THE HUBER MILLS digital power report

Dear *Digital Power Report* Subscribers,

With this month's issue of the Digital Power Report, we are pleased to announce some enhancements to your subscription.

First, is our website **www.digitalpowerreport.com** . If you haven't visited the site lately, you're in for a treat. The Digital Power Report team has fully overhauled the site featuring much easier navigation, a well-populated library of articles not only by Peter Huber and Mark Mills, but also by others, which will help you build out your knowledge of the digital power sector. You can use the site to keep current on important developments and technologies relating to digital power and to easily access information on the companies listed on the monthly *Power Panel*.

Within your subscriber-only section, we've added a virtual Digital Power Lounge! Using this new message board, you can communicate directly with other readers to discuss whatever is on your mind regarding the digital power technologies and companies. We expect that Peter and Mark will be occasionally listening in and from time to time they and their associates will join the online discussions. Just click on "Powercosm Forum" and follow the simple instructions to register.

As always you can easily find more information on this year's Powercosm 2001 event (June 27-29 at the San Francisco Fairmont Hotel) and other activities surrounding your subscription to the Digital Power Report. We've just added the program agenda to the site for your reference. Remember, your email address is your password to the subscriber-only area. We look forward to your comments regarding the new website and further suggestions on how we can make the site most useful to you.

Yours truly,

Lauryn Franzoni
Publisher, Digital Power Report
Gilder Publishing

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Powering the Telecosm
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Electron Cache

Ultracapacitors represent the lion's share of Maxwell's electronic components business, and the largest opportunity for extraordinary growth

Every engineer and manager in the building can look out on the new production line. A glass wall runs down the middle of the building, separating cubicles on one side from clean mini-rooms and automated assembly systems on the other. Maxwell's (MXWL) CEO, Carl Eibl, wants to keep everyone's focus where it belongs: on producing millions of commercial units for paying customers. A radical notion? Not if you're making soda or soap flakes. But the technology behind this glass window was developed to help the military initiate nuclear explosions, fire lasers, launch projectiles in electric guns, and energize pulse radar.

Maxwell started out as a research lab spin-off from General Dynamics (GD) in 1965. During the Reagan years its ultracapacitors were enlisted to save the planet from Russian missiles. During the Gore years, they were reenlisted to save the planet from Detroit's car engines. Now, reality: industry, not government, has caught up with what Maxwell's "PowerCache" ultracapacitors deliver–electron storage in a soda can. Big storage. Small can. Sold at mass-production prices. With a track record of turning R&D outfits into successful manufacturers, Eibl is going to deliver.

Built in 1746 by Pieter van Musschenbroek at the University of Leyden (Holland), the first man-made capacitor had a capacitance of perhaps a millionth of a Farad. The biggest capacitor you could fit in a soda can in 1960 ran about one-tenth of a Farad. Over the course of two-plus decades of intensive R&D, Maxwell learned how to pack more and more of this old and familiar technology into less space. Maxwell's biggest PowerCache–its PC2500–now weighs in at just over one pound and 2,500 Farads in a stretched out soda can.

Maxwell is now mastering thin-film technologies, micro-material engineering, and automated production lines to push big capacitors down the cost curve of mass production. Its PC2500 will occupy only half a soda can a year or two from now and cost half as much. Price and size will both drop another factor of two in the two years that follow. Maxwell, in short, is doing for big capacitors what companies like Cypress (CY) Micron (MU), Samsung (SSNHY), and IBM (IBM) did for little ones, the capacitors that constitute the dynamic digital memory of a computer. By packing more capacitors into less space, the 64 kB of digital capacitance (RAM) on your desktop in 1980 became 64 MB today.

Other vendors supply the microfarad capacitors that circle a Pentium on the motherboard–power capacitors needed to provide microseconds of load-leveling storage for the femtofarad (billionth of a microfarad) capacitors that constitute the RAM itself. Maxwell's kilofarad soda cans can circle a 10-kW server, or the 100-kW engine of a Pontiac, or the electric brakes on a General Electric (GE) locomotive. GE's medical division uses them in power supplies for IV pumps and monitors and other patient-critical medical equipment. PC manufacturers will use big capacitors to put 10 seconds of "ride- through" backup on a circuit board. Server manufacturers need them to build ride-through protection into the frames and backplanes of racks. VCR manufacturers can use them to liberate us all from the curse of the blinking digital clock.

War and Peace

Six years after van Musschenbroek, Ben Franklin used a kite and a storm to charge up his own replica of the "Leyden Jar." The next two people who tried that stunt were killed. Killing usually counts against a technology, but not in the military. Maxwell rose and prospered during the last decades of the Cold War by learning how to provide short bursts of electric power where the Pentagon wanted them. Ignition systems for nuclear weapons have to match the clock speeds of nuclear chain reactions. Laser weapons require pulses of power big and fast enough to pierce incoming missiles. Electromagnetic pulses can launch projectiles or disable hostile electronics.

