THE HUBER MILLS digital power report

Powering the 21st Century

March 2002/Vol. 3 Issue 3

Published by Gilder Publishing, LLC

Lithium Batteries for the Silicon Body

Greatbatch has all the bona fides of a firmly established leader in digital power

A miniature brushless DC motor, built by Danaher's Kollmorgen (DHR) (*Digital Movers, February 2002*), runs the 10,000 rpm pump in the AbioCor artificial heart. An ultra-high-energy-density lithium battery, implanted inside the heart itself, supplies about 30 minutes of primary power to the motor. That battery is recharged, in turn, via a magnetic charging system (no wires through the wall of the chest) that links to a larger (VCR-sized) lithium battery pack that the patient wears on a belt. Both batteries are manufactured by Wilson Greatbatch Technologies (GB).

If the battery's going into your body, it almost certainly has lithium inside it, and Wilson Greatbatch's name on the box. Artificial hearts remain rare, but there are over 500,000 lithium-powered devices implanted in humans every year. When it comes to ultra-high-power density, and equally high reliability in a stable, safe, temperature-tolerant battery, nothing else comes close.

Greatbatch's core products fall into five broad categories, defined by their chemistry: Lithium-iodine cells used for pacemakers, lithium-silver vanadium-oxide cells used primarily for defibrillators, lithium-thionyl-chloride cells used in drug infusion devices and neurostimulators, lithium-carbon-monofluoride cells that are an alternative to lithium-vanadium-oxide, and lithium-ion rechargeables. Greatbatch sells standardized off-the-shelf batteries; it also customizes systems for the OEMs in the medical implant business. In addition to the ultra-compact, ultra-high-performance batteries, Greatbatch supplies the complementary hardware needed for a complete implantable power system. Power electronics aside, for example, Greatbatch supplies three-fourths of the components that comprise a pacemaker.

Thanks to rapid advances in drugs, motors, materials, digital logic, and digital power, implants are now being developed very quickly, to boost or supplant a very wide range of biological functions. Similar technology makes possible the far larger market for "implants" that displace the human body completely—the exoskeletons, remotely piloted vehicles, new-generation robots, and the constellation of other semi-autonomous or fully autonomous devices discussed in last month's issue.

There are other manufacturers of lithium batteries. But with $140 million in annual sales and about 90 percent of the market, Wilson Greatbatch Technologies is the clear leader in batteries that get installed in the highest-end of all high-end platforms. Greatbatch's revenues were up nearly 40 percent last year. Take note, however: Almost 70 percent of the company is still held by the merchant bank that engineered the company's transition from a private to a public entity in September 2000.

Priceless Payloads

When kilowatt-hours are pumping an artificial heart, the cost of a power failure is infinite. The cost doesn't run quite that high when the power is controlling a pilotless military vehicle, or running a sensor in a nuclear power plant, and it's lower still when the battery is only powering a humble license-plate-mounted transponder that clears a car through toll booths. But in all such applications, the cost of losing the power rises in tandem with the value of the whole payload at the far end, or the cost of going in periodically to recharge the battery or replace it. Increasingly often, the most cost-effective approach is to spend a lot more for the best possible battery.

Built by Abiomed (ABMD) of Massachusetts, the plastic and titanium AbioCor has now been implanted in five patients. The custom one-inch diameter Danaher motor moves an average of five liters of blood per minute, and can pump twice that at full power. The motor and pump

over three million people around the world have electrically powered implants

are optimized not only for longevity and corrosion resistance, but also for efficiency, to extend battery life. The Transcutaneous Energy Transfer (TET) recharging system designed by AbioMed uses a high frequency magnetic field induced in an external coil to transfer energy to a receiving coil permanently implanted just below the skin's surface. Implanted power electronics convert the energy into a DC current to recharge the primary battery inside the heart itself. Additional implanted electronics monitor patient activity, adjust pumping action to match, monitor the performance of the pump, and wirelessly communicate its status.

The artificial heart made recent headlines, but the implantable nervous system defines, for now, a much larger market. The first implantable pacemaker was invented by Wilson Greatbatch in 1958, and subsequently licensed to Medtronic (MDT). Greatbatch shifted its focus to developing a source of power to keep the pacemaker running. Using the basic design of James Moser and Alan Schneider, Greatbatch adapted the lithium battery for the special needs of implants and marked a milestone in pacemaker development. The new battery was lighter, easier to shape, more reliable, and longer lasting than the zinc-mercury battery it replaced. Cardiac Pacemakers Inc. (now a division of Guidant (GDT)) made its mark as well by commercializing lithium battery powered pacemakers. Today, over three million people around the world have electrically powered implants, and 500,000 new pacemakers alone are installed every year. Heart defibrillators and a new class of heart resynchronizers define additional markets.

