

Direct carbon conversion: progressions of power

BARBARA HEYDORN WITH STEVEN CROUCH-BAKER

Broad commercialization may be a long way off, but direct-carbon fuel cells could one day hold the key to cleaner, more efficient stationary-power generation in plants delivering several hundred megawatts of capacity.



New power generation: in the case of grid-connected stationary-power applications, direct-carbon fuel cells will need to be effective as part of a system that extends from the coal mine to the power line.

WHILE MOST FUEL cells are classified by their electrolyte, a new type of fuel cell is being developed that is best classified by its fuel—carbon. Carbon is an attractive fuel because it is contained in a variety of regionally dispersed and easily accessible resources, including coal, lignite, natural gas, petroleum, biomass and waste materials (such as plastic), or refining by-products such as coke. Unlike hydrogen, which is more frequently used to run fuel cells, carbon and carbon-containing materials are easy to store and transport. What's more, many of the researchers currently developing direct-carbon fuel cells (DCFCs) believe that the systems they are working on will one day be robust enough to use carbon-containing sources such as coal directly in the fuel cell.

If DCFCs progress as those researchers hope, the technology will have dramatic implications through its potential to reduce carbon dioxide (CO₂) emissions and expand the range of resources that can be used to generate electricity in stationary-power systems. Put simply, DCFCs represent a way to convert

carbon's chemical energy to electricity efficiently and without forming by-products associated with conventional combustion—i.e. particulates, nitrous oxides (NO_x), sulphur oxides (SO_x) and mercury (although impurities that exist in coal, such as sulphur, will still exist as part of some waste stream). Generating electricity from coal electrochemically will produce CO₂, a greenhouse gas, but because DCFCs could be significantly more efficient than conventional coal-fired power plants, the emissions could be reduced significantly for each unit of electricity generated. On top of this, some DCFC developers expect to recover the CO₂ in a concentrated stream that can be easily captured and sequestered.

DCFCs: the fundamentals

In a DCFC, the overall reaction based on carbon's complete electrochemical oxidation is $C + O_2 \rightarrow CO_2$. This reaction proceeds via mechanisms that vary with cell design and electrolyte. Electrolytes that researchers are experimenting with include

A closer look at thermodynamic efficiency

The “first law” of thermodynamic efficiency, or the intrinsic maximum energy-conversion efficiency (η), is the ratio between the free energy (ΔG ; the maximum energy that can convert to electrical work) and enthalpy (ΔH ; the total chemical energy stored in the fuel) of the cell reaction. Because $\Delta G = \Delta H - T\Delta S$, where T is the absolute temperature and ΔS is the change in entropy, one can alternatively write η as: $\eta = \Delta G/\Delta H = (\Delta H - T\Delta S)/\Delta H = 1 - (T\Delta S/\Delta H)$.

In situations where $\Delta S > 0$ and $\Delta H < 0$, one can obtain efficiencies of more than 100% as long as an external source of heat is provided. In essence, heat converts to power without facing the theoretical maximum efficiency of a Carnot-cycle heat engine. The maximum efficiency of a Carnot-cycle heat engine derives from $\eta = (T_1 - T_2)/T_1$, where T_1 and T_2 are the temperatures of a warmer gas at the inlet and a cooler gas at the outlet, respectively. Under these circumstances, η will always be less than 1.

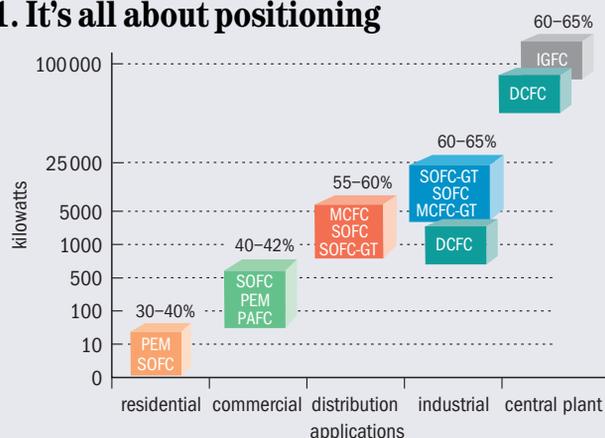
solid state, molten carbonate and sodium hydroxide (NaOH). Depending on the electrolyte, oxygen, carbonate or hydroxide ions participate in the oxidation–reduction reaction.

