THE HUBER MILLS
digital power report
Powering the Telecosm
September 2000/Issue 7
Published by Gilder Publishing

Fuel Cells II: Big and Hot

Fuel cell technologies, FuelCell's included, are long term. However, FuelCell has positioned itself on the shorter end of long

As we discussed in Part 1 of this double issue, the membranes and rare-earth catalysts currently at hand push the small-and-cool fuel cell inexorably toward the fringe, toward the very small and the very cool. For now, the proton-exchange membranes (PEMs) are too imperfect, and the catalysts they depend on are too expensive, to be assembled into higher-power units that are both reliable and affordable. For the foreseeable future the advance of higher-power units is likely to depend primarily on perfecting their fuel supplies. It depends mainly on finding affordable ways to produce extremely pure hydrogen upstream of the fuel cell itself.

We see no imminent prospect of anyone scaling up platinum PEM fuel cells, reformers, or electrolyzers, to meet the high-reliability, high-power needs of the Powercosm hotels, the ones operated by Digex, PSInet, Exodus, Akamai, Inktomi, Qwest and Global Centers, and by countless other owners of silicon-dependent commercial buildings worldwide.

As noted in Part 1, there is a fundamental alternative to small-and-cool and big-and-hot. One company, the ONSI division of United Technologies (UTX), is already selling healthy numbers of commercial units by pushing the technology in that direction. (We like the ONSI technology; but it's buried in the parent conglomerate.) A second, FuelCell Energy (FCEL), is about to join ONSI. FuelCell has pursued the hot, membrane-free fuel cell technology to where it logically leads. But we caution again, as we did in Part 1, that FuelCell and its erstwhile competitors are a lot further away from high-volume commercialization than many of the other Powercosm companies we've looked at in prior issues. All fuel cell technologies, FuelCell's included, are long term. By listening to the technology, however, FuelCell has positioned itself on the shorter end of long.

Less Catalyst, More Heat

Cool fuel cells depend on a single, exceptionally clean fuel, and expensive catalysts. Hot fuel cells can use ordinary, relatively dirty fuels, and much cheaper catalysts. In chemistry, high temperature can substitute for a lot of other expensive, troublesome stuff.

Operating at 400°F, ONSI's cell is at the hottest end of cool. Its electrolyte is phosphoric acid, in a highly durable, gel-like state. The electrodes are copper-coated carbon graphite plates, again enhanced with platinum, but a lot less platinum is needed, because the temperature is higher. Each 1 m^2 plate is machined to perfect flatness, and 240 plates are stacked horizontally within the basic unit. Though it's the hottest-of-the-cool, ONSI's unit still needs hydrogen as its fuel, but it can tolerate over one hundred times as much (up to 300 ppm) of carbon monoxide contaminant in its fuel. Push operating temperature up to 1,200°F, and you get to a molten carbonate electrolyte. Here, carbonate ions (not hydrogen ions) travel through the electrolyte and complete the electrical circuit. At this temperature you can dispense entirely with the platinum catalysts. Cheap nickel will do instead, at both anode and cathode.

That eliminates carbon-poisoning problems. Which means your fuel cell can run on regular carbon fuels. FuelCell's carbonate unit reacts clean natural gas with steam. (The sulfur in gas, which is deliberately added by the gas company upstream to give the gas a smell for safety purposes, has to be stripped out first using activated charcoal filters.) FuelCell brags that the unit can feed on natural gas, marine diesel fuel and even–gasp!–gasified coal. None of this endears FuelCell to the greens. What endears

FuelCell to us is that its technology works, and works reliably, it appears, for tens of thousands of hours.

Push temperatures on up to 1,800°F, and you get to the solid-oxide fuel cell (SOFC), based on solid yttrium and zirconium oxides for the electrolyte, and perovskites (a rare mineral) as the electrode catalyst. This yields high efficiency, and high tolerance to almost any fuel type. Current developers include Siemens Westinghouse Power, SOFCo, Ztek, and McDermott.

So how hot should you go? As high as you have to, but no higher. FuelCell has touched down at just the right spot on the curve, we believe: hot enough to dispense with troublesome platinum and PEMs, but no hotter. Several Japanese companies have reached the same conclusion, and are pursuing the same electrochemistry. M-C Power (Burr Ridge, Ill) was also pursuing it, along with several other dead ends in the carbonate space, until it ran out of cash early this year.