By 1990, government defense contracts made up most of Maxwell's business. Maxwell's engineers either created intense pulses of electric power, or designed circuits to protect electronic components from the same. Demolition and destruction generally come down to concentrating more power in less space. That's how you penetrate the tank's armor, break through the enemy's fortifications, punch through the rear guard, and race with Patton to the Rhine. With weapons and battles alike, as von Clausewitz observed, you want to concentrate your force.

Then the Cold War ended and defense spending collapsed. Maxwell had to find new civilian applications for technology perfected for blasting huge amounts of electric power into tiny spaces. Military customers had known why they wanted to do that. Civilian customers didn't. Maxwell scrambled. It landed a contract from McDonnell Douglas to pulse power into ultra-intense lights to strip paint and rust from aircraft (quite amazing actually, and works well too). It developed a pulsed-light system for sterilizing water, blood, and other medical products. Then it got Department of Energy (DOE) funding to develop ultracapacitors for electric cars. But the DOE's focus was all wrong. Earth-in-the-balance bureaucrats aimed to displace the internal combustion engine itself. They should have aimed for the drive train.

In 1994, a new team of executives from Silicon Valley took charge at Maxwell. They went on a spree, acquiring small companies involved in software, ceramic capacitors, and space electronics. The company developed technology, but not products, and not the manufacturing expertise to move its engineering into mass production. It remained locked in a mentality of cost-plus contracting.

In July 1998, Eibl was appointed a director. He had been CEO of Mycogen, an agribusiness/biotech company, and then CEO of Stratagene Corp, another privately held biotech. A year after Eibl became a Maxwell director, he took over as CEO. Maxwell's Farads offered Eibl the same business opportunity as Mycogen's DNA codons. In just five years, Eibl had transformed Mycogen from a technology boutique into a $260 million business, which he then sold to Dow (DOW) for $1.1 billion. The civilian world, Eibl grasped, was now ready for Maxwell's most unique technology–its ultracapacitors. The challenge was to push the PowerCache up the production curve, and down the cost curve–to move it from the Pentagon's volumes and prices to the world of General Motors (GM) and Honeywell (HON), Dell (DELL) and Compaq (CPQ).

Headquartered in San Diego, today's Maxwell bears little resemblance to what it was just two years ago. The company has about 1,000 employees, 160 of them scientists and engineers; over two-thirds of the workforce was hired in the last 14 months. During that same period, Maxwell has invested $70 million in automated manufacturing and quality control. Over 70 percent of the company's revenues are now from commercial customers, and by our rough measure, over 90 percent of Maxwell's business falls squarely in the heart of the Powercosm. The new Maxwell shares only one important thing with the old: it still knows how to build huge capacitors in soda cans better than anyone else.

Peaks and Valleys

But why should anyone out of uniform need a huge capacitor? Because a capacitor is fast, and behaves much the same coming and going–you can charge it fast, discharge it equally fast. This makes it the perfect bridge between cruise/trickle power upstream, and peak/pulse power downstream, or vice versa. Hand it a steady flow, and it can give you back a spike; hand it a spike, and it can give you back a steady flow. When supply suddenly dips, it can level it up, and when supply spikes, it can level it down. It is the perfect technology, in short, for resolving short-term mismatches between power supply upstream, and load downstream. It is the ideal arbitrageur of electrons.

And that single capability is now in high demand. Car engines, generators, and turbines–slow mechanical systems that move at the speed of *crawl*–must interface smoothly with electrical motors, generators that move at the speed of *zap*. And the low-9s, *zap*-speed electrons of the old electrical world must in turn interface with the high-9s, *think*-speed electrons on which smartchips depend. At each interface, the downstream demand can change orders of magnitude faster than the upstream supply. A Pentium can go from "0 to 60" in a few clock cycles, or several billionths of a second–but ordinary electrical circuits require hundredths of a second to respond. Electrical actuators controlling an engine's valves, or a car's steering or suspension, likewise require pulses of power that change much faster than the car's mechanically spun generator can.

Events in the outside world often fluctuate inconveniently fast, too. A municipal water pump kicks on, lightening strikes, or a squirrel gnaws through a transformer's insulation a mile up the grid. A driver abruptly steps on the gas when he reaches the on ramp. The car's electric suspension meets a pothole. Or its electric brakes confront a darting child. Every time, you can get a huge mismatch between cruise power on one side, and pedal-to-the-metal demands for power on the other.

