Designing and Optimizing Battery Systems for Mission-Critical Portable Applications

MICRO POWER™

Executive Summary

Portable medical, military, rugged computing and data collection devices are vital to our modern mobile world. These devices share many common characteristics—they are critical to the tasks involved, often shared by multiple users, and subject to unprecedented power demands because of ever increasing functionality. In addition, they are often used in harsh environments, for long time periods. As organizations are increasingly reluctant to invest in new equipment, these devices are characterized by longer product life cycles as well. This means they must perform optimally for months, sometimes years. With device sizes shrinking, it is also becoming necessary to supply ever greater amounts of power to ever-smaller form factors.

These market issues mean that supplying battery power to today's portable devices poses design challenges that tax even the most experienced engineers. Portable defibrillators, tactical military radios, rugged computers, wireless barcode scanners—all require a high level of technical sophistication from the engineers who design the battery systems.

Battery systems are no longer simply a collection of isolated components, but a complete electro-mechanical structure that plays an integral role in the function of a portable device. Yesterday's "dumb" battery system typically consisted of the battery cells, safety components, and a physical enclosure. However, today's "smart" battery systems offer the addition of a fuel gauge and battery management components that enable communication to the host device. Sometimes these systems also include on-board charging capabilities.

This paper is intended for engineers who may be familiar with designing power systems for plug-in devices, but who are now forced to broaden their expertise into the realm of mobile power supplies.

This primer discusses battery design basics as an integrated system, including cell and chemistry selection, battery pack characteristics, operating requirements, "smart" battery management, design validation and charger issues.

First Steps: Plan Ahead for Optimal Results

Creating an optimal battery pack design for a power-hungry field device is a difficult and complex undertaking. It requires advanced design skills, rigorous processes and sophisticated equipment. The design problems grow dramatically more difficult in the presence of high currents, dynamic loads, wide temperature variants, aggressive power management and certain charging regimens. These operating factors dramatically alter the performance of the battery pack.

Underestimating the complexity of the battery system and the interrelationship between the battery circuitry and the device circuitry can only lead to setbacks during product development, or worse, the potential failure of the entire system in the field. Planning for the battery system early enough in the design process, however, along with proper implementation, can eliminate the possibility of battery problems.

The rise in the number of field-related battery problems indicates that many original equipment manufacturers (OEMs) are encountering design issues that they may not have the tools or internal expertise to solve when it comes to developing high-performance battery systems. As system complexity and capacity increases, it becomes more difficult to ensure battery system safety. There have been numerous reports of dangerous battery failures in the field. Often these incidents were associated with aftermarket battery packs which are not properly designed for the host device's specific use scenario and operational requirements.

Critical Performance Factors

Total battery system integration involves a host of considerations. Paramount among these:

- cell selection (including chemistry and vendor considerations)
- pack characteristics (the number of cells in a pack and their configuration in series or parallel strings)
- operating requirements (how, when and where the device will be used)
- battery management (seeing the pack as an integrated system with cells, board, management and, in some cases, charging units)
- correct calibration or learn cycle (to ensure the design functions properly)