At 30 tons and 1 MW, the basic FuelCell unit, the "Direct Fuel Cell" (DFC™), is too big to be of any help in retiring the internal combustion engine. As noted in Part 1, this forest-green DFC can stands 12' high and 12' around. Inside the unit are four "stacks," in each stack, 350 identical "cells." Each cell consists of a pair of sintered nickel sheets, 2.5' x 4', separated by a porous solid-ceramic, lithium aluminate, sponge. A stainless steel corrugated sandwich provides space for the flow of gas and steam above and below each cell. The nickel plates constitute both anode and cathode; the cell requires no additional catalyst to operate. The contacts between the cells are physical (not soldered)–the cells are simply stacked & clamped in their big steel can. Each cell creates a roughly 0.8 V potential; 350 in series create a 280 V potential, and four stacks in parallel produce 1 MW of power from the can. Total power will rise to 1.5 MW when the current cells are replaced with the next generation design, currently in beta.

FuelCell's DFC units aren't by any means as compact as NASA's, but they are compact enough as megawatt-level powerplants go. A complete two module, 2 MW set-up (3 MW in phase two), with common gas filter (to remove sulfur), water treatment (for boiler quality water/steam), heat recovery to preheat fuel and make steam, and electric switch gear and controls, all of which occupies about the same space as a tennis court–4500 ft^2. Not a system you'd try to mount on a circuit board, but very possibly one you'd install on the floor of a large building or in the power center of a corporate campus. Few other technologies can deliver that combination of power density and total power. A stripped 2 MW Caterpillar diesel, by comparison, has a 1200 ft^2 footprint; two 1 MW turnkey Cat tractor trailers occupy about the same amount of space.

A single 1 MW can provides enough waste heat to run several 50 kW micro-turbines alongside. With federal funding, FuelCell is exploring how best to run that heat through turbines to boost overall efficiency (an interesting exercise, with the unintended potential to further add 9s by virtue of the co-location of additional prime generators). And DFC units can easily be run fuel rich, at much less than full load, which greatly improves load following, the speed at which a unit can boost its electron output in response to rapid changes in demand-side load. This lowers efficiency, but supplies all but instantaneous load following capability–sub-millisecond response times, every bit as good as a huge stack of batteries.

Dutch Treat

Bernard Baker, FuelCell's founder and current Chairman, first studied the carbonate fuel cell in 1959, at the University of Amsterdam. He left Holland to develop hydrazine-nitrogen tetroxide alkaline fuel cells in California at the dawn of the space age, then put in another eight years at the Institute of Gas Technology in the 1960s, returning to his earlier interest in the carbonate fuel cell. Baker founded Energy Research Corporation in 1970 to develop fuel cells and advanced batteries for defense applications. The company spent nine years in a joint venture with Westinghouse, pursuing the phosphoric acid fuel cell–ONSI's current technology.

But Baker and Westinghouse both finally concluded that for the power ranges they were interested in, they had to push the chemistry a lot hotter. Westinghouse is now pursuing solid-oxide technology, way up the temperature curve. Baker chose the slightly cooler, molten-carbonate path.

Both groups were motivated, initially, by the pursuit of higher thermodynamic efficiency. But the biggest advantage of higher temperature has turned out to be simpler, more robust chemistry, and much less delicate innards. For the small-and-cool set, carbon monoxide is a lethal poison. ONSI's hottest-of-the-cold unit will tolerate some carbon monoxide in its feedstock. For FuelCell, carbon monoxide isn't a poison at all–it works fine as a raw fuel.

Editors	Peter W. Huber
	Mark P. Mills
Publisher	Richard Vigilante
Managing Editor	Debi Kennedy
Designer	Julie Ward
President	Mark T. Ziebarth
Chairman	George Gilder

The Digital Power Report is published monthly by Gilder Publishing, LLC. Editorial and Business address: P.O. Box 660, Monument Mills, Housatonic, MA 01236. Editorial inquiries can be sent to: peterhuber@gildertech.com or markmills@gildertech.com. Single-issue price: $50. For subscription information, call 800.261.5309, e-mail us at help@gildertech.com, or visit our website at www.Powercosm.com

Baker's operation moved full bore into carbonate fuel cells in the late 1980s, and finally settled on the DFC's current design. Baker set up demonstration systems in Elkraft, Denmark in 1989 (an 8 kW unit), a 20 kW and then a 70 kW unit with PG&E in California in 1990 and 1991, and then a 2MW unit with a California municipal utility in Santa Clara in 1996. The latter facility, the largest fuel cell system operating in North America, comprises four 250 kW units, each of which contains a stack of 340 cells. Mitsubishi Electric is a FuelCell development partner and has its own 200 kW unit in operational testing.

