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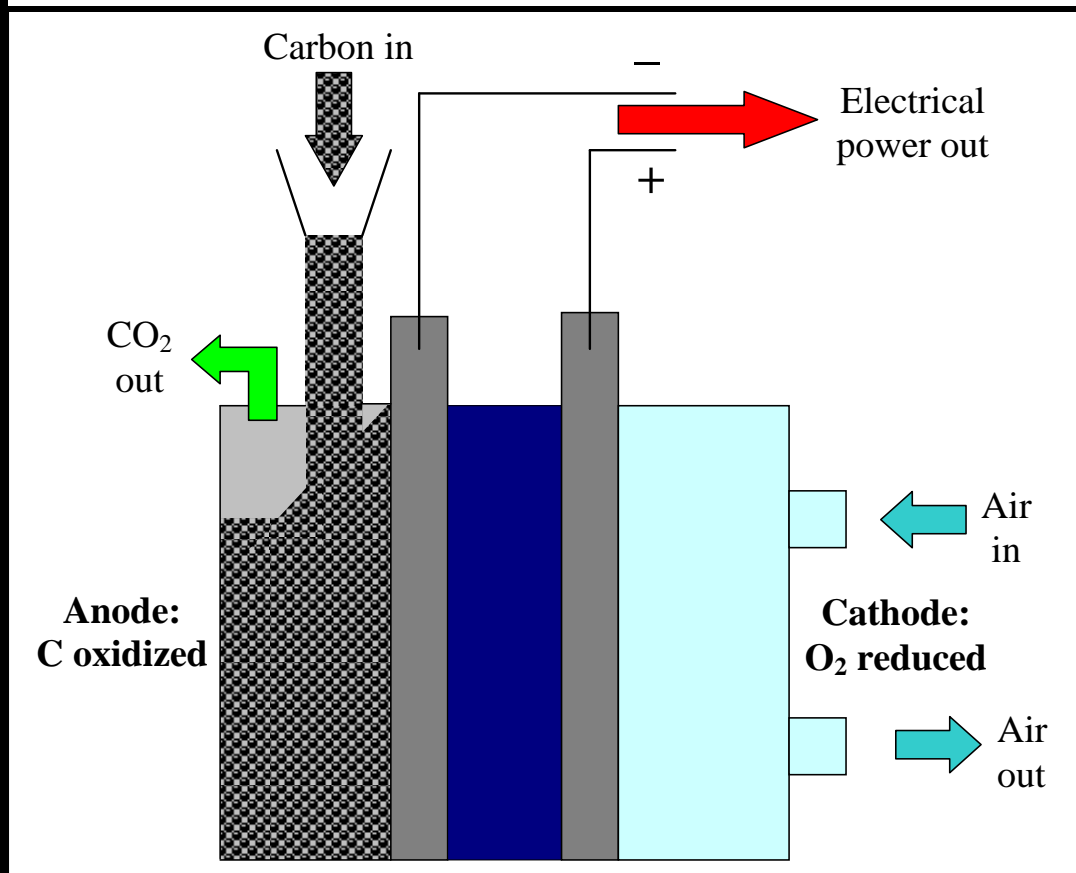Development Center

ERDC-CERL Fuel Cell Program

Direct Carbon Fuel Cells:
Converting Waste to Electricity

Ronald H. Wolk, Scott Lux, Stacy Gelber,
and Franklin H. Holcomb

September 2007

Carbon in

CO_2 out

Electrical power out

−

+

Air in

Air out

**Anode:
C oxidized**

**Cathode:
O_2 reduced**

Direct Carbon Fuel Cell Configuration
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Direct Carbon Fuel Cells: Converting Waste to Electricity

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Final Report

Abstract: The U.S. Army has policies to minimize production of waste materials, maximize recycle of waste materials, and minimize energy consumption on its installations. A beneficial way to implement these policies is to convert paper, wood, vegetation, and Municipal Solid Waste (MSW) fractions into a carbon-rich feed stock by pyrolysis to fuel Direct Carbon Fuel Cells (DCFCs). DCFCs potentially offer a unique approach for the direct conversion of biomass-derived, carbon-rich solid fuel to electricity at very high conversion, with the production of a CO_2-rich flue-gas. This work gathered information on the quantities of waste material available at U.S. Army installations from installation reports and from the U.S. Army Solid Waste Annual Reporting System (SWARS) database, then estimated the amount of electricity that DCFC technologies could generate from those wastes, and finally compared those amounts with the current average annual electrical loads at the 10 largest Army installations.