Conventional coal-fired power plants burn coal to convert coal’s chemical energy to thermal energy. The thermal energy is used to create steam, which powers turbines that use kinetic energy to generate electricity. Clearly, converting coal’s chemical energy directly to electrical energy in a DCFC should be much more efficient, especially since DCFCs are a particularly efficient type of fuel cell. A fuel cell’s total efficiency is a product of many factors. Three of the most important are thermodynamic (or theoretical) efficiency, fuel use and voltage efficiency. DCFCs have a significant advantage over other fuel cells in terms of their thermodynamic efficiency, are likely to perform better than alternatives in terms of fuel use, and perform as well as other fuel cells in terms of voltage efficiency.

In a DCFC, carbon’s complete oxidation to gaseous CO_2 is accompanied by almost no entropy change, which means that the thermodynamic efficiency is close to 100% (see “A closer look at thermodynamic efficiency”, above). In conventional fuel cells, such as solid-oxide fuel cells (SOFCs) fuelled with gaseous hydrogen, $\Delta S < 0$ and the theoretical efficiency is < 1 . A hydrogen-fuelled SOFC, for example, has a theoretical efficiency limit of 70% at high temperatures – i.e. about 70% of the chemical energy converts to electricity, with the remaining 30% converting to heat. In contrast, virtually all the chemical energy can convert to electrical energy in a DCFC.

Fuel utilization refers to the fraction of the fuel (for example, hydrogen or carbon) that converts to electrical energy once it enters the fuel cell. Pure hydrogen fuel entering a high-temperature fuel cell rapidly converts to its reaction product, steam. As the steam accumulates in the cell, the ability of the remaining diluted hydrogen to produce electrical energy (its chemical potential) decreases. One cannot convert 100% of the hydrogen to fuel at practical rates; fuel-cell developers find that 80% use is often the point of diminishing returns.

1. It’s all about positioning



Source: Dan Rastler, EPRI.

Estimated size and electrical efficiency (lower heating value) of various fuel-cell technologies. In the long term, direct-carbon fuel cells (DCFCs) are expected to be competitive with solid-oxide fuel cells (SOFCs) and molten-carbonate fuel cells (MCFCs) in a range of stationary-power markets up to several hundred megawatts capacity. Target applications for DCFCs may exist in low-cost power, combined heat and power, and peak shaving/load-management applications.

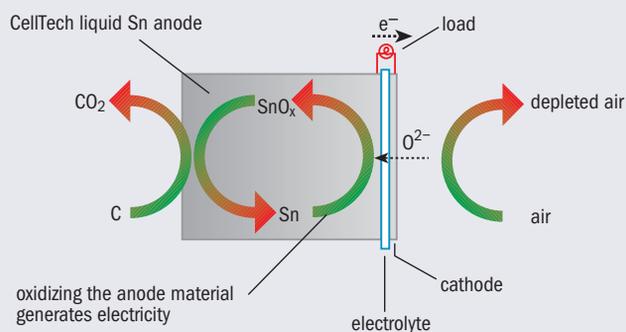
In the case of carbon, all the fuel entering the cell may convert to electric power at a fixed voltage, because the reaction product, CO_2 , is in a separate gas phase and at a constant pressure – i.e. its presence does not diminish the chemical potential of the carbon. In practical terms, the fuel utilization may not be quite 100% because, depending on the cell design, there could be some energy penalties associated with ensuring that the carbon fuel remains in contact with the electrode interface. Moreover, at high temperatures (for example, in excess of 850°C), some of the carbon may be chemically converted to CO .