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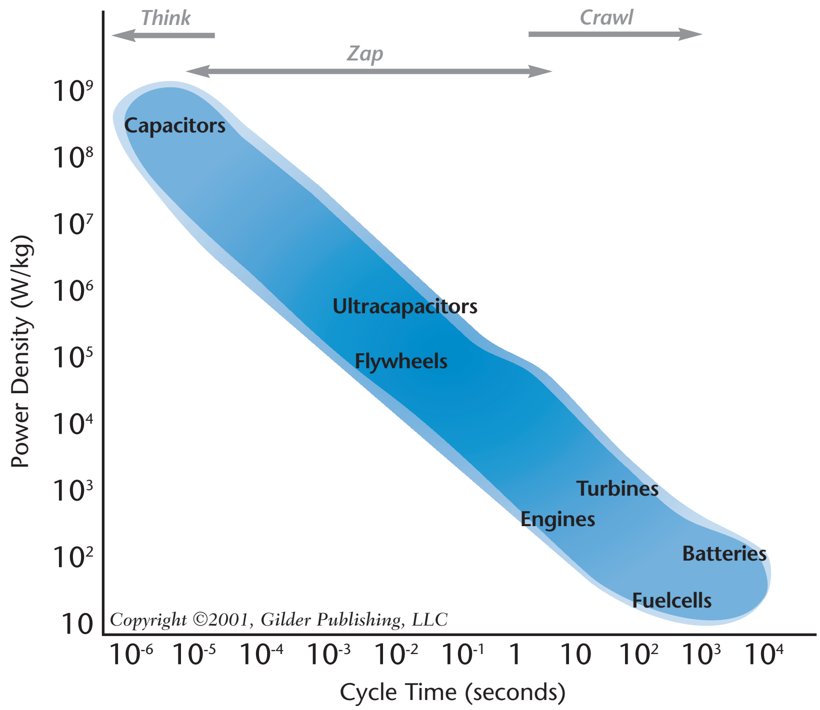
Power: Density and Cycle Speed



Information technologies operate at think-speed, 10 orders of magnitude faster than crawl-speed mechanical and chemical energy systems. With comparatively high power densities, and cycle speeds of 100 Hz to 200 Hz, ultracapacitors bridge the gap.

These peak-to-average chasms have traditionally been bridged by overbuilding. To accelerate a car from 0 to 60 in seven seconds, you build an engine that can cruise at 120 mph. Power supplies for buildings and circuit boards are oversized in much the same way. An uninterruptible power supply for a desktop PC runs full time doing nothing–except for a few seconds on a typical day, and perhaps an hour in a typical year, when it's called on to supply several hundred watts. All are designed around requirements for peak, short-term power–which leaves them grossly oversized for normal operations. Over-sizing is the strategy for subtracting unwanted power peaks, too. Pile on metal to divert the pulse that lightening creates when it strikes the grid, or to decelerate a car from 60 to 0 in an emergency stop.

Clumsy, expensive, and wasteful overbuilt systems work, but only up to a point. Peak-to-average power gaps keep widening because clock speeds keep rising, and because tolerance for anything less than perfect power keeps falling. Engineers can't go on bridging the gap forever, by just making the old thermal and chemical engines (and their brakes) bigger and bigger. Most of the time, they'd rather do just the opposite–make engines smaller and run them steadier, closer to cruise, to lower weight, improve efficiency, and slash emissions. One half of their mission is to push everything toward a slow-and-steady optimum at the speed of *crawl*. The other half is to keep pace with the ever-fluctuating, ever-accelerating speed of *think*.

Capacitors can bridge the gap. If you can make them really big. In soda cans.

Kilofarad Capacitors

The basic technology was simple enough for an eighteenth-century Dutchman to master. Place an insulating layer (dielectric) between two flat metal plates, and attach a wire to each plate. Apply a voltage and some charge moves from plate A to plate B. Remove the voltage and the charge flows back the other way. The "capacitance" is how much electrical charge gets stored by one volt. More plate area and closer spacing raise capacitance. So does a better dielectric–mineral oil, for example, is about twice as good as air. The two most widely used solid dielectrics are plastic (or wax paper) films and ceramics. "Electrolytic" capacitors use oils.

It sounds pretty simple, and it is–until you try to pack a lot of capacitance into a small space. To push area up and spacing down, you start with a huge sheet, make the thinnest possible sandwich, and jellyroll it up. But then the innards are frail. A single short circuit through the insulator anywhere in the roll can kill the whole device. And with insulators exposed to both thermal and electrical stresses, capacitors fail all too often. The burnt-out aroma wafting from a suddenly dead TV or stereo is usually the smell of toasted capacitor.

Toasted or not, there are lots of them. Capacitors are in motor drives, automation systems, silicon power plants, radios, radar, stereo power supplies, cell phones, fluorescent lights, and ignition systems. Trailer-sized, high-voltage capacitors mediate power pulses at grid-level utility substations. Across these applications, capacitances span the micro- to the single-Farad range. Until military contractors like Maxwell got into the game, however, nobody aspired to stick *thousand*-Farad capacitors into a soda can. It couldn't be done.