Many more are now emerging. Electro-stimulation of the brain holds great promise for the treatment of epilepsy, Parkinson's disease, and other neurological malfunctions, as well as depression, dementia, and chronic pain. Stimulating the thalamus at frequencies above 130 Hz appears to blocks tremors. Deafness can now be treated with cochlear implants that bypass dysfunctional components of the inner ear to send electrical impulses directly to the brain. Similar technologies will be used to provide direct stimulation to the visual cortex, and thus to restore sight, in the not too distant future. Implantable speech processors replace vocal chords lost to cancer surgery.

Implantable therapies for irregular breathing and muscle spasticity are coming too. Breathing pacemakers, for example, boost or substitute for signals ordinarily sent by phrenic nerves to the lungs and diaphragm, stimulating smooth, rhythmic contractions similar to normal breathing. Implanted electrical devices will eventually mitigate spinal cord injuries. Evolving directly from pacemakers, "functional electronic stimulation" devices generate electronic pulses that bypass the injured spinal cord to stimulate muscles directly. Work to date has focused on devices that allow standing, walking, gripping with the hands, and the function of bowels and bladder.

The next-generation implantables will go beyond the body's electrical grid, to its internal transportation system, boosting or substituting for the muscles themselves. The AbioCor replaces the entire heart. Ventricular assist devices are implanted in tandem with the beating heart instead (generally to buy time, awaiting a heart transplant). A wide variety of much smaller, implantable pumps can infuse drugs into the body as required. In a typical configuration, a small pump is driven by a lithium battery and controlled by an electronic module. The reservoir that holds the drug can be refilled periodically by using a needle that penetrates both the skin and a self-sealing septum. Micro-sized insulin pumps and a fully mechanical prosthetic pancreas, complete with electronic glucose sensor, pump, and an algorithm to control the release of insulin based on sensor readings, are now in advanced stages of development. An even wider range of prosthetic devices will eventually move digits and limbs.

Coming soon as well are various data and communication features to expand the capabilities of implants that monitor critical patient information. Patient vital signs, and implant operations, will be transmitted to

Authors	Peter W. Huber Mark P. Mills
Publisher	Lauryn Franzoni
Designer	Julie Ward
Subscriber Services	Melissa McNally
President	Mark T. Ziebarth
Chairman	George Gilder

The Digital Power Report is published monthly by Gilder Publishing, LLC. Editorial and Business address: 291A Main Street, Great Barrington, MA 01230. Editorial inquiries can be sent to: peterhuber@gilder.com or markmills@gilder.com. Single-issue price: $50. **To subscribe call 800-223-0491**, e-mail us at hmpowerreport@gilder.com, or visit our website at www.digitalpowerreport.com

physicians in real time via RF and Web links. Implant makers forecast with near breathless enthusiasm that an implant itself will soon 'dial' 911 for an ambulance *before* a problem becomes life threatening.

All of these medical devices must be built into packages small enough to implant, and electrically frugal enough to run on tiny batteries—they must be almost as compact and power efficient as the biological systems they complement or replace. No conventional mechanical or electrical system can begin to approach that standard of performance. Microscale digital power plants can, and now routinely do. And they begin, almost invariably, with an implantable lithium battery.

Near-Priceless Payloads

Because the products sold into it command such high premiums, and because the market is growing so fast, the silicon body is an important arena in its own right, and is now poised for very rapid growth. The implanted medical device market is over $6 billion and will double in five years. Even more importantly for the longer term, the silicon body defines the leading edge of a far larger universe of very-high-value payloads that depend on the ultra-compact, ultra-reliable storage of electrical power.

As we discussed last month, electronic motion control is now transforming the business of moving *things*. Electricity impels the motion, powerchips control the electricity, and smartchips control the powerchips: this is the convergence of digital logic and digital power. Much of this is happening in stationary applications—on the factory floor, for example—where the grid provides the main source of power, and bulky lead-acid batteries, flywheels, and standby generators provide backup. Mobile applications define a quite separate arena, however, which presents uniquely important power demands.