In practical use, all fuel cells tend to operate at about 80% voltage efficiency because of kinetic losses, cell resistance and trade-offs between fuel-cell efficiency and cost. For example, cell voltage and fuel-cell efficiency could be increased by decreasing current density, but as the current density decreases, the active cell area must increase to obtain the necessary power, which in turn increases capital costs.

Progressions of power in DCFCs

The DCFC concept is not new. William W Jacques, a US electrical engineer and chemist, described a DCFC in 1896 in US Patent 555511 for a “Method of converting potential energy of carbon into electrical energy”. Jacques used coke electrodes in a molten NaOH electrolyte. There were problems, though, including the cost of making carbon electrodes and electrolyte degradation as a result of ash in the fuel and interactions between the fuel and the electrolyte. In addition, the carbon anode also served as the fuel source, and the NaOH electrolyte was consumed in the reaction when it reacted with the CO_2 product to form Na_2CO_3 . Because an operator would need to

2. A carbon-fuelled battery or fuel cell



Source: Thomas Tao, CellTech.

CellTech's system can function as a primary battery, secondary battery or a fuel cell. In battery mode, oxygen ions cross the ceramic electrolyte (typically yttria-stabilized zirconia, or YSZ) to react with molten tin, after which the resultant metal oxide dissolves into the liquid-metal anode. This reaction can continue until the liquid-metal anode is completely converted to oxide. To "recharge" the system, or operate it as a fuel cell, carbon fuel is added to the anode to reduce the tin oxide so that it is ready to react with oxygen.

shut down the entire device periodically to refuel and replace the electrolyte, it ran as a battery and not as a fuel cell. In practical terms, the cell was expensive (in part because of the high cost of NaOH). Furthermore, when the energy required to make NaOH is taken into account, the cell was very inefficient.

Researchers had trouble duplicating Jacques' results until the 1970s, when a series of studies at SRI International (Menlo Park, California) verified that complete electrochemical oxidation of carbon can generate electricity. Although the SRI group proved the concept and added several innovations to the DCFC approach, the system was still impractical. In the 1990s, several other organizations began working on DCFCs and related areas. The latest advances in materials science, fuel cells and basic electrochemistry have given researchers hope that the technology will be commercially viable in limited small-scale applications within five years, and in large-scale applications within 20 years.

The Fuel Cell Seminar in Palm Springs, California, in November last year featured a special workshop on direct-carbon conversion. Organized by Dan Rastler, technical director at the Electric Power Research Institute (EPRI; Palo Alto, California), the session featured an invited panel that included US researchers, organizations involved in commercializing direct-carbon conversion technologies and an electric utility.

Rastler kicked things off with an overview of the status of commercially available stationary fuel-cell power systems and an introduction to DCFCs. He outlined two key drivers for DCFC technology. First, the technology provides a new option to the power industry, which is under increasing pressure to reduce emissions while continuing to provide reliable, afford-

Advanced power generation

Today's coal-fired power stations produce many undesirable emissions, including oxides of nitrogen and sulphur, particulates and greenhouse gases such as CO₂. New coal-utilization technologies, such as integrated-gasification combined-cycle (IGCC) systems, promise to lower emissions and increase efficiency. IGCC is a combination of two key technologies: coal gasification, which uses coal to create a clean-burning gas (syngas); and combined cycle, which is the most efficient, commercially available method of producing electricity.

- **Coal gasification:** the gasification portion of the IGCC plant produces a clean coal gas (syngas) which fuels the combustion turbine. Coal is combined with oxygen in the gasifier to produce the gaseous fuel, mainly hydrogen and CO. After clean-up, the coal gas is used in the combustion turbine to produce electricity.
- **Combined cycle:** this design consists of a combustion turbine/generator, a heat-recovery steam generator and a steam turbine/generator. The exhaust heat from the combustion turbine is recovered in the heat-recovery steam generator to produce steam. This steam then passes through a steam turbine to power another generator, which produces more electricity. Combined cycle is more efficient than conventional power-generating systems because it reuses waste heat to produce more electricity.