The likes of Maxwell VP Richard Smith did it anyway. A physicist by training, Smith spent 28 years at Teledyne (TDY) running a gallium arsenide chip fab, developing power and RF components, fiber optic sensors, Doppler radar, altimeters and a range of defense technology exotica pushing the envelope of physics and materials. He arrived at Maxwell in 1994. Step by difficult step, the Maxwell scientists and engineers who preceded him had gained a deep understanding of the physics of capacitance.

Much of the company's early work was with film capacitors, but Maxwell eventually turned to a fundamentally different surface architecture. Its PowerCache now uses as its plate the huge (microscopic) surface area of activated carbon, of the kind used in gas masks. Maxwell works closely with suppliers on a proprietary process to get the thin carbon cloth (20 to 50 thousandths of an inch thick) in just the right form, and just the right uniformity in porosity. Maxwell electrically sprays an aluminum plasma into the carbon cloth–a key proprietary part of the recipe that gives Maxwell an important edge. The impregnated cloth is then pressure bonded to a 1 to 2 mil-thick aluminum foil.

The aluminum-carbon cloth is saturated with a liquid electrolyte. A top layer of standard polymer insulator comes next, then a mirror image, aluminum-carbon layer, to form a double-layer capacitor sandwich The sheets can then be stacked, folded, and packed into anything from stamp- to soda can-sized packages. Maxwell jellyrolls the foil to make the smaller units, and currently uses a stacked-cell structure for the soda can-sized larger ones. Capacitances range from Farads to kilofarads. They get that high because the aluminum-carbon-liquid complex stores charge across the vast microscopic surface that carbon-liquid interface supplies, by separating positive and negative ions in the electrolyte. This may sound a lot like a battery–but there's no on-going chemical reaction, and no net current flow through the liquid.

Getting the aluminum-carbon "plate" right accounts for much of Maxwell's intellectual property–seven core patents, more pending, and raw engineering know-how alongside

Charge does, however, move from metal to carbon to liquid and back again. To lower electrical resistance, it's essential to get a good electrical contact between the carbon cloth and the aluminum foil. Early designs (some still in use by other companies) relied on untreated carbon cloth, which results in high resistance where the cloth meets the foil. Maxwell's technique cuts overall resistance ten-fold, to the lowest level in the industry. Pushing resistance down lets you push peak operating speed up: and lower resistance means less heat dissipated in every charge-discharge cycle. The upshot–Farad to kilofarad units that can cycle at up to 200-Hertz speeds. At the same time, Maxwell manages to keep internal leakage of charge very low–a PowerCache can hold its charge for weeks or months. Standard big electrolytic capacitors manage only hours.

Ultracapacitors run at low voltages (typically 2 V to 4 V, in contrast to 500 V to 1,000 V for ceramics or films). In itself that sharply lowers the peak energy that ultracapacitors can store–capacitor energy rises with voltage squared–but huge surface area more than compensates. And there's a benefit to low voltage–very long capacitor life. Maxwell has run its big units for hundreds of thousands of cycles without a problem; in a typical automotive or industrial application that means several lifetimes of the vehicle. And if low-voltage ultracapacitors do develop internal shorts, they don't kill the whole device, as they usually do with film and ceramic capacitors, but they increase internal leakage current a bit.

It's by no means easy to optimize such a design to yield the most capacitance in the least space, in a durable package. There are all sorts of ways to blow the carbon fiber cloth apart, or clog up the pores, or create uneven blobs of useless aluminum on the surface. Getting the aluminum-carbon "plate" right accounts for much of Maxwell's intellectual property–seven core patents, several more pending, and a lot more raw engineering know-how alongside.

Pentiums and Pontiacs

One large opportunity for PowerCache capacitors is in providing short-term ride-through power. At least 90 percent of power problems are voltage fluctuations that last no longer than a few seconds. The problems originate not only on the public grid but also on private premises, when loads switch on and off, technicians tinker, toasters burn out, and harried dads diddle with fuse boxes. The best protection includes a compact ride-through system situated right at the end of the line–downstream of all other technicians and toasters. Maxwell's postage-stamp-sized PowerCaches are compact, passive devices that can do exactly that. A PC4F, for example, can provide several hours of ride-through for the digital clock in any home appliance.

Ultracapacitors can likewise be mounted directly on circuit boards in desktop computers and servers, to provide a crucial, front-end layer, reliability-boosting hardware. Several PC and server vendors are now looking to mount gum pack-sized PC100F units on their motherboards. Maxwell's own I-Bus/Phoenix group already incorporates PowerCaches into the custom-designed server backplanes and enclosures it builds for customers like Compaq, Alcatel (ALA), Rockwell (ROK), Ericsson (ERICY), and Hammer. General Electric puts PowerCaches in the power supplies for medical equipment. Ultracapacitors are also a more compact and reliable alternative to a spring-actuated shut down in electric valves when power fails. Such valves are manufactured in the millions by companies like Honeywell, to control gas and liquid flows in factories and homes.