In 1990 Baker hired Chris Bentley, a TRW and GE engineer with vast experience in product manufacturing; Baker then took the company public in 1992. In 1997 he hired an experienced industrial manager to take over as CEO, with Baker himself staying on as Chairman. Finally, in 1999, Baker was ready to move decisively beyond his 47 patents and ten years of carbonate-focused R&D, to put his company on its final trajectory to commercial manufacturing. The company spun off a successful battery business (Evercel), and adopted its new name, FuelCell Energy. Jerry Leitman, the new CEO, is another alumnus of Sweden's ABB–like Ake Almgren of Capstone (see July DPR). Like Almgren, Leitman embraced and accelerated FuelCell's decision to design and engineer a product suitable for real-world commercial production.

Leitman led FuelCell into a second successful round of financing last April, and now is using most of the $60 million raised to expand the company's Torrington, CT, manufacturing facilities. FuelCell is shipping a pre-commercial unit to the Rhone Klinkum Hospital in Bad Neustadt, Germany, for start-up in November. The company expects to deliver 300 kW, 1.5 MW and 3MW fuel cell power plants to commercial customers in the second half of 2001.

High Temperature, High 9's

The main advantage of the big-and-hot systems: they work and they keep working. They work because their electro-chemistry is relatively simple and easy to engineer, and because they tolerate rough fuel. High-temperature fuel cell designs deliver 9s by dispensing with delicate membranes. High-temperature units still require skillful engineering in chemistry and metallurgy, but along lines that the technology naturally impels and accommodates. The hot fuel cells are huge batteries, really, in which the key electro-chemicals are continuously replenished from the gas line.

By using gas directly as their primary fuel they add reliability from the get-go. A buried gas line is less vulnerable than the vastly more fragile and exposed overhead wires that almost universally comprise the grid. And a backup supply of methane or propane is quite easy to store in a tank on premises. Platinum PEM fuel cells take advantage of the gas line too–a reliability boosting first step–but only by adding delicate, reliability-sapping stages of reformer and membrane downstream. The big-and-hot manufacturers rely on indelicate heat, instead.

As discussed in Part 1, hot, thermal systems scale up well, but not down. When you're running hot, bigger runs better. Bigger systems are suited to big, stationary configurations, not to small or mobile ones. And like batteries, large fuel cells can easily be deployed in multiple-unit arrays. The main limitation of all the big-and-hot fuel cells: a cold start takes a lot of time. Run these cells full time, or don't bother running them at all. FuelCell's units take 20 hours to pre-heat. But they can easily be maintained on hot standby, using under 0.5 percent of their full-load fuel.

FuelCell has touched down at just the right spot on the curve, hot enough to dispense with troublesome platinum and PEMs but no hotter

FuelCell's basic, four-stack can produce 1,000 kW, which makes it a nicely sized building block in an uncrowded segment of the power curve. If you're looking for high-9s backup power for 4 MW loads–rich territory not just in the Powercosm, but in a wide range of silicon-enabled and thus power-sensitive commercial and industrial businesses–the most likely alternative to an array of high-temperature fuel cells would be a small turbine or a diesel. Both of which have to go in the parking lot, not in the building.

And you'd need to put in two turbines to get comparable reliability–an excellent turbine has 92 percent availability; two 2 MW turbines are less reliable, overall, than four 1 MW fuel cells. SurePower Corp. (CT, private company) has engineered a system around ONSI cells (together with two five-ton Piller, Inc. flywheels, and two independent sets of 1,250 kW Onan generators) for the Omaha National Bank. Mtechnology (Boston, MA), an MIT-trained team that learned its business doing "probabilistic risk assessment" for the nuclear and defense industries has systematically calculated the "Independent Failure-based Unavailability" of the Bank's power to be 3×10^{8} (0.99999997).