In an integrated-gasification fuel-cell (IGFC) architecture, the combined-cycle power system is replaced by a fuel-cell generator.

able power. Secondly, the technology has the potential to provide a host of benefits to the power industry in terms of lower cost, higher system efficiency, reduced complexity, modular structure, improved CO₂ management, potential new applications and the opportunity to use widely available, cheap domestic fuels such as coal and petroleum coke.

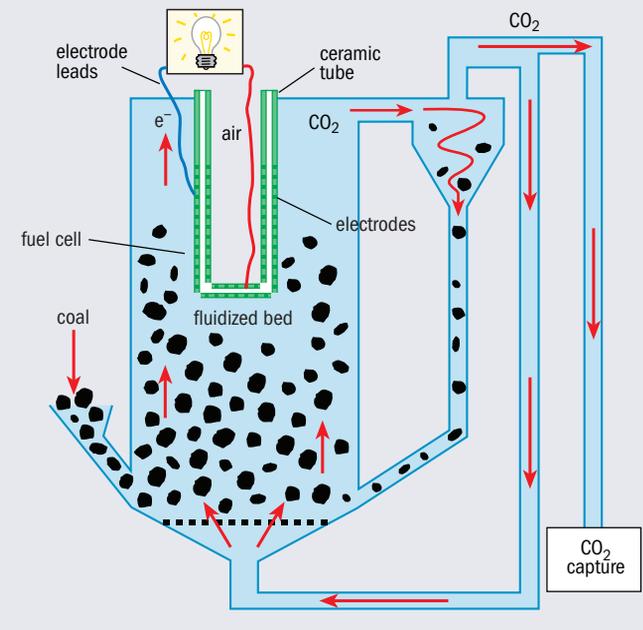
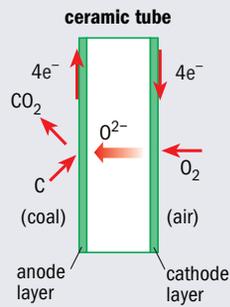
Ultimately, DCFCs are expected to be competitive with SOFCs, molten-carbonate fuel cells (MCFCs) and even integrated-gasification fuel cells (IGFCs), such as those under development by GE Energy's Hybrid Power Generation Systems and by Siemens Power Generation (see "Advanced power generation", above). Specific applications for DCFCs may exist in low-cost power, combined heat and power, and peak shaving/load-management applications (in which DCFCs help utilities to balance supply and demand during periods of high electricity demand).

Rastler stressed that for DCFC systems to be competitive, however, they must present an attractive alternative not only to today's technologies, but to technologies that will be available when DCFCs are eventually commercialized (figure 1). For example, the US Department of Energy (DOE) roadmap for coal-based fuel-cell systems has put aggressive targets in place, which it expects to achieve with IGFC technology. The DOE's Fuel Cell Coal-Based Systems programme wants to hit 50% efficiency (higher heating value), 90% CO₂ capture, and testing technology that is scaleable to >100 MW over the 2011–2015 period. Meanwhile, the Coal Utilization Research Council

3. Technology transfer

CCE describes its DCFC approach, which is based on intellectual property licensed from Stanford University, as combining SOFC and fluidized-bed technologies. The company is working with a number of development partners in China.

Source: Alvin Duskin, CCE.



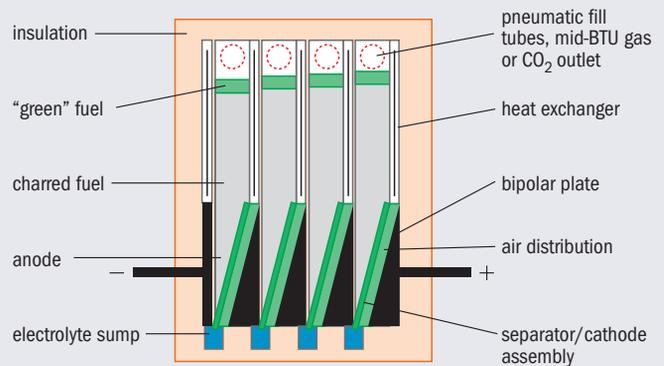
(CURC) roadmap through 2020, which is a consensus roadmap representing the goals of CURC, EPRI and DOE, calls for 100 MW systems that are 60% efficient by 2020.