Systems Overview Diagram

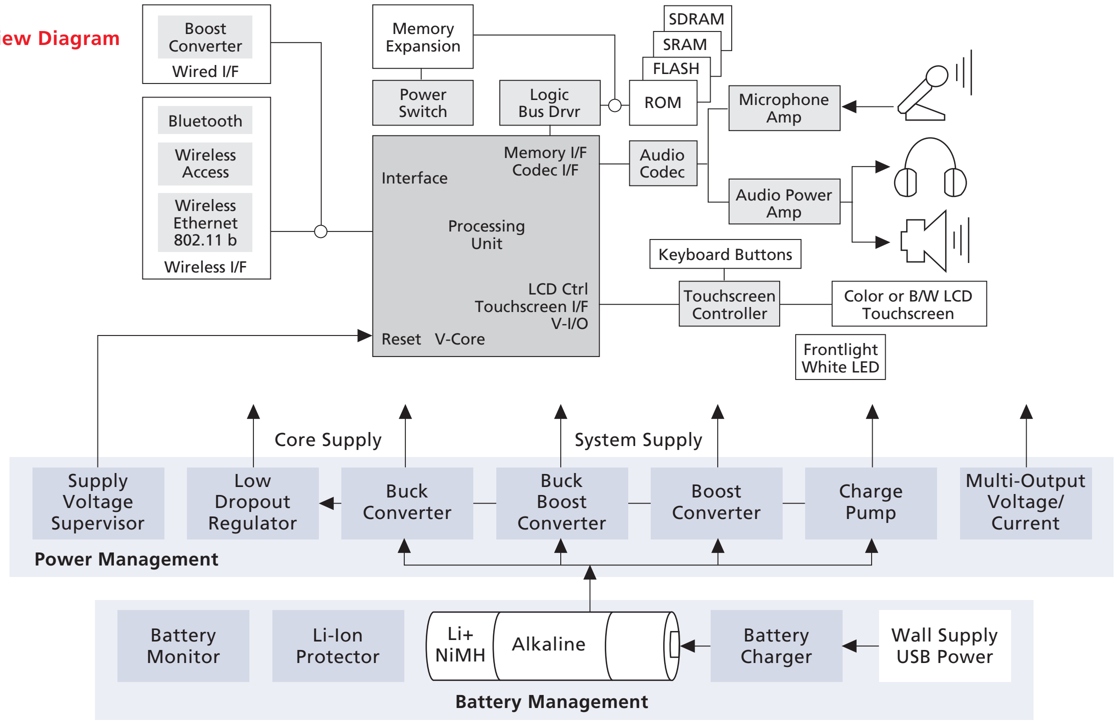


Diagram courtesy of Texas Instruments.

Battery System Design Challenges

The need for smaller battery systems is making design-for-manufacturability increasingly important. As form factors shrink, design and manufacturing challenges grow. Due to the diminishing size of portable applications, it has become even more difficult to fit the required components into the available space. As component congestion increases, there is a greater risk of accidental pinching or shorting of wires and contacts.

The physical layout of the components also becomes important in battery systems, as it can make the assembly process more difficult or create hot spots inside the pack. Although venting is less crucial with Lithium ion (Li-ion) than it is with Nickel Metal Hydride (Ni-MH), ensuring that heating is even throughout the pack enables on-board safety devices to trip when appropriate and minimizes cell balancing problems. Furthermore, the designer must work carefully to ensure that vital contacts are not placed too closely together, since they can potentially short if the battery system is subjected to vibration or dropped. Contacts should also be recessed to prevent external short circuits.

Another design challenge associated with smaller battery systems is the mechanical fit. With smaller tolerances, the contact points, energy director (for ultrasonic welding) and locking mechanism must be designed and manufactured with greater precision and care. Smaller packs usually utilize thin walled plastic (.040” thick) that can make ultrasonic welding difficult without cracking. These packs must also be tested to ensure adherence to drop test requirements.

Soldering, resistance welding and ultrasonic welding are core processes that are critical success factors in the development of a reliable battery system. But each can be a challenging process. It takes many years of experience to be able to create high-quality joints on a consistent basis. Poor solder and weld joints are the greatest source of industry defects. Without effective training, controlled processes, high quality equipment and rigorous inspection procedures, it is possible to create weak weld and solder joints that may not be discovered until the portable unit is in the field, where it may fail. Major causes of battery pack field defects are cold, fractured, or missing solder joints. These can create an electrical connection that is sufficient to pass a functional test, but which is susceptible to breaks in the field due to vibration or thermal stress conditions.

Resistance welding is particularly difficult to master with Li-ion chemistries. Because they have thinner outer walls, Li-ion cells are more delicate than Ni-MH and Nickel Cadmium (Ni-Cd) cells. If too much or too little energy is applied during the welding process it can result in cell wall destruction and failure-prone joints, respectively.

To ensure consistent high quality welds, it is important to use only state-of-the-art computer controlled welding equipment, perform window studies on every design, use statistical process control methods, and perform rigorous pull tests to ensure achieving the highest levels of reliability.

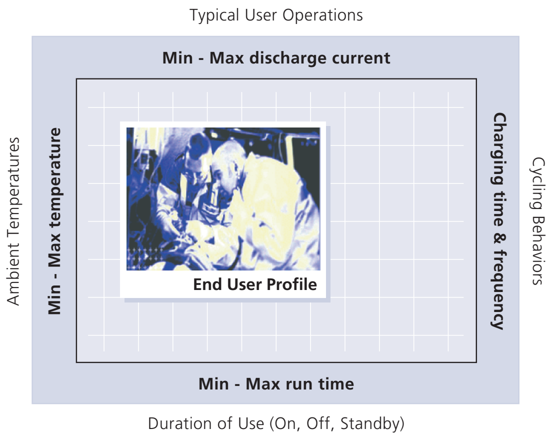
Creating a *Real World Usage Profile™*

Another challenge of today’s move to portable power systems for developers is in dealing with exposures to higher current drains and greater temperature extremes. High discharge rates and extreme temperatures can lower a battery system’s performance, reliability, and even its capacity. In the worst case, extremely demanding conditions may also cause a battery system to fail or create a safety hazard.