A pacemaker manufacturer needs premium power because there's a heart and a human life at the other end of the battery. A key virtue of the military Remote Piloted Vehicles is that they don't endanger a human pilot—but the all-silicon body that now flies, steers, or navigates the new military platform isn't one you want to throw away either, least of all because of a failed battery. The military's Black Widow Micro Air Vehicle, for example, is being designed by Aerovironment as a 6-inch span, fixed-wing aircraft with a color video camera that downlinks live video to the operator. It flies at 30 mph with a maximum communications range of 2 km. Among its potential missions: Visual reconnaissance, situational awareness, damage assessment, surveillance, biological or chemical agent sensing, and communications relay. Lithium batteries give it 30 minutes of endurance.

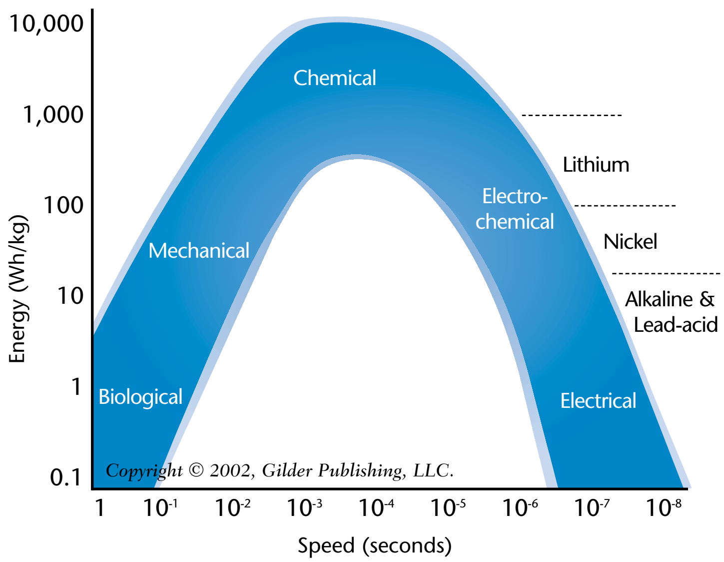
Millions of dollars of hardware likewise ride on the reliability of the battery when an oil company dispatches a remote-controlled submarine to survey undersea terrain, or mounts comparably expensive probes to sense and sniff for oil at the far end of a bore hole miles under the earth. The smarter, more dexterous, more capable, and more autonomous the robot becomes—the more we spend to build it, the more we depend on it when it's running—the more critical its power supply becomes. What the operator will spend on a better battery rises in tandem with what stands to be lost when the battery fails. In seismic sensors, automotive applications, ocean buoys, balloon-borne radiosondes, and countless other applications, that is often quite a lot.

The long-term reliability of the power supply is important, as well, in quite a number of other applications that seem much more mundane. As we've discussed before (*The Power of Millimeter Waves, November 2001*), airport screening is coming to the rest of civilian life. In post-9/11 America, we must continuously track people, vehicles, and packages—pretty much everything that moves. Threat identification in civilian life centers largely on the exchange of information with cooperative targets. Most of the clearing of passengers or luggage through airports, for example, comes down to knowing who the traveler is, and who owns which suitcase. Increasingly, the tracking of objects—cars, parcels, and so forth—will depend on embedded radio-frequency ID tags (RF ID).

Tollbooth transponders are now spreading rapidly across the United States—New York's E-ZPass system is an example. They track cooperative targets very effectively and save willing cooperators a lot of time, compared with the toll collectors or coin baskets of old. Similar technologies can separate innocuous packages from the suspect ones that need closer inspection. Most everything that's shipped by UPS, FedEx, and even the Postal Service (if it's dispatched through a postal meter rather than with ordinary stamps) is already bar-coded and repeatedly scanned while in transit.

But technology can now move tracking far beyond the printed code and the optical scanner. Motorola's BiStatix radio-frequency identification technology, for example, combines silicon with printed ink to embed smart electronic tags ubiquitously in packaging materials, so that packages automatically announce their whereabouts, without any human having to scan them. Like the implantable heart, the implantable ID card requires onboard power. The battery must be compact, have a long life, and operate under a wide range of environmental conditions. With toll tags, for example, the expected service life is ten years. And the battery must be small and flat enough to fit on a tag or under a sun visor.

Storing energy



In the world of digital power, the two primary metrics of performance are always energy density and speed—how much energy is packed into how little weight or space, and how fast you can tap it, control it, process it, and deliver it to the payload. Batteries store less energy than chemical fuels (like gasoline) but can release it as high-grade electricity much faster. When it comes to ultra-high-power density, and high reliability in a stable, safe, temperature-tolerant battery, nothing else comes close to lithium chemistries.