Detroit presents an even larger opportunity. One early application for smaller units will be to keep power locks, windows, and inside lights functioning when cars lose battery power in accidents. Pushed just a bit further, ultracapacitors can entirely eliminate the wiring harnesses across a door's hinges by simply storing enough power to keep locks and windows running when the door is open.

But the really huge PowerCache play is under the hood. Under the hoods of buses to begin with. In early January, Maxwell announced a major deal to supply packs of PC2500F units to GM's Allison Transmission unit, for incorporation in hybrid drive trains sold to manufacturers of big buses and trucks. Now qualified by

GM global procurement, Maxwell shipped the first twenty packs—incorporating 10,000 PC2500Fs—in December 2000. Allison's hybrid is a cleverly designed, continuously variable transmission that puts two electric motors in parallel with the drive shaft to provide 135 kW of electrical acceleration. The PowerCaches pack enough punch to accelerate and drive a city bus several blocks before the small, highly efficient, ultra-clean diesel kicks in, both to recharge the capacitors and to add torque to the wheels. Allison is designing clever predictive software that can learn a bus's route and optimize things even to the point of maintaining silence when the vehicle passes a hospital. Emissions drop 90 percent; fuel efficiency rises 60 percent.

The 4,000 city buses put into service every year in the United States represent an early entry point, because they are expensive and long-lived, and because many are operated by pollution-conscious, technology-pushing municipal authorities. (New York City, for example, recently announced plans to begin converting its bus fleet to hybrids.) Boston-based Solectria, a manufacturer of hybrid and electric vehicles, has completed its tests of the PowerCache, and is now pursuing development with Maxwell of a hybrid drive train for a commercial, mid-sized bus (20 to 40 passenger); the potential market is about 30,000 vehicles per year. Short-haul trucks make up a still larger market with similar performance requirements. Nissan Diesel Motor has announced plans to build a truck hybrid centered on an ultracapacitor; Maxwell is bidding on the job and should get at least a piece.

Hybrid cars won't be far behind. With the convergence of smartchip and Powerchip, as we discussed last December, broadband electric power is going to supplant the old click-click bang-bang drive train, belt by belt, pulley by pulley, shaft by shaft. Not necessarily the internal combustion engine itself, just all the rest downstream of the piston rods. And not because electric power is greener, though it is, but because it responds faster and performs better. For the next decade, the great opportunity is at the interface, between an old mechanical engine kept running—when it's running at all—at a steady cruise, and an electrical drive train in which peak-to-average loads vary enormously.

Honda (HMC) and Toyota (TM) have already introduced commercial hybrids (Insight and Prius); Ford (F) recently announced aggressive plans to push electric subsystems into its 2003 Explorer. Every other major manufacturer in the United States will be rolling out commercial hybrid-electrics on a similar timetable. Maxwell is already active with the Tier 1 automotive suppliers including Delphi (DPH), Visteon (VC), and Valeo (France); Maxwell has also been working directly for several years with major car manufacturers, including Volkswagen (VLKAY), Daimler (DCX), BMW, and GM.

In Detroit and elsewhere, both Maxwell and its customers view ultracapacitors as complements, not substitutes, to primary engines, turbines, and batteries. Ultracapacitors don't displace grid power when mounted in server racks or alongside electric valves; they won't displace batteries, internal combustion engines, or fuel cells either.

In the car itself, the most immediate opportunity for ultracapacitors is to extend the battery's life and boost its functionality. Batteries depend on room-temperature chemistry, which pushes them to the very slow edge of *crawl* technologies. Their optimum clock charge/discharge rates are measured in hours. They much prefer trickling power to pulsing it. It's certainly possible to pile on enough batteries both to start and to propel a car—but where battery technology stands, it makes no engineering or economic sense.

Maxwell and its customers view ultracapacitors as compliments, not substitutes to primary engines, turbines, and batteries

The much better approach is to use the chemical system for longer-term electrochemical storage, with the ultracapacitor downstream to serve as an interface between the *crawl*-speed battery and the *zap*-speed electrical systems under the hood. Ultracapacitors also protect batteries from what harms them the most—the accumulation of charge-discharge cycles. And ultracapacitors can cover for the battery's other great weakness—it all but shuts down when it gets too cold. So long as a battery can trickle, however, it can charge up an ultracapacitor, which can then start an engine. By incorporating PC10 and PC100 units in their designs, manufacturers of wireless consumer products, automatic meter readers, scanners, and power tools, already shrink their batteries, and extend their lives.