High currents and temperature extremes also harm the battery system’s electronics—damaging key components, destroying traces on the circuit board, melting wires, or degrading the performance of the safety circuitry, battery management electronics and system communications.

Every portable device has a unique set of power drain and temperature profiles that must be characterized, understood and addressed during the initial phases of development.

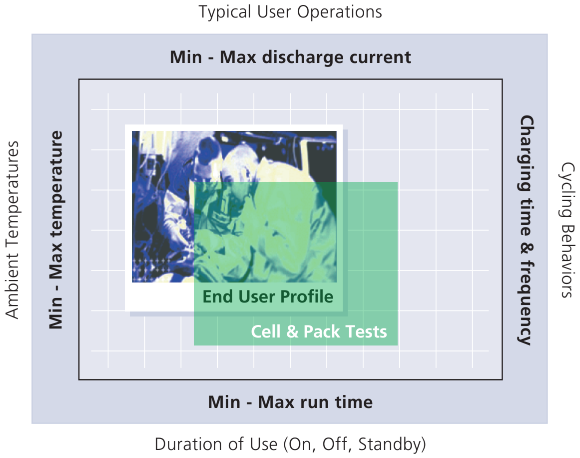
Create a *Real World Usage Profile™*



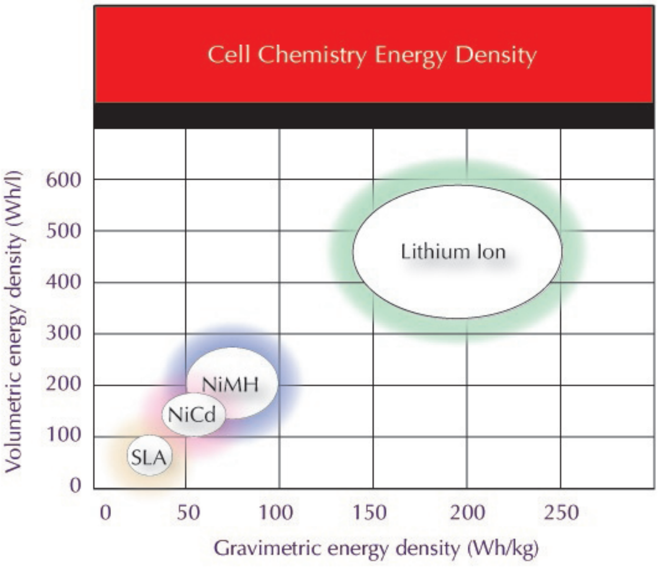
Cell Selection: From Ni-Cd to Li-ion and Beyond

When choosing a cell technology appropriate to the target device, first choose a chemistry suitable to the architecture and design goals. Factors such as operating range, cell availability, maximum cells in series, cell capacity range, cycle life and cost play into your choice.

Evaluate which cells work best



Your first consideration should be the operating voltage. It is extremely important to know the range of voltage that your device can handle and where cutoff voltages should be. A small variation in cutoff voltage will affect the battery pack's life cycle. The significance of this is that pulsed current loads lead to variable voltage response and without careful system consideration this voltage drop leads to premature battery shutdown.



It is also important to consider both volumetric and gravimetric energy densities. A comparison of energy densities for various chemistries is shown in the accompanying figure. Li-ion, and the similar Li-polymer, chemistries have the highest energy density that is commercially available.

Designers must accept that there are specific trade-offs in cell packaging. Cell size has much to do with a battery's run time. However, in comparing cylindrical versus prismatic or Li-polymer form factors, keep in mind that the thinner polymer cells may require additional packaging to add protection.

While the thin profile can be a plus for prismatic and polymer form factors, these cells carry several possible downside considerations. These include:

- swelling issues
- higher costs because they are more difficult to manufacture
- lower energy density (for prismatic Li-ion)

Form factors change quickly with the market. If you are going with a prismatic cell, you should try to stick with a generic footprint, which currently tends to be 34mm by 48-50mm, at various thicknesses ranging from 3.5mm to 10mm.

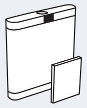
Cylindrical cells, on the other hand, offer long term stability of design due to their availability in industry standard sizes or 18mm in diameter by 65mm length, or 26mm diameter by 70mm length. However, the sizes vary slightly from one manufacturer to the next, so it is important to design with the largest intended source in mind.