Industry perspectives on DCFCs

Another keynote speaker at the Palm Springs workshop, John Schneider, a technology consultant with American Electric Power (AEP; Columbus, Ohio), presented an industry perspective on how DCFCs might contribute to future electricity generation. AEP is the largest US electricity generator and the largest coal user. According to Schneider, barring a re-emergence of nuclear energy, coal is the only viable near-to mid-term energy-source option that is abundant (with a >250 year supply at today's consumption levels), affordable (at \$1.2–\$2.0/million British thermal units, or MMBtu) and domestic. That said, environmental constraints mean that the search is on for cleaner, more efficient utilization.

For utilities considering new baseload generation capacity in the near term, available technologies include traditional pulverized-coal plants, natural-gas combined-cycle (NGCC) plants and IGCC plants. In recent years, natural-gas prices have risen dramatically, from an average of about \$3.9/MMBtu in 2002 to about \$6.8/MMBtu in 2005, making NGCC plants

4. Self-feeding cells: a technology platform



Source: John Cooper, LLNL.

Researchers at LLNL have designed a self-feeding cell that can be refuelled pneumatically with cleaned coal. The cell incorporates a pyrolysis step that produces hydrogen (which can be used as fuel for a conventional fuel cell or as a chemical reactant), low-molecular-weight hydrocarbons and a non-agglomerating char that is reactive and sufficiently conductive for use in the DCFC.

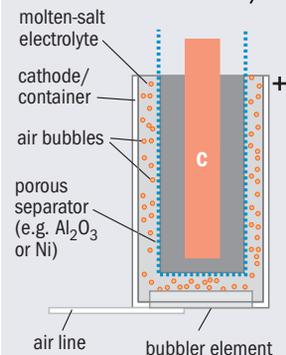
uneconomical today. Similarly, the increase places additional challenges on the economics of natural-gas-powered SOFCs.

In AEP's opinion, IGCC technology, while relatively new, is the near- to mid-term alternative to underpin coal-fired plants that are cleaner and more efficient than those based on conventional technologies; AEP expects to bring on-line a 600 MW IGCC unit by 2010. Technologies such as IGCC have the potential to change what future energy utilities may look like. In addition to electricity, they may become providers of syngases, chemicals and heat. Still, there would be plenty of pull for a technology that offered double the efficiency of conventional technologies, low emissions and carbon capture in a sequestration-friendly manner. The bottom line is that if DCFCs can fulfil their promise, they present an important alternative in the quest to develop cleaner and more efficient central power plants.

Following on from AEP, five researchers presented overviews of the work they are doing on DCFC systems. Each of the researchers is pursuing a unique technical approach, using various electrolytes – including yttria-stabilized zirconia (YSZ), mixed carbonates and mixed hydroxides – and various anode configurations. There's a common goal, however: the promise of increased efficiency relative to conventional power plants and the elimination of combustion by-products.

• *CellTech Power*: Thomas Tao, chief technology officer at CellTech Power (Westborough, Massachusetts), founded the company in 1998 to commercialize DCFC technology. To date, Tao and his team have received \$12 m in three rounds of venture-capital financing, plus several million dollars of government funding. Initially, the company was focused on distributed generation applications, though that focus has currently shifted to the use of plastic waste for portable power

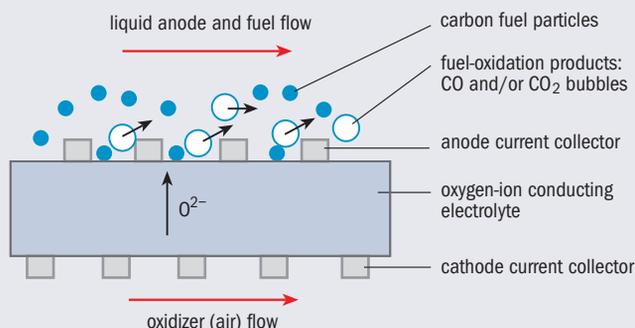
5. Carbon anode, carbon fuel



Source: Ned Patton, SARA.