FuelCell can't yet boast ONSI's real-world experience with commercially operating units, but it's clearly on the right trajectory, and far ahead of the small-and-cool alternatives. In a partnership with the MTU subsidiary of DaimlerChrylser, FuelCell has had one unit pumping high-9s electrons into the University of Bielefield hospital near Dusseldorf, Germany for the past year. (MTU's main line of business is propulsion and power generation for ships and large off-road equipment.) Last June, FuelCell took off-line and tore down a 250 kW cell in its Danbury, CT facility, after the cell had supplied 1.8 million kWh of power, in 11,800 hours of zero-maintenance, flawless operation.

FuelCell has also performed accelerated tests to validate five years' operational life for its stacks–after which, stack replacement runs about 30 percent of the cost of a new unit. (A typical turbine requires a 5-year overhaul, too.) FuelCell has 17,000 real hours on a sub-scale stack of commercial design. The company plans to guarantee first-generation stacks for 3 years; the follow-up stacks will be guaranteed for 5 years. FuelCell has measured stack degradation at 0.25 percent per 1000 hours, which translates into about 90 percent output, at the same efficiency, after 5 years of operation.

The worst, but readily addressable news: output eventually drops off completely, and abruptly, if an aging stack isn't replaced in time. A five-year scheduled replacement will do fine. This would be a serious problem if these were smaller units intended for home-owner use, where maintenance schedules aren't likely to be respected. But FuelCell is on reasonably safe ground in counting on periodic (five-year) maintenance of units at 250kW and above. Large diesels and turbines, the main competition, require at least as much (and usually much more) regular attention.

Because it builds relatively simple systems, FuelCell's main technology edge lies in the raw know-how of engineering robust boxes. FuelCell has earned that know-how the old fashioned way, not by raising money fast on Wall Street but by building real systems. As noted, the company's founder has almost 40 years of experience in fuel cells, beginning with the astounding engineering problems of putting cells in space.

One big and early problem in FuelCell's technology was that the nickel in the stainless steel would migrate out of steel and cause short circuits**.** And the electrolyte itself would migrate out of each of the cells. Both problems appear to have been overcome through diligent, old-fashioned engineering. Much of the rest of the company's art has centered on manufacturing to very fine tolerances, and solving basic, important, chemistry and material integrity issues. Each quarter-inch thick fuel cell sandwich is manufactured to flatness uniformity of +/- 0.5 thousandths of an inch**.** Ceramic porosity also has to be controlled precisely. Manufacturing to very tight tolerances raises efficiency and makes possible the higher operating temperatures that permit the FuelCell unit to dispense with exotic catalysts. FuelCell's IP–centered on proprietary manufacturing methods and some 47 patents–lies mainly in the architecture, and manufacturing solutions it has developed to address these electrochemical and physical-chemical issues.

FuelCell needs power electronics to convert the fuel cell's megawatt-level DC output to AC for initial distribution. General Electric is supplying all the power electronics for the first two commercial units. But FuelCell hasn't fixed on a single vendor yet for switchgear and inverters: GE, ABB, Emerson and others of that class are all in the running, and any of them could supply the credibility, resources, reliability, and long-term supply agreements that FuelCell will need in the early going. Leitman understands the key role of power electronics, and intends to get the best, from the outside. He doesn't plan to reinvent the silicon wheel, and doesn't have to. His company's core competency is in electrochemically propelling the electrons; he'll leave the conditioning to others.

Through MTU, FuelCell will be supplying its technology to RWE AG (Germany's largest utility) and Ruhrgas AG (Germany's largest natural gas firm), which will invest $68 million in commercialization of FuelCell technology. The German team is fabricating its own units under license. FuelCell is targeting a wide range of other markets, as well, and is forging some impressive partnerships. The company is pursuing the marine market–a good-sized market in its own right, since the horsepower propelling the world's ships is about the same as the horsepower driving the generators in the total U.S. electric grid. Commercial ships are pursuing all-electric propulsion to gain precious space for payload customers and cargo. FuelCell is also working with Bath Iron Works (Bath, ME) and General Dynamics to produce the marine defense version of its DFC. A DFC able to run on widely available dirty diesel oil is the Navy's target. This also happens to make the DFC very appealing for developing-country and non-gas-grid applications. High levels of sulfur in the most commonly available diesel fuel presents a challenge, however. There are ways to remove it (using bottled hydrogen gas and zinc oxide filters) but they do push FuelCell back into the kind of fuel pre-treatment chemistry that it so effectively sidesteps when it has ready access to sulfur-free fuels.