Thus, properly used, ultracapacitors don't eliminate batteries, they improve battery functionality and expand battery markets overall. The major battery manufacturers understand this. Maxwell is discussing collaborative arrangements with the likes of Johnson Controls (JCI), Duracell and Moltech, and with major battery users, like UPS manufacturers Liebert (Emerson Electric EMR), Exide (EX), and SPD Technologies (part of Level 3, LVLT). Last May, Maxwell also signed an agreement with (and took an equity stake in) Onemocall, a Korean manufacturer of energy generation and control systems. Maxwell will supply several million ultracapacitors to be incorporated in Onemocall's microgenerators and power management circuits for cellular telephones, PDAs, and other handheld devices.

There is a somewhat greater possibility of direct substitution between ultracapacitors and flywheels, though here too the technologies will more often complement each other than compete. A PowerCache array has about the same footprint as an equivalent flywheel system. Maxwell estimates that when the unit price falls below $50, arrays of

PC2500s beat flywheels in providing several second ride-through to wireless towers and other small, remote platforms, particularly where small size, fully passive, all-electric systems are more attractive than spinning mechanical ones. But flywheels will likely prevail where longer ride-through and larger amounts of power are required; the genius of the ultracapacitor is power, not energy.

The piece that interests us most, Maxwell's electronic components division, will account for about 40 percent of the company's revenues

From UPS to car engine to battery, the ultracapacitor delivers the same two, mirror-image benefits. Upstream, it lets you shrink the prime mover, isolate it from manic-depressive fluctuations in downstream loads, and thus run it slower and steadier, closer to cruise. For the prime mover, that means less metal, less chemical, less transformer, and longer life, because the main power plant and its electronics are isolated from the biggest electrical swings downstream. Downstream, the ultracapacitor delivers just the opposite–bursts of power when they're needed. The overall pay-off: better control, better performance, higher efficiency, and lower emissions.

Mass Production

Maxwell's biggest challenge lies inside the company itself. It has to complete the transition from a cost-plus government contractor, with a portfolio of high-technology but low-profit interests, to a focused, cost-driven, quality-driven, mass producer of the units that Detroit and many others will buy by the tens and hundreds of millions.

Carl Eibl has already taken Maxwell through a cathartic corporate housecleaning. In the past two years, Maxwell has sold off operations in high voltage wound film capacitors, power supplies, time card and job cost accounting software, and glass-to-metal seals. Its PurePulse sterilization business is up for sale. In January, Maxwell signed letters of intent to sell its defense contracting business.

What's left? Cash in hand that could fund a strategic acquisition–perhaps a polymer battery company? And a business now centered squarely on what Eibl calls "high-availability electrical systems."

One solid keeper (for the near term at least) is Maxwell's I-Bus/Phoenix group, which accounts for over half of Maxwell's current revenues. This is the unit that custom-designs backplanes and enclosures for servers, medical equipment, and telecommunications systems. OEM manufacturers are increasingly buying unpackaged circuit boards from high-end server vendors like SUN (SUNW) and Intel (INTC), and building them into their own racks and cabinets, with their own specifications for shielding, power quality, cooling, and so forth. When Eibl took over in mid-1999, Maxwell's I-Bus group was mainly an assembler of such third-party boxes; Eibl has since built it into a serious design and engineering unit. We guess he'll eventually sell it too–perhaps to one of the other major players in this specialized but growing niche, like Liebert, OnLine Power (OPWR), Teal Electronics, or Square D. But for now this group remains a growth center inside Maxwell itself, and is a natural internal market for PowerCache technology.

The other keeper is the piece that interests us the most: Maxwell's electronic components division. It will account for about 40 percent of the company's revenues, once Maxwell completes the sale of its government contracting unit. Along with PowerCache, this division designs and manufactures high-reliability electronic components. Maxwell has a long history of building sophisticated filtering circuits to maintain power-quality in military satellites, guidance and communications systems in tanks and other weapons platforms–systems that need protection from hostile electromagnetic pulses. Maxwell has adapted the same technology to protect pacemakers, defibrillators, and other medical implants and devices from the cacophony of electromagnetic noise that grows steadily louder in the rising wireless economy. The market for powered implants is growing especially fast, and Maxwell has built a solid fence of intellectual property around its filtering circuits.

But ultracapacitors represent the lion's share of Maxwell's electronic components business, and–with Detroit now buying them–represent by far the largest opportunity for extraordinary growth. Maxwell expects demand for the kilofarad units (PC1200 and PC2500) to hit 200,000 units next year (up from 50,000 this year), and to break 1 million in 2003, if Maxwell meets its own price targets. If the company's ultracapacitors are designed into just 1 percent of new cars by 2005–an entirely plausible projection in our view–Maxwell will have to produce 10 million of them a year.