Weigh trade-offs in cell packaging

Cylindrical

	Pros	Cons
	Higher energy density	Not thin
	Standard sizing	Tolerance issues
	Wound electrodes	Capacity gains slowing
	Lower cost per watt hour	Most development 18650

Prismatic

	Pros	Cons
	Thin profile	No standard
	Al cans reduce weight	Swelling
	Volumetric efficiency in pack	Higher % packaging material
	Rounded edges/ergonomic	Higher price per Watt hour

Investigating Cell Chemistry Subtypes

While sealed lead acid is still the lowest price option, and Ni-MH is still useful in some low voltage, price sensitive applications, Ni-Cd is being completely phased out—various subtypes of Li-ion have become the leading edge technologies over the past several years. Let's look at some of the advantages and limitations of Li-ion batteries:

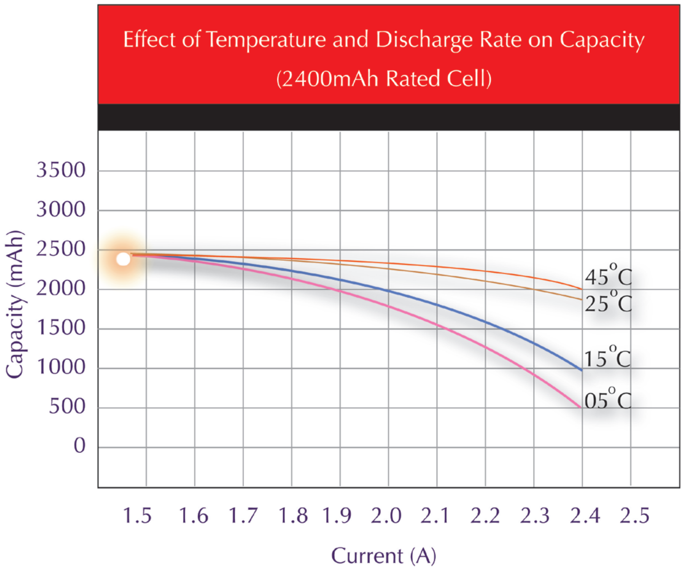
Advantages

- high energy densities lead to the potential for yet higher capacities
- fuel gauge calibration is unnecessary with the latest gas gauges
- relatively low self-discharge (less than half that of nickel-based batteries)
- low maintenance (no periodic discharge is needed) new chemistries can deliver very high power

Limitations

- requires protection circuit to maintain voltage/current within safe limits
- subject to aging (even if not in use)
- Temperature range is somewhat limited
- transportation restrictions (large shipments may be subject to DOT regulatory control; not applicable to personal carry-on batteries)

As the next chart demonstrates, Li-ion batteries can exhibit lower capacity when the current draw is high. Temperature can also affect the available capacity. Therefore, it is important to choose the correct type of Li-ion cell for your application. Some cells are designed to perform well at high current, and even cells with similar data sheets can have varying performance in non-standard conditions.



Effect of Temperature and Discharge Rate on Capacity (2400mAh Rated Cell)

It is predictable that new cell technologies will emerge with smaller package sizes, better shelf life, improved capacity and better performance under a variety of temperatures and current loads.

Cell Qualification: Testing Critical Parameters Against Specs

Cell manufacturers must be held to high standards. It is easy to make a few cells in a laboratory. It's another matter entirely to make millions of cells on a production line. Design engineers must be assured of a manufacturer's conformance to specs, packaging dimensions and process consistency. An example of the need to validate manufacturer's specs before qualification is as follows: an 18500 cell was spec'd at 1.4Ah but actually ran about 4 percent less than that at a C/5 rate. While this doesn't seem like much, this cell, at a C/10 discharge, would translate into a half-an-hour decrease in run time from spec.

Cell Verification: Testing Similar Cells from Multiple Manufacturers

All battery cells are not created equal. Each cell has unique characteristics and behaves differently under real world operating conditions—even those composed of the same chemistry.

Performance data published by cell manufacturers are all based on an ideal standard (C/5 @ 20˚C). This makes it easy for customers to make comparisons. But even the specs often don't tell the whole story.

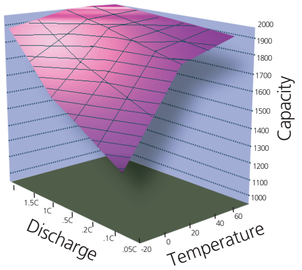
In the real world a device's profile rarely matches this idealized spec. As profile characteristics diverge, each battery cell behaves differently, particularly when there are high current pulses and temperature extremes involved.