Wireless passive infrared sensors used in security systems have comparable power requirements; they don't draw much power, but they must run reliably, for extended periods of time. So does electrically powered marine technology for buoys, emergency systems, GPS and tracking devices, current meters, transponders, harbor lights, acoustic releases, seismometers, and other oceanographic devices. Similar transponders are going into cargo-container tracking devices. Sandia National Labs uses D-cell-sized lithium-thionyl-chloride batteries to power an array of motion and environmental sensors and associated electronics used to monitor nuclear materials extracted during the dismantling of weapon systems.

The batteries used in all these applications can't be recharged daily, like a cell phone. A wireless phone requires highly reliable power to light the silicon inside, when it's actually running—but if it isn't running at all, that's generally not a catastrophe either—you borrow someone else's phone until you get around to recharging your own. When your pacemaker's battery fails, you have a much bigger problem. With your cell phone, there's plenty of opportunity to check, replace, and recharge the battery. There isn't for the data-phone that links a remotely piloted drone to the military command center miles away. Nor for the sealed license-plate tag that clears a passenger car automatically through highway tollgates.

Batteries

On the ground, in stationary applications, in places where weight and space are no object, lead batteries still rule (*Silicon and Lead, July 2001*). Per kilowatt-hour stored and retrieved, no battery storage technology is as cheap as the rechargeable lead-acid cell, so long as you have the space to keep it, the resources to maintain it, and a way to recharge it. In mass-market consumer applications, governed by front-end cost, disposable "dry" batteries dominate. They come in only a few basic flavors, categorized according to their chemistry—the traditional LeClanche "dry cell," the alkaline battery, and the zinc-air battery. But the highest-end mobile platforms don't use any of the above. They use lithium.

In the world of digital power, the two primary metrics of performance are always energy density and speed—how much energy is packed into how little weight or space, and how fast you can tap it, control it, process it, and deliver it to the payload. There are other metrics too, of course, with batteries as much as with other power technologies: cost (obviously), how high and stable a voltage the battery generates, how long it lasts in normal operation (measured in months, or in discharge cycles), how long a shelf life it has, what range of temperatures and other environmental assaults it can tolerate, will it blow up or burst into flames when mishandled, and so on. But energy density and speed are paramount.

The most fundamental problem in the pursuit of those objectives is that in the end, batteries come down to chemistry, not engineering. You can't double a battery's performance by etching a smaller gate, as you can on a Pentium chip; you have to find a better, different chemical soup.

Manufacturers of rechargeable batteries for PDAs, cell phones, laptops, and other portable applications chase cadmium, nickel, silver, zinc—and then, finally, lithium. These exotic materials offer high power densities. In the balance of cost versus performance, nickel-cadmium (NiCd) and nickel-metal-hydride (NiMH) batteries emerged some years ago to dominate the world of portable communications and computing equipment (and hand tools). NiCd is now giving way to NiMH's two-fold edge in power density, and to environmental concerns about cadmium. Overall, NiMH offers worse life cycle and worse performance at temperature extremes, but the high energy density offsets the rest for portable computing and communications.

And then there's lithium. Originally developed for military applications, lithium batteries offer by far the most energy storage, in the least amount of weight and space. There are ten chemical combinations based on lithium, but five dominate: poly (carbon monofluoride) lithium ((CF)XLi); manganese dioxide lithium (MnO_2Li); sulfur dioxide lithium (SO_2Li); iodine lithium (I_2Li); and thionyl chloride lithium ($SOCl_2Li$).

In terms of energy density (both per unit weight and per unit volume), the last of these—lithium-thionyl—beats the other lithium alternatives by a factor of two or more. Thionyl-chloride-lithium cells also supply the highest open-circuit voltage, 3.6 V, and can offer an unmatched 15 to 20 years of service. They are so tough they can survive electronic assembly and soldering temperatures as high as 280º C. They heat up when shorted, but if suitably built, they don't get hot enough to cause a safety hazard.