Chase 9s, Not Greens

Ships, like laptops and cell phones, do offer the fuel cell an extra slack, some extra margin for success. As it does in a spaceship, the fuel cell's edge on a ship can center on higher energy density and smaller footprint–not more electrons per dollar, but more electrons per pound or per square foot. Weight and space are at a much lower premium in cars however. Notice how profligately both are already wasted in SUVs.

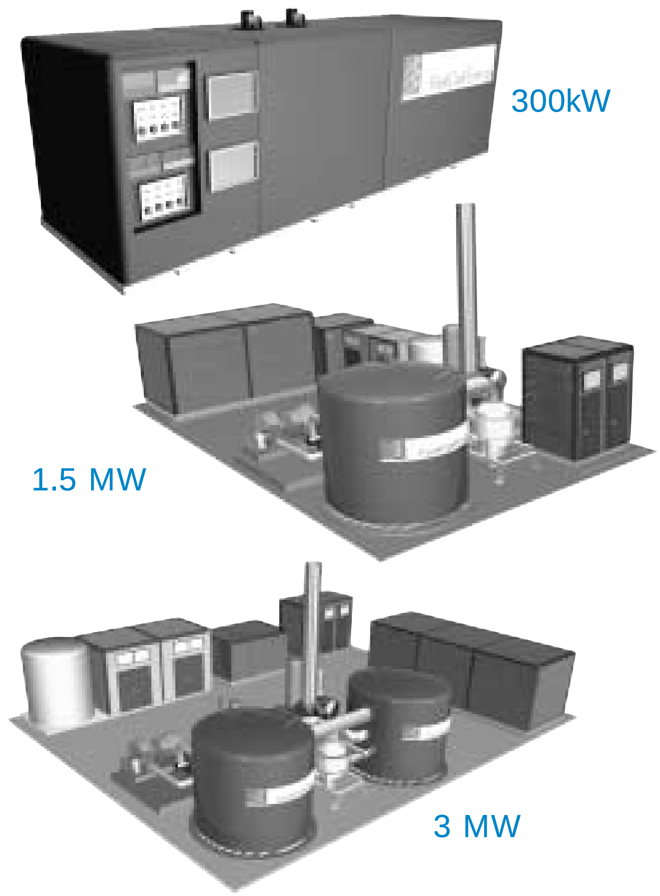
In most stationary applications, the smaller-greener-footprint just isn't enough of an advantage; if fuel cells are to compete at all, here, they must add 9s. FuelCell's Santa Clara demonstration unit was a $20,000/kW project; the units now going into field trials are down to about $8,000/kW. But a standard gas-fired turbine runs in the $500/kW range, a coal plant $1,000/kW. DFC electrons end up at about 20¢/kWh–pretty good compared to a lot of other fuel cells, but still not competitive compared to standard run-of-day grid electrons which typically go for 7¢/kWh. This means the DFC will sell only if it provides extra 9s, which it can indeed do. Few of the small-and-cool fuel cell vendors can do the same, least of all those that are aiming to build a greener car.

The other great hope for the fuel cell is the green one. But much of that hope is grounded on what remains, for now, little more than a wishful fantasy about the emergence of the "hydrogen economy," coupled with willful disregard of how much ready supplies of hydrogen, if they ever arrive, would improve the performance of non-fuel cell technologies. Assume a perfect fuel, and it's easy enough to design a perfect power plant. That is the trap into which most of the fuel cell pack has fallen. The easiest way to make a perfectly green fuel cell is to assume the ready availability of a perfectly green fuel–pure hydrogen. But if you have that fuel readily at hand, you don't really need a fuel cell at all. As we've said, feed it with hydrogen and a Caterpillar diesel will run fantastically clean, too. So will a Capstone turbine. So will a Honda engine.