Cell Pack Verification

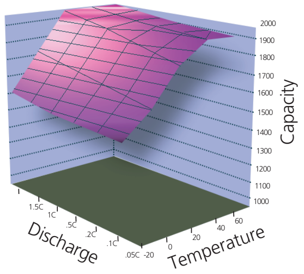
Packs should be built with cells from a single manufacturing lot, and incoming lots should be evaluated to ensure less than a 2% variation within the lot. The weakest link will bring down all its companion cells. Control processes are key to getting lot-to-lot consistency. That means an automated production process, a clean operation and facility with no airborne contaminants, and formed cells that are charged and discharged before shipping. The following charts illustrate variations from spec among cell packs.

Test similar cells from multiple manufacturers

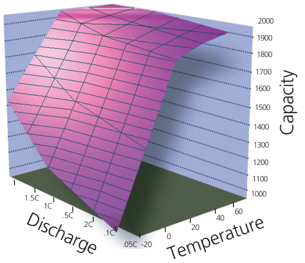
Cell Manufacturer A



Cell Manufacturer B



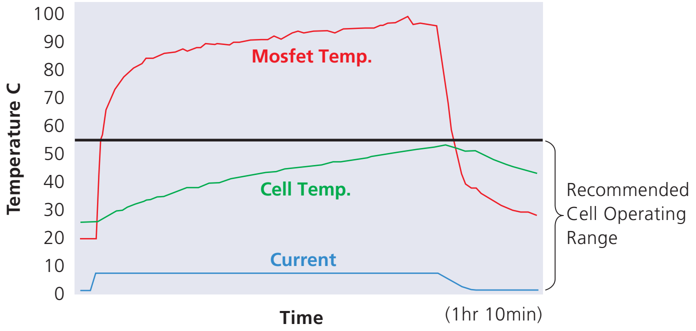
Cell Manufacturer C



Test pack to verify design margins

1C Discharge Test

3S3P Li-ion 18650 Pack



Test pack to determine the optimal cell

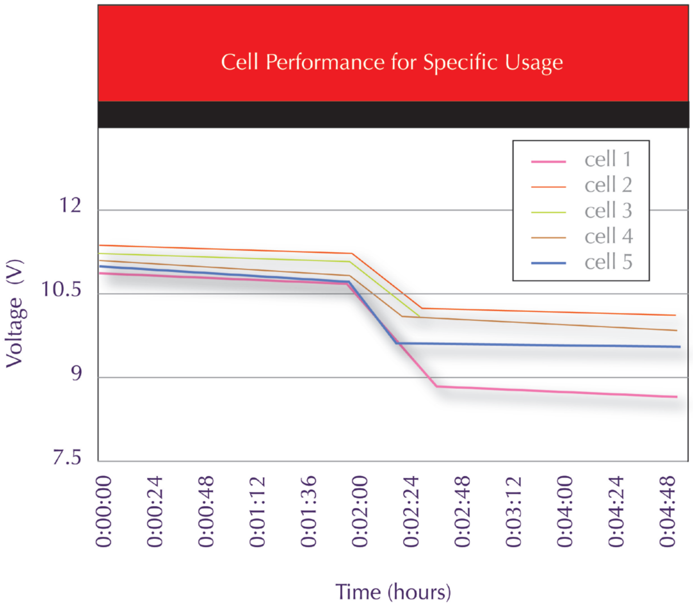
	PACK A			PACK B			PACK C		
START:	2.62 AMP-HR	19.95 WATT-HR	24.67 TEMP	3.66 AMP-HR	27.36 WATT-HR	23.23 TEMP	3.91 AMP-HR	28.95 WATT-HR	23.46 TEMP
TRIAL 1	0.45	3.39	27.35	0.44	3.39	23.71	0.45	3.37	29.24
TRIAL 2	0.46	3.37	30.58	0.45	3.36	26.6	0.46	3.35	32.87
TRIAL 3	0.46	3.35	32.35	0.46	3.34	28.56	0.46	3.33	34.71
TRIAL 4	0.47	3.33	33.63	0.47	3.32	30.3	0.47	3.32	36.31
TRIAL 5	0.48	3.31	35.69	0.47	3.3	32.06	0.47	3.3	37.39
TRIAL 6				0.48	3.28	33.83	0.48	3.29	39.02
TRIAL 7				0.48	3.26	36.41	0.48	3.28	40.12
TRIAL 8							0.49	3.24	43.17
TRIAL 9									
RES. CAP.:	0.19	1.26	36.21	0.31	2.02	38.24	0.06	0.41	42.33
TOTALS:	2.5	18.01	N/A	3.55	25.27	N/A	3.83	26.89	N/A