Lithium performs so well because of its place high on the periodic table. It's the lightest solid element. Its intrinsic negative potential exceeds that of all metals, so it can generate the highest voltage from the get go. It reacts very strongly with water, so it can't be used with an aqueous electrolyte, but with the right electrolyte it can generate 2.7 to 3.6 volts of potential from a single cell—higher than all other cells, and high enough to run many common silicon logic and radio devices. Lithium batteries also have terrific shelf life (i.e., low self-discharge rate)—up to 15 years, depending on storage conditions. And they generally operate well over a very wide range of temperatures. Thionyl-chloride systems can pump out electrons from temperatures as low as -55ºC, and as high as +150ºC, a range that alternatively halts completely or burns out most other battery chemistry. Historically, the largest concern has been one of safety, because lithium is so highly reactive, but those concerns have been addressed with hermetically sealed cells and protective circuits.

Rechargeable lithium-ion batteries are widely used, too, in laptop computers, PDAs, camcorders, and cellphones (and specialized versions are slowly showing up in certain implant applications, such as the AbioCor). But the very highest energy density lithium batteries are "primary" batteries, built for one-time use. Throwing away the battery raises costs prohibitively in many applications, but it's just right for many others, where the objective is to build a sealed unit (like a RF ID transponder on a car tag) that will simply run for a very long time without further attention of any kind. Disposables also avoid the cost and bulk of recharging circuitry. And they can be manufactured to have much better shelf life—most rechargeables, by contrast, self-discharge much faster.

Wilson Greatbatch

A WWII aviation radioman, Wilson Greatbatch launched his first company in a barn workshop in 1960. He had conceived of the implantable pacemaker soon after he earned his electrical engineering degree from Cornell, and he participated in the first human implant in Buffalo, NY, in 1960. Greatbatch immediately licensed his implantable pacemaker to then fledgling Minneapolis-based medical electronics firm, Medtronic. In 1970, he founded his namesake company to advance the pacemaker's power systems. In July 1997, DLJ Merchant Banking led a management leveraged buyout of then private Wilson Greatbatch. A successful initial public offering followed in September 2000, raising $84 million for the company. Today, Greatbatch has all the bona fides of a firmly established market leader: deep history, major commercial alliances, and research collaborations with the likes of NASA, the Jet Propulsion and Sandia National Laboratories, SUNY, Villanova, and Johns Hopkins Universities. The company's manufacturing facilities are in Clarence and Cheektowaga, New York; Canton, Massachusetts; and Columbia, Maryland.

Lithium performs so well because of its place high on the periodic table.

Early pacemaker power came from large zinc-mercuric-oxide batteries with limited two- or three-year lifespan, unpredictable failure modes, and generated hydrogen gas (making it impossible to seal the battery). In the early 1970s, Greatbatch introduced an implant-optimized lithium-iodine battery that remains the main pacemaker driver to this day. Lithium-iodine batteries last about six years, are reliable, and when they fail, they fail predictably. Higher power levels came with lithium-silver-vanadium-oxide chemistry in the 1980s, used to power implanted defibrillators. Greatbatch introduced incremental improvements at every step along the way, leading to lighter, thinner, higher performance devices. The introduction in 1997 of a new lithium-carbon-monofluoride compound for pacemakers, for example, added 10 to 15 percent longer run time, and higher pulse power capability.

Greatbatch expanded its operations with its August 2000 acquisition of Electrochem-Canton from Hitachi-Maxell. Formed in 1977, Electrochem was a small specialty battery manufacturer that has since become a leader in the development, application, and packaging of lithium batteries for non-medical commercial applications—oil and gas exploration, recovery equipment, pipeline inspection gauges, down-hole pressure measurement systems and seismic surveying equipment, NASA space shuttles, emergency position locating beacons and locator transmitters, electronic circuit breakers for industrial applications, weather balloon instrumentation, and wear monitors for train cables. In June 2001, GB acquired the Sierra-KD medical electronics business unit from Maxwell Technologies (MXWL) (*Electron Cache, March 2001*) that produces proprietary (military-derived) electromagnetic interference (EMI) filtering systems for implantable medical devices. While fewer than 25 percent of implanted medical devices currently have EMI protection, the share is certain to expand to provide protection from potentially damaging stray electric fields including those from cell phones and security scanning systems.

Greatbatch's implantable medical expertise extends to the critical feedthroughs—that get power out of the battery case—and electrodes that connect to the target organ to deliver the meticulously shaped electrical signal. In August 1998, GB expanded its capabilities with the acquisition of feedthrough and electrode component maker Hittman Materials and Medical Components. Greatbatch's medical-grade feedthroughs use a ceramic-to-metal seal, and can incorporate an EMI filter. Using state-of-the-art sputtering and powder metallurgic techniques, Greatbatch's electrodes can incorporate chemical coatings to enhance electrical properties; in some cases the electrode tip will even contain medication, such as steroids, to prevent scarring.