In its core concept, at least, the fuel cell is an old and humdrum technology. Volta (1800) and Sir William Grove (1839) were coaxing electricity out of combustion-free chemical soups quite some time ago. The real magic came from Faraday (1821) with his discovery that rotating a coil of wire in a magnetic field would generate a current too, without the messy chemicals. Thereafter, electricity could be generated by anything that could turn a shaft–water, wind, steam or a hot gas. If Faraday had only arrived on the scene in the 1990s, we'd be using nothing but Grove's fuel cells to generate our power for the last two centuries. The breathless headlines today would surely be about the miracle of the gas turbine and the power generating capabilities of the Caterpillar diesel-powered rotating machines. Powered by an internal or external combustion engine, the electromagnetic generator has so completely eclipsed the electrochemical that many observers can see little more than the triumphant technology's problems, even as they imagine that the losing electrochemical technology doesn't have any.

Fuel cell buyers get a $1,000/kW outright subsidy from the Department of Energy, and some states offer additional incentives on top of that. The subsidy alone is 3 to 4 times the price of buying a diesel generator. Additional subsidies have been created by the Clinton Administration in the Defense Department's Climate Change Action Fuel Cell Program. (Why DOD should be defending climate eludes us, but it is.) In some

FuelCell Energy Power Plants: The Sweet Spot



FuelCell Energy's DFC units "burn" standard fossil fuels, but at high efficiency and with almost zero emissions. FuelCell builds a unit that can supply megawatt-level on-premises power in the heart of the Powercosm. It isn't aiming to get under the hood of cars, where the internal combustion engine will be very difficult to displace.

states, fuel cells qualify for renewable energy credits because … well, because regulators like them, not because their fuel is in fact "renewable." (Hydroelectric dams run on rainfall, which is indeed renewable – which by government logic means, of course, that they do not get renewable energy credits.) On top of all that, many states now require their incumbent utilities to obtain some share (typically 10 percent) of their primary supply from "renewables." Eleven major corporations–GM, IBM, J&J, and (perhaps predictably) Dupont–recently pledged to support an effort to develop a market for 1,000 MW of green power. Considering how hard it is to squeeze any serious amounts of power out of photovoltaics or wind, these regulatory and corporate commitments amount to an all-but-guaranteed market for fuel cells, regardless of price, so long as they actually work. FuelCell's do. Most of the rest don't.

All this green favor has turned out to be as much curse as blessing for many other fuel cell developers. To begin with, it has pushed them toward developing for the mobile platform–for the car–to overtake the internal combustion engine. This has pushed them away from the two edges of the curve where fuel cells hold the most promise–the very small-and-cool, where pure hydrogen is easy to deliver and membrane performance is comparatively easy to perfect, and the very big and hot, where neither pure hydrogen nor perfect membranes are required. Propelling a car requires (in electrical terms) about a 25 kW power plant–the toughest possible place to try to deploy a functioning fuel cell and supply it with a fuel that won't kill it.

Fuel cells that add reliability are going to be big-and-hot, like FuelCell Energies DFC, or very small, along the lines of the Hockaday cell

Even Ballard, the most touted of the mid-sized, vehicle-targeting PEM-cell companies, seems to be inching toward that conclusion. The new Ballard Power Systems, formed early last year, is a non-transportation joint venture between Ballard, GPU International, Inc (a NJ utility holding company), ALSTOM SA (France, makes electric generating equipment) and EBARA Corporation (Japan, makes fluid machinery). BPS finished its first prototype PEM-based 250 kW power plant in August 1999, marking the culmination of five years of development activity; it claims it will start shipping commercial units in 2002 or 2003.

Another often overlooked pitfall for the fuel cell in green pursuit of the internal combustion engine is that the target isn't standing still. While the PEM fuel cell inches forward to a thousand commercial sales, combustion-engine manufacturers relentlessly pour research dollars and drive down the emissions of real power plants that they build in multi-million-unit production runs. With its three catalytic converters, the new Nissan Sentra CA (stands for "Clean Air") burns gasoline and still meets California's SULEV (Super Ultra Low Emission Vehicle) standard. The new Honda Civic GX (not battery, not hybrid, just gasoline) meets SULEV too. Engines with powerchip-enhanced actuators will soon eliminate dozens of moving parts, which will lower emissions still more. High-temperature ceramic engines can burn cleaner still.