↑ **Ran 5 procedures without recharge**

↑ **Ran 7 procedures without recharge**

↑ **Ran 8 procedures without recharge**

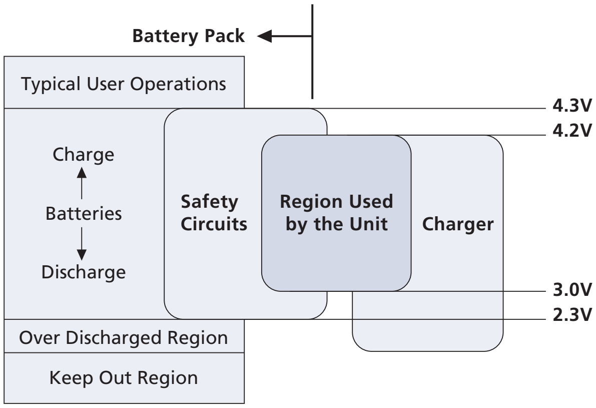
The next chart shows the difficulty of choosing cells. For this application, voltage suppression under load at cold temperature caused the battery pack to fail if the cell illustrated in pink was chosen. However, all of the other cells were able to support cold temperature operation. It is important to note that all of the cells tested had similar data sheets.



Safety Circuits: A Critical Step

The development of leading-edge battery technologies also presents several safety design challenges. Older sealed lead batteries do not generally require safety components beyond a fuse in or around the battery. But because Li-ion and Li-polymer technologies can be hazardous when overstressed, extra caution must be taken during the design process to ensure that the cells are being utilized in a manner appropriate to their technology. Voltages must be kept between strict operating ranges. The use of a safety circuit within the battery pack must be utilized to protect the pack from external stressors. These include over-charging, over-discharging, short-circuiting and excessively high or low operating temperatures.

Typical circuit lay-out



The introduction of complex Printed Circuit Assemblies (PCAs) in a battery pack brings with it a number of smart battery system design and assembly concerns. Because most battery packs are encased in plastic that requires Ultra-Sonic Welding (USW), the PCA may be damaged during the assembly process. Proper PCA location is vital.

The PCA's physical configuration and method of connectivity to the rest of the battery system directly influences the reliability, quality and cost-effectiveness of the battery system. Mistakes made by the less-experienced design engineer in this area are among the most common and expensive in the development of battery systems.

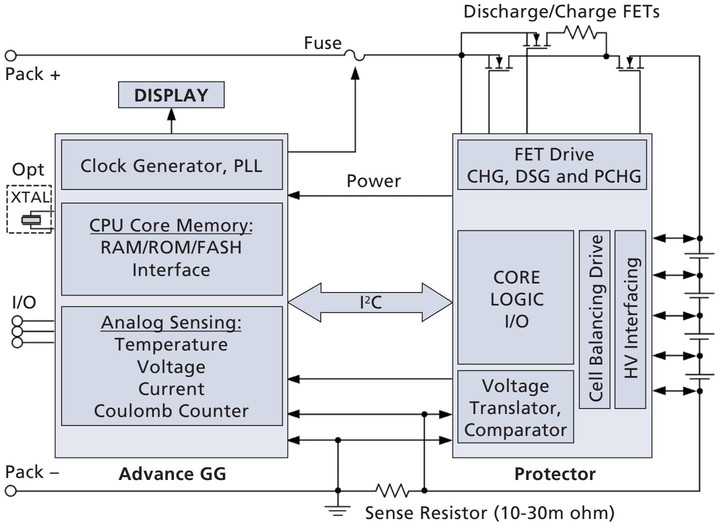
For example, high current and temperature extremes can cause internal heating within the pack and the pack's electronics. Even though cells may be specified at 1C discharge currents, large packs (three or more cells in parallel) constantly drained at this level may experience internal heating of 15-20°C above ambient. This can harm the battery system's electronics. There may be damaging of key components, destroying traces on the circuit board, melting wires, or degradation of safety circuit performance, battery management electronics and system communications.

Choosing the Optimal Battery Management System

The basic functions of battery management circuits are:

- control of energy flow into and out of the battery
- prevention of abusive conditions so that user safety comes first
- monitoring critical parameters and communicating that information to the system

Typical battery management system



Today, engineers can take a couple of different approaches to solving smart battery system development challenges. One is the selection of a “standard” or off-the-shelf battery pack. A standard battery pack is designed to offer a general solution for a wide range of applications and provides a pre-determined set of performance characteristics and packaging alternatives. The advantage for the OEM is that there is limited R&D and non-recurring expense (NRE) costs. Time-to-market is short.

However, repeated experience has shown that a reliance on standard battery pack resources often proves to be shortsighted. Although it may seem attractive to select off-the-shelf standard battery packs for design projects subject to severe time-to-market and cost limitations, these standardized solutions do not typically meet most of the unique design specifications and demands of a custom application. Strapped with a standard battery system, the designer has little or no control over physical pack configuration, including the cell selection inside.