Maxwell's production of its smaller PC5F and PC10F ultracapacitors has already topped 5,000 per day, and it will pass 50,000 per day in the second quarter of this year. To get to those volumes, Maxwell has worked closely with Ismeca, the world-class Swiss firm that specializes in designing and building factory automation machinery. (Ismeca's U.S. headquarters are in San Diego, just 30 miles from Maxwell's.) The Ismeca machines are now built and in final "burn in." They will be headed for Maxwell's factory floor as this letter goes to press.

Mass production of the larger PC1200 and PC2500 will come next. In 1999, Maxwell's maximum production kilofarad units reached about 50 units per day. The run rate was about 400 per day at the end of 2000. Prices have dropped apace. A PC2500 was $500 in early 1999, it's at $125 today; Maxwell projects $75 by 2002 off a "mechanized" production line, and $30 by 2003 off a fully automated line. With gross margins holding steady all the while, at about 40 percent.

Production of the under-100 Farad (100 F) units was automated first, because they can already be assembled in a jellyroll structure. The larger units are still assembled as stacked cells. A "Z-fold" architecture will come next, then a jellyroll. In qualifying its product for General Motors, Maxwell successfully demonstrated the next big step, a process in which the carbon gets deposited on the aluminum foil, instead of the aluminum being sprayed into the carbon cloth, without raising the device's electrical resistance. Unlike cloth, which has to be folded, foil can be wound; that makes foil-based production much easier to automate. Other changes in the work will let Maxwell transition to a cheaper form of carbon, available from a broader array of vendors.

Eibl has assembled his own team of automation engineers, including one hired from Ismeca itself. He has hired from the disk drive industry, whose engineers know a lot about shrinking size, paring cost, and high-tech mass production. He has hired from the battery industry, and from Hewlett Packard (HP), for talent in cost control and supply chain management. Major customers that have audited Maxwell's manufacturing line and roll-out plans include GE's medical products and locomotive units, Lockheed Martin (LMT), Boeing (BA), Rockwell, and–most recently–General Motors. EPCOS (EPC), the 1999 electrical components spinout from Siemens Matsushita, put Maxwell through a Teutonic white-glove evaluation, and has elected to become a licensed manufacturer and seller of the PowerCache units.

The EPCOS license is particularly significant, because EPCOS had spent years trying to develop ultracapacitor technology of its own. It will be some other vendor's ultracapacitor–not a battery or a fuel cell–that will emerge as the main competition for Maxwell's PowerCache. But whose? In some segments of the market, Panasonic (a division of Matsushita Electric) is already a serious competitor. It currently makes both the small 5 F to 10 F supercapacitors as well as a 1,200 F unit. But Maxwell apparently remains well out ahead in its ability to deliver kilofarad units in volume. NESS (NESS), a Korean lithium-ion battery company, announced 2,500 F to 3,000 F units in late January, though it too is apparently unable to ship production-level volumes at this point. Maxwell is in active discussion with NESS over a cross-licensing partnership. Both companies are competitors to be reckoned with; but Maxwell beat out both in the bidding to supply GM's hybrid program.

No other ultracapacitor vendor that we know of manufactures kilofarad units commercially. Polystor makes both polymer batteries and ultracapacitors, but its largest capacitor tops out at 50 F. Moreover, Polystor's aerogel technology offers only about one-third as much storage per unit volume as a PowerCache. Elna (a unit of Asahi Glass, ASGLY) units also top out at about 50 F. Cooper Electronics Technologies (a new subsidiary of Cooper Industries, CBE, the $4-billion manufacturer of electric equipment) offers a line of small units (under 10 F), licensed from Polystore. ABB, FullPower, CapXX (Australia), and various universities and national laboratories are all doing R&D on ultracapacitor technology, but none is close to commercial production.

In any event, ultracapacitors are so new and their potential so large, that–for now at least–we count the emergence of other manufacturers as more validation than threat. From all we've seen, Maxwell still maintains the big lead it built up over many years on the Pentagon's payroll. And there's still plenty of space in the technology to double power density and halve price, several times more. Ultracapacitor researchers have a history of over-promising–but not Maxwell. The company says it's well on track to rolling out the next-generation units, with substantially lower internal resistance and higher operating voltage, which will translate into higher speed, more power, and more energy storage.

Newton, Carnot, Maxwell, and Moore

The ultracapacitor addresses a fundamental engineering problem, one that comes up in almost every system that depends on chemistry or combustion to power electric motors, microprocessors, radios, or lasers. The world of electrons and bits gravitates toward the fast and wildly variable, in deference to laws of James Maxwell and Gordon Moore; the world of inertia and friction gravitates toward the slow and rock steady, in deference to laws of Isaac Newton and Sadi Carnot. One side builds ever higher and sharper peaks and valleys; the other yearns for the prairies. One side moves at the speed of *crawl*, the other at the speed of *zap*, and onward, to the speed of *think*.