Meanwhile, the closer you examine the fuel cell, the less green it looks. Most mid-sized hydrogen systems still rely on fossil fuel plus reformer so the energy costs and emissions of reforming must be included in any honest green accounting. As a consequence, for greenhouse gas purposes, the fuel cell isn't much better than a combustion engine, if it's any better at all. In stationary applications, its waste heat can be captured in a cogeneration cycle, but so can the heat from a Capstone turbine or a Honda engine. Ballard's promotional literature attributes carbon emissions to other technologies, not its own, and goes on to lump CO_2 in with NOx as a contributor to "smog"–embarrassing mistakes for a company that's supposed to know its chemistry. The reformer required to extract hydrogen from natural gas just upstream of Ballard's fuel cell dumps the same CO_2 into the same atmosphere. And whatever else it may do to the air. CO_2 doesn't cause smog. Bottom line: The PEM fuel cell looks exceptionally green only if one assumes a hydrogen economy that doesn't exist, and ignores the tough and dirty chemistry required in the upstream refinery.

We certainly aren't advising anyone to shun technologies that have green virtues or green cash behind them, to the contrary. A key advantage of the fuel cell is that it finds so much favor among regulatory and zoning authorities, and among environmentally concerned end users, that it can often be deployed quickly where diesel gensets or even turbines can't be. And there's nothing wrong with accepting green subsidies when they're there for the taking.

But in the Powercosm paradigm, the 9s come first. And the fuel cells that will add reliability–rather than subtract it–are either going to be big-and-hot, like FuelCell Energy's DFC, or very small indeed, along the lines of the Hockaday cell. As for the middle, follow the engineer who has a perfect PEM in the works (we haven't found one yet), or follow the technology that can deliver perfect hydrogen (we like Proton Energy's). Whatever their other virtues, the rest of the pack isn't close, yet, to building reliability-enhancing machines.

Peter Huber & Mark Mills
August 28, 2000

POWERCHIP UPDATE

As we argued in our inaugural issue in September 1999 ("The Powerchip Paradigm"), digital power begins with the silicon switch – the powerchip–just as demand for digital power begins with the silicon microprocessor – the smartchip. From palmtop to desktop to server, from wireless base station to laser pump to RAID, all bits begin or end their digital journey as electrons, and spend much of their time in transit as the quantum equivalents of electrons, i.e. photons. Digital intelligence–the ordering, routing, transmitting and storing of bits–requires digital power–a supply of electrons as predictable, reliable and steady, as logical and orderly, as the bits themselves.

At the most basic level, powerchips supply the key interface between the inherently disorderly and unreliable Carnot world of diesels, turbines, flywheels, and batteries, and the disciplined, quantum digital world of microprocessors, radios, and lasers–between chaotic Macrocosm on one side, and ordered Microcosm and Telecosm on the other. Standard industry forecasts put the global powerchip industry at $12 billion in sales by 2002; a growth of $3 billion over today's sales. Over 50 percent of all power semiconductors sold will be at the high-power end of this market, which defines the heart of the Powercosm. Standard projections have sales at this end of the market rising at a 20 percent per year. A healthy enough figure, but in our view, far too conservative.

In our April issue ("Powerchips: Burn Silicon") we placed two powerchip companies on our panel –IXYS (SYXI) and International Rectifier (IRF). We also identified the privately held Advanced Power Technologies as one of a small group of companies making powerchips suitable for serving one important part of the powerchip power curve. We noted that the company was privately held, but "with an IPO in the future, we believe."

That IPO (APTI) arrived on August 8. It was a busy week for IPOs–the busiest week since 1995. (Powercosm companies were well represented–Active Power (ACPW), which we had covered in our August issue, went public that week too.) In explaining APTI to potential investors, the company's underwriters compared it to two competitors –IXYS and International Rectifier. In a mature market, more competition might be bad news for investors, but in a market this young, this fecund, and growing this fast, it's simply more opportunity. APTI saw second quarter 2000 sales rise over 50 percent; IXYS and IRF experienced the same magnitude of growth from the demand pressures of the Powercosm. For powerchips, there's still enormous demand growth ahead.

Like IXYS and IRF, Advanced Power has the right stuff. Founded in 1984 in Bend, Oregon, the company has pioneered important developments in the high-power IGBTs that are key building blocks of the Powercosm. It has 17 core U.S. patents (plus one pending) and 8 foreign patents (5 more pending).