Greatbatch remains the top manufacturer of cardiac pacemaker power systems. Greatbatch is also leading development of rechargeable lithium-ion power supplies with the introduction of their ReVive batteries in 2000. These rechargeables are needed to handle the much higher power demands of ventricular assist devices (used alongside the heart while patients wait for a transplant), and the new implanted artificial heart. Greatbatch also now produces the entire powered subassembly, including a patented high-performance solenoid pump, that forms the core of implantable drug pumps. Implanted pumps deliver small quantities of drugs or other fluids to a patient. (MiniMed's—acquired by Medtronic last year—implanted insulin pump has been approved in Europe and is awaiting FDA approval in the United States)

Capacitors

Speed is the second key dimension of highly ordered power. And the main drawback of lithium chemistry is that it's inherently slow; lithium batteries do not quickly give back the power that they store. These batteries are therefore said to be best suited to slow, steady, constant-current applications, not pulses, not intermittent loads. But real-world loads are never truly steady. Their power requirements may be tiny, but even remote sensors with RF uplinks, security and environmental sensors, heart defibrillators, and insulin pumps have intermittently variable loads, with peaks much higher than the average.

For many such applications, the optimum solution is to take the lithium anyway, for its energy density, and graft on a capacitor, to add speed. A similar fix is being brought to the universe of lead-acid and nickel-cadmium batteries for automotive applications using, for example, Maxwell's astounding ultracapacitors (*Electron Cache, March 2001*). The battery trickle charges the capacitor. The capacitor then delivers fast pulses of power as needed. But not just any capacitor can perform this arbitrage between energy and speed.

Ultracapacitors, or so-called double-layer capacitors, have recently emerged to fill the gap between standard capacitors and batteries. Ultracaps offer 100 to 1000 times the energy density of standard electrolytic capacitors, but they are also 100 to 1000 times faster than batteries. Electrolytic capacitors store less power, but run much faster. These performance gaps create room for hybrid combinations, that combine the high energy storage of lithium chemistry with the high speed of capacitors.

Tadiran Battery, a leader in non-implant high-performance lithium batteries, offers one hybrid solution. (Tadiran, once part of an Israeli defense conglomerate, was acquired two years ago by Alcatel's SAFT batteries unit, and has itself acquired Germany's Sonnenschein Lithium GmbH, a major European battery manufacturer.) Tadiran integrates its own proprietary, double-layer capacitor into the case of its lithium-thionyl-chloride battery case, in standard AA-, C-, and D-cell configurations that are used, for example, to provide long-life power to automatic-read or prepaid gas and water meters, GPS vehicle tracking systems, and "Mayday" RF systems.

Greatbatch offers its own hybrid solution optimized for the implanted medical market. At the end of 1999, Greatbatch introduced wet tantalum hybrid capacitors for implantable cardiovascular defibrillators (ICDs), creating both high voltage and high energy storage. Greatbatch is the exclusive licensee (for medical applications) of a patented wet tantalum technology from Evans Capacitor, and has developed a portfolio of patented improvements on the technology. The Evans hybrid combines the two core elements of a traditional electrolytic capacitor with those of an ultracapacitor. The electrolytic side consists of an electrode of pressed and sintered tantalum powder, the ultracap side uses amorphous ruthenium dioxide powder; with a sulfuric acid electrolyte. Overall, the devices offer 10 times the energy density of standard, fast capacitors, and at least 10 times the speed of ordinary ultracaps. Evans' own business is oriented mainly toward military markets; the likes of Raytheon (RTN), Lockheed Martin (LMT), and Northrop Grumman (NOC) use the Evans hybrid in avionics, radar and laser systems, satellite phones, and other high-bandwidth platforms.

When Things Start to Think

Neil Gershenfeld of MIT's Media Lab sets out part of the vision in his 1999 book, *When Things Start to Think*. The visionary is now anchored in near-term reality. The book surveys some of the things we can expect to cause the migration of digital intelligence from the desktop into the everyday objects that surround us. The dust jacket includes a blurb from cellist Yo-Yo Ma—Gershenfeld wired his cello bow. And one from the magician Penn Jilette of Penn & Teller, who got a digital "spirit chair." There's a chapter on wearable computers. Why would anyone yearn for a Web browser in his tie clip? "On a lonely street late at night," Gershenfeld points out, "I want as many friends as possible to know what's happening around me."