Power hybrids–slow on one side, fast on the other–are our engineering destiny. Systems that store a lot of energy are inherently slow. Even if we can release the energy fast, through an explosion, we have to surround it with inertia–a cylinder and piston, for example–to keep things under control. And explosions are falling out of favor in any event, because environmental regulators much prefer cooler–and thus, even slower–power plants. But at the same time, we want our systems smart and responsive, which means inherently fast, and getting faster. High-speed smartchips and Powerchips are taking control of motherboards and cell towers, of robots and pacemakers, of steering, suspension, brakes, and valves, because they deliver more bandwidth, more bits, more acceleration, more efficiency, and a smoother ride.

Ultracapacitors will stand between the two, bridging the divide, presenting pulsed power to one side, a level load to the other. Maxwell will build them.

Peter Huber and Mark Mills
February 26, 2001

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	2/23/01 Price	52wk Range	Market Cap	Customers
Electron Storage & Ride-Through Ultracapacitors	Maxwell Technologies (MXWL)	2/23/01	16 23/32	16 23/32	10 9/16 - 22 9/16	165m	GM, Delphi, Visteon, Valeo, Onemocall, EPCOS, Boeing, Lockheed Martin, Rockwell
Flywheels	Active Power (ACPW)	8/8/00	17*	20 5/8	12 3/4 - 79 3/4	800m	Enron, Broadwing, Micron Technologies, PSI Net, Corncast Cable, ABC
	Beacon Power (BCON)	11/16/00	6*	7 3/16	6 1/8 - 10 3/4	341m	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
Hydrogen Generation	Proton Energy Systems (PRTN)	9/29/00	17*	10 5/16	5 1/4 - 36	341m	Matheson Gas, NASA
Power: Heavy-Iron	Calpine (CPN)	1/25/01	40 7/16	43 1/2	18 1/8 - 52 31/32	12.3b	PG&E, Long Island Power, ComEd, Phillips Petroleum, ConEd (NY), New York Power, JFK Airport, Amoco, Sacramento Municipal
Powerchips: Insulated gate bipolar transistors (IGBTs)	Fairchild Semiconductor (FCS)	1/22/01	17 11/16	15 15/32	11 3/16 - 49 1/2	1.5b	GE, Emerson Electric, Rockwell, Siemens, Bosch, PowerOne, Artesyn, Invensys, IBM, Delta, Marconi
	IXYS (SYXI)	3/31/00	6 25/32	14 1/4	3 7/8 - 45 3/8	377m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
	International Rectifier (IRF)	3/31/00	38 1/8	40 13/16	27 3/8 - 67 7/16	2.5b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens
	Advanced Power (APTI)	8/7/00	15	13	11 1/4 - 49 5/8	109m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
Power MOSFETs	Infineon (IFX)	11/27/00	43 3/4	34 1/2	32 3/4 - 88 1/4	21.6b	Siemens, Visteon, Bosch, Mansmann-Sachs, Hella, Delphi
	International Rectifier (IRF)	*(see above)*					DaimlerChrysler, Bosch, Bose, Delphi, Ford, TRW
Network Transmission and UPS: High-temperature superconductor	ABB**	9/29/00	96 61/64	82 29/32	N/A	N/A	National Grid (UK), Microsoft, Commonwealth Edison, American Electric Power
	American Superconductor (AMSC)	9/30/99	15 3/8	18 3/4	16 1/16 - 75 1/8	380m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France
Power: Heavy-Iron-Lite	General Electric (GE)	9/29/00	57 13/16	46 3/16	42 - 60 1/2	457.6b	Reliant Energy, Enron, Calpine, Trans Alta, Abener Energia, S.A.
	Catalytica Energy Systems (CESI)	9/29/00	12 3/8	16 15/16	9 1/8 - 19 1/2	235m	GE, Kawasaki Turbines, Enron, Rolls Royce, Solar Turbines
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/29/00	16*	24 3/16	17 3/4 - 98 1/2	1.8b	Chevron, Williams ECU, Tokyo Gas, Reliant Energy
Fuel Cells	FuelCell Energy (FCEL)	8/25/00	49 7/8	49 3/16	15 3/4 - 108 3/4	777m	Santa Clara, RWE and Ruhrgas (Germany), General Dynamics, LADWP
Micropower Nano-fuel cells	Manhattan Scientifics (MHTX)	8/25/00	2 3/4	1 7/32	1 5/32 - 5 1/16	N/A	Incubator (no customers)
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59	65 1/16	40 1/2 - 79 3/4	27.9b	Citicorp, Verizon, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent
	Power-One (PWER)	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	22 3/4	20 5/8	13 5/8 - 89 13/16	1.6b	Cisco, Nortel, Teradyne, Lucent, Ericsson

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.*

*** ABB's plans to list its stock on the NYSE have been "delayed due to the volatility of the U.S. equity markets."*