SARA has been working on hydroxide-electrolyte-based carbon fuel cells for around 10 years. The configuration here uses carbon as both the anode and the fuel. The cathode reaction is: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. The anode reactions are: $C + 6OH^- \rightarrow CO_3^{2-} + 3H_2O + 4e^-$ and $C + 2CO_3^{2-} \rightarrow 3CO_2 + 4e^-$

6. The secrets of circulation



Source: Iouri Balachov, SRI International.

SRI International's approach combines advances in SOFC and MCFC technology with a circulating liquid-molten-salt anode that incorporates the carbon-containing fuel. Researchers are examining molten salts, including molten carbonate, and using a YSZ electrolyte and a lanthanum strontium manganate cathode.

in a project funded by the US Defense Advanced Research Projects Agency (DARPA).

CellTech uses a liquid anode in a configuration that can function as a primary battery, secondary battery or a fuel cell (figure 2, p17). In battery mode, oxygen from air enters at the cathode side. Oxygen ions cross the ceramic electrolyte (typically YSZ) to react with molten tin. After reacting with the tin, the metal oxide dissolves into the liquid-metal anode. This reaction can continue until the liquid-metal anode is completely converted to oxide. To "recharge" the system, or operate it as a fuel cell, carbon fuel is added to the anode to reduce the tin oxide so it is ready to react with oxygen. In 2004, CellTech demonstrated a fully integrated 2.3 kW alpha system that operated for 2300 h on hydrogen produced from natural gas.

Right now, CellTech is pursuing applications in the portable power range (10–500 W) – i.e. lower capital investment and shorter development cycles. Tao expects the military to be the company's first market, with devices in the 20–500 W range operating on waste plastic.

- **Clean Coal Energy:** Alvin Duskin, chief executive officer of Clean Coal Energy (CCE), explained that the company's DCFC approach is based on US Patent 5376469 (granted 27 December 1994). That patent is held by Stanford University and licensed to CCE; Turgut Gür, one of the two inventors listed on the patent, is CCE's CTO. Duskin described the technology as combining SOFC and fluidized-bed technologies (figure 3). Recently established, CCE claims to have raised about \$300 000 and to have about \$600 000 in the pipeline. The company is working with various organizations in China, but did not have an operating system at the time of the Fuel Cell Seminar.

- **Lawrence Livermore National Laboratory:** John Cooper of Lawrence Livermore National Laboratory (LLNL; Livermore, California) is working with a cell design that uses a cathode similar to those in conventional MCFCs, a nickel or high-fired graphite anode and porous ceramic separator. The anode reaction is carbon and carbonate ions forming CO_2 and electrons. At the cathode, oxygen, CO_2 and electrons from the anode form carbonate ions. The separator holds the melt in place and allows the carbonate ions to migrate between the two compartments.

The LLNL team has also examined the relationship between

the nanostructure of carbons and their electrochemical reactivity in molten salts by correlating significant differences in the 3D atomic structure of carbon fuels with their electrochemical reactivities. One of the team's key findings is that the more disordered the carbon atoms, the more easily they yield electrons – i.e. cell efficiency and power depend on disorder more than on carbon purity or even aggregate surface area.

The scientists found that extremely fine (10–1000 μm) carbon particles with a high degree of structural disorder on the 30–100 nm scale ("turbostratic" carbon) work best. These turbostratic carbon particles, when mixed with molten carbonate to form a dense paste or slurry, operate like rigid electrodes when the melt is brought into contact with an inert metallic screen or graphite current collector. Cooper reports that various de-ashing processes, such as those developed by UCC Energy (Sydney, Australia), the New Energy and Industrial Technology Development Organization (NEDO; Tokyo, Japan) and South African Synthetic Oil Limited (SASOL; Johannesburg, South Africa) can yield fuel at competitive costs (about \$2–3/MMBtu).