Even more dramatic changes come about when the things that start to think start to move under their own power, too. Digital logic and digital power make possible the implantable heart and the Micro Bat. Step by step, such systems will displace every power train in our lives, because intelligence is always far faster, lighter, more frugal, and better performing than stupidity. Much of the time, the intelligence can be anchored to solid earth in the home, the office, or the factory. But much of the time it cannot; it will move with the stuff that moves, from our own hearts on out. And when it moves, it will have to carry its power with it. All bits are packets of energy; all microprocessors are fueled by electrons; all practical forms of electronic memory depend on power for storage and retrieval. The power supplies in the things that think will gravitate toward the densest, most compact, and fastest forms of storage, just as the microprocessors and the memory chips gravitate toward the densest, most compact, and fastest gates. If military platforms and medical implants lead the way, it is because that is where there is no other choice.

Today's silicon body industry for medical implants is dominated by the likes of Guidant, Medtronic, St. Jude Medical (STJ), and Biotronik (Germany). These companies are, by and large, the very skillful integrators of core technologies supplied by others (from powerchips to batteries, titanium to plastic); they also know how to thread their way through the regulators who play such a big role in deciding what comes to market, and what doesn't. All the big players are Greatbatch customers. So are many of the smaller companies—including some of the most innovative—that are converging in this marketplace: Abiomed, Advanced Neuromodulation Systems (ANSI), Cyberonics (CYBX), Thoratec (THOR), WorldHeart (WHRT), and private players like AllHear and Advanced Bionics (cochlear implants), Dobelle Group (implantable breathing pacemaker), MicroMed Technology (with a ventricular assist device suitable for children), and MedQuest.

Medtronic, St. Jude Medical, and Guidant dominate; together they account for about $10 billion in annual implant sales. These three companies also account for over half of Greatbatch's business. All of them are also actual or potential competitors, too. With $5.5 billion in revenues, Medtronic is the largest player in the market and produces power sources for use in its own implantable devices, but it does not sell its power sources to third parties. Other actual or potential competitors include other manufacturers of the thionyl class of lithium batteries, but who currently manufacture largely for non-medical, or non-implant markets. There are only a handful of other high-performance lithium battery companies including Tadiran (which bought Exide's lithium operations), Eagle-Picher Industries, Ultralife Batteries (ULBI), the biggest wide-range (non-implant) producer of lithium batteries, Friwo Silberkraft of Germany, Yardney Technical Products, and Alliant Techsystems' (ATK) Power Sources group that specializes in (and dominates) batteries for the Defense Department (including powering the smarts in smart bombs). Any of them could put competitive pressure on Greatbatch. But the market that requires extremely dense power storage is growing very fast, and the specialized skills needed to serve the medical implant industry in particular are among the most challenging.

Digital logic and digital power make possible the implantable heart

The longer term competitive threat will come from fossil fuels. They offer a very much higher energy density (at least 10 times higher) than even the best lithium batteries—which is why they so completely dominate (and will continue to dominate) as prime movers in the transportation sector. The rest of the drive train, from tank and car, to aircraft and ship, will indeed get electrified—(*The Silicon Car, December 2000*)—but a combustion engine will remain on board to generate electric power and continuously recharge the batteries. Like all thermal engines, however, internal combustion engines don't scale down well, they scale up. Bigger engines run better, smaller ones run worse, and when they get very small, they don't run at all—friction and heat loss overwhelm everything else. Micro fuel cells are a more promising alternative, but again, only in the longer term. Fuel cell technology still has to advance a long way before a vodka-powered unit can drive an implantable heart.

Absent some (unexpected, indeed unprecedented) breakthrough in basic battery chemistry, lithium will remain the leader in the ultra-compact storage of highly reliable power. And Wilson Greatbatch will remain the leader at the leading edge of that sector, the edge defined by implants today, and by the limitless array of "Things that Think" that will infiltrate our lives in the years to come.