The vast majority of standard battery packs are not user-programmable or configurable. The design engineer has almost no opportunity to enhance or optimize any aspect of the pack’s performance. Some examples would include: the pack’s operational protocol (i.e. SMBus or One Wire), battery ID nomenclature, authentication strategies, operating voltages, and or charging regime. Other examples include the alarm limits and optimal fuel gauge settings, and the display characteristics. Additionally, issues that relate to quality and reliability are dynamic and require constant oversight and attention.

Finally the cells and integrated circuits (ICs) used to make the standard packs tend to vary by manufacturer, and one “standard” pack may not perform the same as another, or even operate in an OEM’s application.

With a few exceptions, custom battery solutions provide the best source of power management for any application. Increasingly, designers are looking to custom development and manufacturing for their smart battery systems. Smart systems carry the following advantages:

- maximizing system operation under the cost/performance constraints of the system
- allowing the system to return to operation in a time-frame demanded by system users
- little or no user training or intervention is needed to achieve optimal system performance

By employing a flexible architecture for battery management, such as the Smart Battery System specification, the architecture becomes somewhat independent of the battery chemistry used for the system. This reduces support costs and promotes easier system adoption.

Today’s high-performance smart batteries are complex and sophisticated systems whose capacity, reliability and durability are determined by a wide-range of critical factors. These include the cell chemistry, cell supplier, battery gauge accuracy, discharge rates, environmental temperatures and self-heating. Among the performance factors that can determine the success or failure of the battery system in a portable application are capacity loss, service life reduction and safety.

Design Validation

Considering the impact that high currents and temperature extremes can have on a battery system's performance, safety and reliability, it is critical to validate the battery system using real world usage patterns and operating conditions. This process requires sophisticated programmable test equipment, as it is often difficult to accurately predict a battery system's performance based on a manufacturer's published specifications. Without access to precision verification equipment, less sophisticated calculations are often employed, which can be time-consuming and result in battery system failure in the field.

By validating the battery system against the specifications set by the application at each stage of the process, the designer will be able to ensure that the battery system will perform as expected. This early involvement helps to make certain that the battery system has been optimized to deliver the maximum runtime, reliability and manufacturability.

In implementing early design characterization, optimization and validation to successfully take the battery system from initial specification to volume production, it is possible to uncover potential design problems early in the development process. The knowledge that is gained from these procedures can be used as a test-bench platform during the manufacturing process.

Another design method to achieve higher system reliability and greater manufacturing efficiency is to minimize the number of components used in the battery system by leveraging common components whenever possible. It is important that designers look for opportunities to leverage existing modules, or building blocks, to reduce development time and cut costs.

In today's competitive marketplace, however, it is no longer enough to have the most exceptional design created from advanced characterization and validation procedures. Modern smart battery systems must also be cost-effective and easy to build. It is important that designers adhere to design-for-manufacturability principles by working closely with the manufacturing staff beginning very early in the development process. This work will ensure that battery systems will be relatively easy and cost-effective to manufacture and test.

Charging Systems

Well designed charging systems add value and flexibility to battery systems. Key to the charger design process is consideration of:

- adding charging capabilities quickly and cost-effectively
- form, fit and function for both internal and external chargers
- identifying the right chip sets
- dialing in the most efficient charger design
- developing optional smart chargers

Charging systems range from simple to highly complex. The most sophisticated chargers can vary the charge current and time depending on ambient conditions or the individual battery pack that is being charged.They can bridge different battery chemistries. They are programmable to user preferences. They also provide a conditioning or maintenance cycle to keep batteries at full charge.