Cooper and his colleagues have demonstrated the technology in a number of small, experimental cells with reaction areas between 3 and 60 cm^2 . The team is currently testing a five-cell, self-feeding bipolar stack using pure turbostratic carbon as fuel. As a potential commercial technology platform, LLNL has also designed a self-feeding cell that can be refuelled pneumatically with cleaned coal (figure 4). The cell incorporates a pyrolysis step that produces hydrogen (which can be used as fuel for a conventional fuel cell or as a chemical reactant), low-molecular-weight hydrocarbons and a non-agglomerating char that is reactive and sufficiently conductive for use in the DCFC.

Cooper reports that in repeated tests the cells deliver up to 0.1 W/ cm^2 continuously and are 80% efficient at 80 mW/ cm^2 . The cells have been operated for nearly a week with periodic refuelling

Different takes on DCFC research

Organization (location)	Involvement	Remarks
Agency of Industrial Science and Technology (Tokyo, Japan)	Research	In US Patent 6183896, researchers Teruhisa Horita, Natsuko Sakai, Tatsuya Kawada, Harumi Yokokawa and Masayuki Dokiya disclose an SOFC and a carbon direct-oxidizing-type electrode for the cell. The fuel cell comprises vanadium carbide, which is used as the fuel electrode. The vanadium carbide and a carbon-series fuel are used in the fuel electrode.
Brown University (Providence, RI)	Research	Joseph Calo received DOE funding to examine "Spouted bed electrodes for DCFCs".
Duke University (Durham, NC)	Research	Hadley Cocks and Neal Simmons received DOE funds to examine "Carbon ionic conductors for use in novel carbon-ion fuel cells".
HCE (Oakton, VA)	Private company to commercialize DCFC and related technologies	HCE formed in July 2003 to commercialize an integrated-plasma fuel-cell (IPFC) process that Meyer Steinberg proposed. IPFC integrates two technologies: a carbon-black manufacturing technology – the hydrogen-plasma black reactor – and a DCFC.
Technische Universiteit Delft (Delft, the Netherlands)	Research	Kas Hemmes and other researchers have examined DCFCs based on carbonate electrolytes.
University of Akron (Akron, OH)	Research	Steven Chuang received DOE funding to examine a "V ₂ O ₂ -Pt catalyst for carbon oxidation in DCFCs".
University of Colorado at Boulder (Boulder, CO)	Research	Alan Weimer is developing a solar-thermal transport reactor that thermally dissociates methane, producing hydrogen gas and nanosize carbon-black powder. A graduate student is investigating this powder's reactivity in a direct-oxidation-type fuel cell.
Virginia Polytechnic Institute and State University (Blacksburg, VA)	Research	Alan Kornhauser received DOE funding to examine "Modelling and design for a DCFC with entrained fuel and oxidizer".

Source: SRI Consulting Business Intelligence

and little change in performance. To enhance the technology, the researchers are examining a new cell configuration and developing ways to reduce corrosion of the metal-clad bipolar plates, improve the cathode structure and current-collection technique, and control separator wetting. At the same time, the team is addressing the energy and power losses that occur within the electrode structure with the aim of doubling the power output.

The next step is to scale up the demonstration unit from the 3 W experimental cell to a stackable 75–100 W engineering module with 750 cm² of active area. Starting in 2005, Cooper's team has been receiving support from Contained Energy (Shaker Heights, Ohio) towards commercialization of the technology.

- *Scientific Application & Research Associates*: SARA (Cypress, California) was formed in 1989 to carry out R&D in a variety of areas, including novel energy production. In the mid-1990s, SARA began research on hydroxide-electrolyte-based carbon fuel cells and in March 2001 received US Patent 6200697 for its work. Ned Patton described SARA's process, which uses carbon as both the anode and the fuel. SARA has also tested both potassium and sodium salts as the electrolyte and both porous ceramic (zirconia) and metal (nickel) separators (figure 5, p19).

