the product that utilizes the *smart charging* circuitry and less efficient power supply. This is because the efficient power supply in the second product consumes less power in *idle mode* than the first product (compare 2W and 5W).

General Industry Trends

This section summarizes the trends that were observed at a battery industry conference in Denver, CO, "Advancements in Battery Charging, Conditioning, Monitoring, and Testing," June 2003. Here, NRDC commissioned its consultant Ecos to give a presentation detailing the results to date of its battery charging efficiency research. Companies that supply and design battery charging, monitoring, and testing technology attended the conference, which was primarily technical in nature.

***Energy Efficiency* -** The interest in energy efficiency among people in the technical community is high, and in general, they support the idea. The presentation given by Ecos was well attended and a number of designers and engineers approached the speaker and inquired further about the topic. In general, attendees of the conference had not considered the concept of total system efficiency of battery chargers. Designers and manufacturers are concerned about efficiency, but only when the device is running on the battery. Engineers identified the major barrier to improving the efficiency of battery charging systems as cost. They reiterated that they are under extreme cost pressures as they design.

***Market* -** Cell phones represent a large percentage of the market for battery charging systems. This is followed by laptop computers and digital cameras.

Battery Chemistry Technology - NiMH and Li-Ion technologies are replacing NiCd. Research is being conducted on chemistries that include Zinc-Air hybrid and Metal-Air and Carbon-Air. These are projected to be used in niche military applications in 2008 or 2012. There are no new chemistries to be released short term.

Fast Charging - Fast charging is now a fairly well developed technology. We are uncertain at this time if fast charging will reduce or increase *active* efficiency. Because all cells of the battery must be monitored closely during fast charging, the charge algorithm could potentially respond to the battery based on its characteristics, and therefore prevent overcharging. It is also possible that the fast charging may attempt to push charge into the battery faster than it is able to accept the charge, wasting a lot of energy in the form of heat.

Fuel Cell Technology - Fuel cells are a long way off from replacing batteries in small devices, though promising prototypes and proofs of concept have been shown. The first generation fuel cell device is likely going to have to be a hybrid system that has both a battery and a fuel cell.

Current Industry Challenges - Battery technology is lagging far behind the power requirements of silicon technology. Battery technology improves roughly linearly in time, silicon technology exponentially in time. This discrepancy between the technologies cannot be remedied and battery life is consequently short for most applications. This issue will be aggravated further as portable devices increase their functionality (incorporating devices such as a camera, phone, and PDA into one unit), and the power demand from a single device consequently increases. These multi-function devices, or "3G" (third generation) devices, will have to incorporate better power management while running on the battery because it is unlikely that the battery technology itself is going to be able to deliver a longer runtime in the near future.

Recommendations

Based on our measurements of more than 60 rechargeable products and our discussions with industry, we offer the following suggestions to further increase the energy efficiency of battery chargers:

- *Clear and Consistent Indication of Full Battery Condition* - Given the large amounts of time many battery chargers spend in *idle* mode (plugged in with fully charged batteries), it is surprising that many of these products provide no clear indication to the user that the batteries are fully charged. Even those that do provide such an indication do so in an inconsistent manner (indicator light comes on, indicator light changes colors, or indicator light switches from blinking to steady operation). We would encourage all battery charger manufacturers to provide a clear and consistent indication of the full battery condition. Many users might still elect to keep the charger and batteries plugged in to prevent self-discharge, but the indicator would help other users know when to unplug the charger, saving a significant amount of energy.

- *More Information on Battery Charger Duty Cycles* – Detailed energy consumption and savings estimates are based on a duty cycle that describes how a product is used over the course of its lifetime. Duty cycle data indicate the number of hours spent in each power mode (*unplugged, standby, idle*, and *active* charge). This type of data for battery charging products are largely unavailable and are also likely to vary widely because products that contain battery chargers have a variety of end-uses. We have measured battery charger power consumption in *idle, standby*, and *active* for a variety of products and would recommend that future work focus on developing reasonable duty cycles for each type product that contains a battery charger.