Peter Huber and Mark Mills
March 5, 2002

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	3/04/02 Price	52wk Range	Market Cap
Electron Storage & Ride-Through	Wilson Greatbatch Technologies (GB)	3/04/02	25.36	25.36	17.26 – 39.00	527.0m
	C&D Technologies (CHP)	6/29/01	31.00	20.13	16.35 – 38.60	525.3m
	Maxwell Technologies (MXWL)	2/23/01	16.72	10.70	5.81 – 22.50	108.8m
	Beacon Power (BCON)	11/16/00	6.00*	0.69	0.64 – 8.20	29.5m
	Proton Energy Systems (PRTN)	9/29/00	17.00*	6.27	4.00 – 15.12	208.1m
	Active Power (ACPW)	8/8/00	17.00*	4.08	3.13 – 30.20	165.4m
Project, Sense, and Control	Danaher Corp. (DHR)	1/29/02	61.56	71.80	43.90 – 69.94	10.3b
	FLIR Systems (FLIR)	1/9/02	41.64	58.64	7.19 – 57.00	970.8m
	Analogic (ALOG)	11/30/01	36.88	40.58	33.40 – 50.00	535.9m
	TRW Inc. (TRW)	10/24/01	33.21	50.60	27.43 – 51.71	6.4b
	Raytheon Co. (RTN)	9/16/01***	24.85	38.68	23.95 – 40.00	14b
	Rockwell Automation (ROK)	8/29/01	16.22	20.99	11.78 – 49.45	3.9b
	Analog Devices (ADI)	7/27/01	47.00	43.95	29.00 – 53.30	16.0b
	Coherent (COHR)	5/31/01	35.50	31.00	25.05 – 45.55	887.9m
Powerchips	Cree Inc. (CREE)	4/30/01	21.53	16.81	12.21 – 36.65	1.2b
	Microsemi (MSCC)	3/30/01	14.00	17.69	9.47 – 40.10	504.3m
	Fairchild Semiconductor (FCS)	1/22/01	17.69	29.45	11.86 – 30.33	2.9b
	Infineon (IFX)	11/27/00	43.75	25.24	10.71 – 44.40	17.5b
	Advanced Power (APTI)	8/7/00	15.00	11.10	6.50 – 18.00	96.8m
	IXYS (SYXI)	3/31/00	6.78	10.30	4.27 – 19.45	276.3m
	International Rectifier (IRF)	3/31/00	38.13	44.74	24.05 – 69.50	2.8b
Network Transmission	ABB (ABB)	9/29/00	24.24**	8.43	6.10 – 18.95	10.0b
	American Superconductor (AMSC)	9/30/99	15.38	7.99	6.50 – 27.90	163.5m
Distributed Power ****	General Electric (GE)	9/29/00	57.81	40.20	28.50 – 53.55	399.3b
	Catalytica Energy Systems (CESI)	9/29/00	12.38	3.85	3.25 – 24.00	66.8m
	FuelCell Energy (FCEL)	8/25/00	24.94	16.54	10.48 – 46.72	646.5m
	Capstone Turbine Corp. (CPST)	6/29/00	16.00*	3.21	2.75 – 38.25	247.8m
Silicon Power Plants	Emerson (EMR)	5/31/00	59.00	63.36	44.04 – 72.09	26.7b
	Power-One (PWER)	(see below)				
Motherboard Power	Power-One (PWER)	4/28/00	22.75	8.20	5.32 – 27.35	646.6m

Note: This table lists technologies in the Powercosm Paradigm, and representative companies that possess the ascendant technologies. But by no means are the technologies exclusive to these companies. In keeping with our objective of providing a technology strategy report, companies appear on this list only for the core competencies, without any judgment of market price or timing. Reference Price is a company's closing stock price on the Reference Date, the date on which the Power Panel was generated for the Digital Power Report in which the company was added to the Table. All "current" stock prices and new Reference Prices/Dates are based on the closing price for the last trading day prior to publication. IPO reference dates, however, are the day of the IPO. Though the Reference Price/Date is of necessity prior to final editorial, printing and distribution of the Digital Power Report, no notice of company changes is given prior to publication. Huber and Mills may hold positions in companies discussed in this newsletter or listed on the panel, and may provide technology assessment services for firms that have interests in the companies.

** Offering price at the time of IPO.*

*** Effective April 6, 2001, ABB was listed on the NYSE. The reference price has been adjusted to reflect this change. The 52-week range covers the period from April 6, 2001 only.*

**** The October 2001 issue closed on September 16, 2001 and was posted at 8 a.m. on September 17, 2001. Due to the markets' close in the week after September 11, our reference price reflects Raytheon's closing price on September 10, 2001.*

***** The former category, "Power: Heavy-Iron–Lite" has been rolled into "Distributed Generation." All the companies previously listed remain, but are now included in this one category, a rationale consistent with the general metrics outlined for these companies in the relevant issues of the DPR.*

More information about the Powercosm and its technologies is available on www.digitalpowerreport.com