The team has ongoing experiments to determine the optimum separator material and porosity; examine issues associated with contaminants in coal and their potential impact on the electrolyte; extend the system's operating life; and develop an optimal stack configuration for scale-up. Initially, SARA is developing a stackable fuel-cell design capable of generating

10–20 W. In terms of commercial applications, the company is evaluating the system as a carbon battery at utility substations.

- *SRI International*: Iouri Balachov, with the not-for-profit research institute SRI International, described an approach that combines advances in SOFC and MCFC technology with the conceptual breakthrough of using a circulating liquid-molten-salt anode that incorporates the carbon-containing fuel (figure 6, p19). The team is examining various molten salts, including molten carbonate, and using a YSZ electrolyte and a lanthanum strontium manganate cathode. To date, a variety of fuels has been tested, including biomass, coal from the Powder River Basin (PRB), tar, coke containing 6% sulphur, acetylene black, plastic and mixed waste. Using conventional PRB coal without pretreatment, SRI has achieved power densities >100 mW/cm², which is comparable to the power densities achieved by commercial MCFC plants operating on natural gas.

The team is working to improve the power density of its system to about 200 mW/cm² and to increase the cell's operating life. Having demonstrated its novel concept at a single-cell level in the autumn of 2004, SRI is now examining issues of system integration and scale-up. To date, the work has been funded with internal investment from SRI International.

- *Alternative DCFC approaches*: Although many of the leading DCFC researchers were able to participate in the Fuel Cell Seminar, there are other organizations conducting significant R&D in this field (see "Different takes on DCFC research", above). The work being done by Kas Hemmes at the Technische

Universiteit Delft, the Netherlands, for example, makes use of an alternative mechanism for electrochemically reacting carbon and oxygen. Partial electrochemical oxidation proceeds according to the following mechanism: $C + \frac{1}{2}O_2 \rightarrow CO$. This reaction allows the direct conversion of heat to electricity, which can increase the efficiency to more than 100% as long as heat comes from an external source. Although most research emphasizes cells based on complete oxidation, Hemmes has proposed using solar heat to drive the conversion of C to CO and electricity. The CO can then be used in an SOFC, burned to provide heat or reacted with water to form hydrogen and CO₂.

In addition to work on the DCFC itself, other teams are active in work relating to fuel preparation. For example, CENfuel (Charleston, West Virginia), the University of Kentucky (Lexington, Kentucky) and West Virginia University (Morgantown, West Virginia) are all examining coal preparation techniques that may make DCFCs more practical.

A long way to go

One stumbling block to communicating the current status and future potential of DCFCs is the lack of clear performance metrics. What's more, because the technology is so new, substantial work is needed to identify potential commercial markets and optimum fuels, to scale up the technology and to establish market-specific performance requirements. To date, most researchers have focused on workable cell designs. Ultimately,

though, DCFCs must be effective as part of a system that extends from the mine to the power line (in the case of grid-connected stationary-power applications).

Specific areas of concern include determining to what extent coal may or may not need pretreatment and what happens to the contaminants in coal (whether they are removed before entering the fuel cell or after). Equally, coal contains volatile components, so the DCFC system must be designed so that the coal can be introduced to the hot fuel cell without the explosive release of volatile components.

While CellTech is alone in focusing on portable applications that it may be able to develop within a two to five year time-frame, most of the other research teams are focusing on systems for stationary-power generation. Although the market potential is enormous, this application will in all likelihood require 15–20 years before systems are ready for broad commercialization. To date, DCFC technology has received limited government support. That support will need to grow in the near to medium term, given the challenges of finding industry support at this early stage of technology development. ●

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Steven Crouch-Baker, a senior materials scientist at SRI International, also helped in the drafting of this article. Further information on SRIC-BI's fuel-cell programme can be found at www.sric-bi.com.

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