As we discussed in the April DPR, switching speed and low energy losses are the most important metrics in the powerchip space, with the key market falling in the middle of the power curve, at 1 kW and above. Advanced Power's chips are fast (critical to handling high power and providing logic functionality), low-loss (vital to minimizing the destructive potential of the inevitable, residual amounts of power absorbed by the switch), and targeted at just the right power levels. Their own new class of IGBTs, designated Thunderbolt,™ hit high-speeds (150 kHz), and handle power levels high enough (0.5 kW) to place them at the low end of the Powercosm sweet spot. Like IRF and IXYS, APTI also produces MOSFETs powerchips of a different architecture that have their own niche in the Powercosm. Among its customers, Advanced Power counts Power One, a top-notch manufacturer of DC silicon power plants. (See June DPR)

APTI's CEO, Patrick Sireta, is a Texas Instruments veteran who joined APTI in 1985, holds a engineering and statistics degrees from Ecole Centrale de Paris. *Bienvenue* to the PowerPanel.

The Power Panel

Ascendant Technology	Company (Symbol)	Reference Date	Reference Price	8/25/00 Price*	52wk Range	Market Cap	Customers
Electron Storage & Ride-Through Flywheels	Active Power (ACPW)	8/8/00	$17***	47 3/4	40 - 57 3/4	$1.8b	Enron, Broadwing, Micron Technologies, PSI Net, Corncast Cable, ABC
	Beacon Power	IPO date pending	TBD	N/A	N/A	N/A	Century Communications, Verizon, SDG&E, TLER Associates, Cox Cable
Hydrogen Generation	Proton Energy Systems **	IPO September	TBD	NA	NA	NA	Matheson Gas, NASA
Distributed Power Generation Microturbines	Capstone Turbine Corp. (CPST)	6/30/00	$16***	82	27 3/8 - 81 15/16	$6.2b	Chevron, Williams ECU, Tokyo Gas, Harbec Plastics
Fuel Cells	FCEL	8/25/00	99 3/4	99 3/4	12 1/16 - 95 1/2	$767m	Santa Clara, MTU, RWE and Ruhrgas (Germany), Bath Iron Works (General Dynamics), Marubeni (Japan), LADWP
Micropower Nano-fuel cells	Manhattan Scientifics (MHTX)	8/25/00	2 3/4	2 3/4	2 - 3 3/8	N/A	Incubator (no customers)
Silicon Power Plants In-the-room DC and AC Power Plants	Emerson (EMR)	5/31/00	59	69 1/16	40 1/2 - 70 3/8	$29.5b	Citicorp, NTC, GTE Wireless, Nokia, Motorola, Cisco, Exodus, Qwest, Level 3, Lucent, etc.)
	Power-One (PWER)	*(see below)*					
Motherboard Power Bricks, High-end DC/DC converters	Power-One (PWER)	4/28/00	68 1/4	155 5/8	9 3/4 - 160	$5.7b	Cisco, Nortel, Teradyne, Lucent, Ericsson
Powerchips: Insulated gate bipolar transistors (IGBTs)	IXYS (SYXI)	3/31/00	6 25/32	37 15/16 †	1 1/2 - 45 3/8	$928m	Rockwell, ABB, Emerson, Still GmbH Eurotherm Ltd. (UK), Alpha Technology
IGBTs	International Rectifier (IRF)	3/31/00	38 1/8	61 3/16	14 11/16 - 65 1/2	$3.8b	Nokia, Lucent, Ericcson, APC, Emerson, Intel, AMD, Ford, Siemens
	Advanced Power (APTI)	8/25/00	22 3/8	22 3/8	15 1/2 - 23 7/8	$176m	Alcatel, Ericsson, ITI, Power-One, Advanced Energy Industries, Emerson
Network Transmission and UPS: High-temperature superconductor	American Superconductor (AMSC)	9/30/99	15 3/8	43 7/8	11 13/16 - 75 1/8	$882m	ABB, Edison (Italy), ST Microelectronics, Pirelli Cables, Detroit Edison, Electricite de France

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 of the month prior to Digital Power Report 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 provide technology assessment services for firms that may have interests in the companies.

** Because this month's Digital Power Report was printed prior to the end of the month, the reference date for the September Report is the last trading day prior to the press date rather than the last day of the month as is the usual practice.*

*** At the time this publication went to press, Proton Energy Systems IPO was scheduled for September 2000.*

**** The offering price on the date of the IPO.*

† *Split adjusted this issue.*