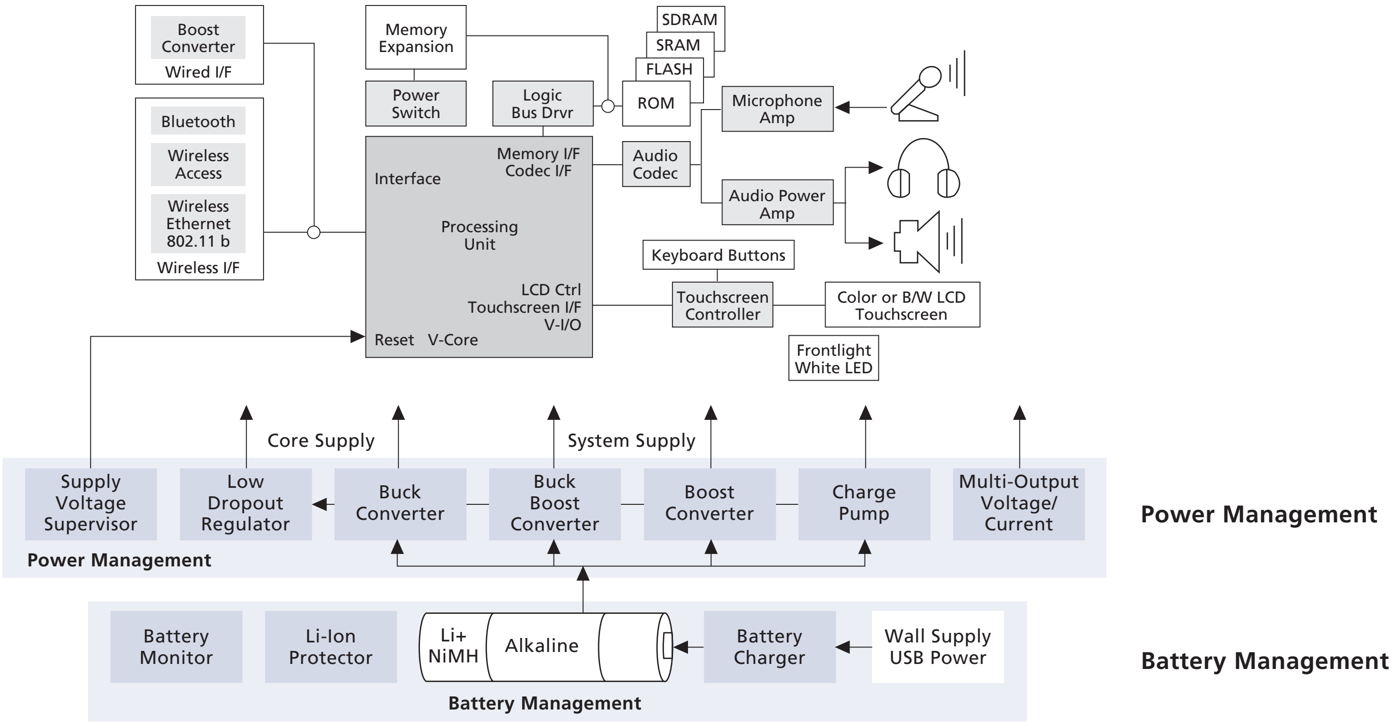
Chargers are subject to the same design criteria as their battery packs. They take the same course of development; must adhere to strict fit, form and function parameters; and must conform to proper charging rate specifications. Other factors include heat dissipation, size/space availability, safety, efficiency and EMC noise.

Chargers may be stand-alone (single or multiple bays), integrated into the battery-powered device, or integrated into the battery pack itself. Uses, costs and microprocessor interfaces may all determine whether built-in vs. stand-alone are appropriate avenues.

Chargers may operate in linear, switch or pulse mode. However, design engineers must understand proper charging techniques for different chemistries. For example, Li-ion must be charged with a constant current-constant voltage charge algorithm.

"Smart" chargers can communicate with other elements of the portable power system, including the battery pack, via SMBus protocols. To optimize charging, smart chargers allow the battery-operated device to interrogate and control the charger by monitoring charge parameters and charge status.

After adding a charging system, the complete mobile power solution architecture looks like this:



In Summary...

The mobile world is demanding higher performance, lower weight, longer effective usage times, and absolute consistent reliability from applications as diverse as emergency medical instruments, test and measuring equipment and portable data collection devices. These systems rely on increasingly sophisticated battery packs for their power requirements.

Design engineers are faced with an array of challenges in designing effective battery systems – from cell and cell pack selection to intelligent power management; from safety concerns to charging systems. This paper presents an overview of the building blocks involved in battery design for mobile applications. For a more detailed discussion of these topics, as well as case studies that illustrate how smart battery systems are making a difference in the field, please visit Micro Power's web site at *www.micro-power.com.*

About Micro Power Electronics Incorporated

Micro Power Electronics supplies custom battery systems to the portable medical, automatic data collection, and commercial military markets. As a pioneer in the development of lithium battery systems, smart battery packs, chargers, docking stations, and power supplies, Micro Power has more than 20 years of experience developing battery solutions. Micro Power has domestic and Asian production facilities. Micro Power is registered with the Food & Drug Administration (FDA) for design and manufacturing services, registered with the U.S. State Department for International Traffic in Arms Regulations (ITAR) programs, ISO 13485 and 9001:2000 certified.

With a proven track record of technical excellence, quality solutions and award-winning service, Micro Power is the global leader in portable power systems.