- *Labeling Programs to Reduce Standby and Idle Consumption* –Given the variation in battery charger power consumption, labeling programs or standards may be needed to help shift the market toward designs that consume virtually no power when no batteries are installed, and minimal power after the batteries reach full charge. Table 2 represents one possible standards approach. Industry designers indicate that there are a number of ways to technically implement low *standby* and *idle* conditions. For example, even chargers that are designed to trickle charge full batteries to prevent self discharge could do so every few hours or once a day, rather than providing a continuous trickle charge.

- *Labeling Programs to Encourage Higher Active Mode Efficiency* - Once *standby* and *idle* mode energy use have been addressed, some consideration of *active* mode efficiency may be warranted, particularly for the charger types that currently exhibit efficiencies of less than 30%. Based on conversations with industry, it is possible to design more efficient charging circuitry. In addition, it is clear that significant improvements are possible simply by incorporating highly efficient switching power supplies instead of bulkier, cheaper linear power supplies. The power supplies are often external to the product and an internal redesign of the product would not be necessary. A labeling program that recognizes the more efficient power supplies and the products that employ them could be a good solution. It is also possible that a specification that addresses *standby* and *idle* could have a later phase that addresses active efficiency (Table 2).

Table 2 – Potential Energy Specification for Products Containing Battery Chargers

Energy Standard for Products Containing Battery Charging Systems	
Phase 1 (effective initially)	Products consume no more than A watts in *idle* mode and B watts in *standby* mode.*
Phase 2 (effective 2 years later)	Products consume no more than C watts in *idle* mode and D watts in *standby* mode, where C and D are lower than A and B, respectively. Request that manufacturers test and list *active* mode (charging) efficiencies.Ä
Phase 3 (effective 4 years later)	Products consume no more than C watts in *idle* mode and D watts in *standby* mode. *Active* mode efficiency should be at least XX%.

* In our measurements of over 60 products that contain battery-charging systems, *Idle* power ranges from approximately 0W (digital camera) to 26W (power tool) and *Standby* power ranges from 0W (PDA) to 7W (portable phone). A and B would therefore be set somewhere within these ranges.

Ä Active efficiency is defined as energy extractable from the battery divided by AC energy to charge battery to full capacity. We have measured active efficiencies as poor as 6% (AA battery charger) and as good as 68% (laptop computer), with the majority of the efficiencies falling around 20% (including cell phones.) It seems reasonable that these active efficiencies could at least be at 50%, meaning that they waste half of the energy that they use during the charging process.

Table 2 - This three phase efficiency standard for battery chargers is one possible approach to encouraging better efficiency in *standby*, *idle*, and *active* modes. Another possible approach is to scale the *standby* and *idle* limits relative to the capacity of the battery, allowing higher power levels for higher capacities.

In the course of our investigations regarding battery chargers, we have gained expertise regarding rechargeable batteries in general. We offer these recommendations that are that relate to issues other than energy efficiency of rechargeable battery systems:

- *Toxicity of NiCd Batteries* - Given the extreme toxicity of nickel cadmium batteries, the European Union currently has a directive that encourages recycling of NiCd batteries and requires the labeling of cadmium-containing batteries. A number of amendments to this 1991 directive are currently under consideration and could include creating recycling targets of 75% or could ban NiCd batteries in most applications by 2008. Such an approach is likely warranted in the U.S. as well, especially with the advent of more advanced battery chemistries and chargers. The most promising way to assure that primary and rechargeable batteries are both recycled is some type of a deposit on their initial sale, which would be refunded when the products are returned to a retailer for recycling. This approach works well with lead acid batteries, glass bottles and aluminum cans, and could help accelerate a market shift from throwaway and toxic rechargeable batteries to more environmentally benign rechargeables.

- *Replacing Throwaways with Rechargeables is Environmentally Preferable* - About 3 billion throwaway batteries are purchased and discarded in the U.S. per year. Sales of rechargeable batteries are much smaller but growing rapidly, and now total about 300 million units per year. The potential environmental and economic benefits from rechargeable batteries are enormous, with typical designs lasting for 500 to 1000 charges before replacement. Even including the greater cost of the batteries, their smaller capacity (compared to most throwaways), the cost of the chargers, and the cost of the electricity to operate them, rechargeable batteries can save consumers hundreds of dollars over the lifetime of the batteries compared to purchasing throwaways. Paybacks are very rapid (a few months to a year), depending on how heavily the batteries are used.