Executive Summary

The U.S. Army has policies in place to minimize production of waste materials, maximize recycle of waste materials, and minimize energy consumption on Army installations. Paper, wood, vegetation, and fractions of Municipal Solid Waste (MSW)—all waste materials generated on Army installations—can be converted into a carbon-rich feedstock by pyrolysis.

Direct Carbon Fuel Cells (DCFCs) offer a unique approach to directly converting this feedstock (a biomass-derived, carbon-rich solid fuel) directly to electricity at very high conversion, likely to be about 65 percent, with the production of a CO_2-rich flue-gas. Although DCFC technology is not yet a "mature" technology (it is at an early stage of development), several vendors are currently exploring different technical approaches to implementing DCFCs. It is as yet uncertain if any of them will succeed in producing a technically successful product at their cost targets of about $1500/kW. A major R&D investment spanning at least the next decade would be required to bring this technology to commercialization.

This study estimated the quantities of solid waste material available at the studied installations based on installation reports, data in the U.S. Army SWARS (Solid Waste Annual Reporting System) database, and other sources. The amount of electricity that could be generated from those wastes in DCFC was calculated and compared with the current average annual electrical loads at those installations.

Table ES1 lists the percent of electrical demand that could be produced from waste generated at the 10 largest Army installations in the United States. At nine of the 10 largest Army installations studied, waste generation would support the production of 8–15 percent (an average of 12 percent) of the installations' annual average electricity consumption. At the tenth installation, waste generation could produce 33 percent of the installation's annual average electricity demand. Additional vegetation-based energy could be produced on installation land. The economics of these "energy plantations" were not examined.

Table ES1. Percent of electrical demand that could be produced from waste generated at the 10 largest Army installations in the United States.

Rank by Base Population	Facility	Electrical Demand that Could Be Produced from Waste
1	Fort Bragg, NC	33%
2	Fort Hood, TX	15%
3	Fort Campbell, KY	11%
4	Fort Benning, GA	8%
5	Fort Lewis, WA	11%
6	Fort Leonard Wood, MO	10%
7	Fort Jackson, SC	14%
8	Fort Sill, OK	13%
9	Fort Knox, KY	15%
10	Fort Stewart, GA	11%

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Preface

This study was conducted in collaboration between U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) and the Department of Energy (DOE), Office of Fossil Energy through the Interagency Agreement DE-AI01-05FE69134, "Research in Advanced Energy Conversion Technology." The technical monitors were Victor Der and Samuel Biondo, USDOE-HQ (FE-22).

The work was performed by the Energy Branch (CF-E), of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL principal investigators were Scott Lux, Stacy Gelber, and Franklin Holcomb. This work was executed by Wolk Integrated Technical Services under Contract No. W9132T-06-P-0063. Ronald Wolk is associated with Wolk Integrated Technical Services. Dr. Thomas Hartranft is Chief, CEERD-CF-E, and L. Michael Golish is Chief, CEERD-CF. The associated Technical Director was Martin J. Savoie, CEERD-CVT. The Director of CERL is Dr. Ilker R. Adiguzel.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Richard B. Jenkins, and the Director of ERDC is Dr. James R. Houston.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
British thermal units (International Table)	1,055.056	joules
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
ounces (mass)	0.02834952	kilograms
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (force)	8,896.443	newtons
tons (force) per square foot	95.76052	kilopascals
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
yards	0.9144	meters

1   Introduction

1.1   Background

1.1.1   Direct Carbon Fuel Cell Technology

Direct Carbon Fuel Cells (DCFCs) have begun receiving attention as an additional type of fuel cell. The Electric Power Research Institute has completed some initial assessments and concluded that the potential is high, but the technology is still at very early stages of development and further experimental and system analysis work is necessary.

Conventional fuel cells typically operate on gaseous fuels. The fuel (natural gas, propane, alcohol, etc.) is reformed to a hydrogen syngas, which is fed into the fuel cell stack. The DCFC, however, can operate directly on solid carbon fuel such as coal, biomass, or organic waste. Table 1 shows a general comparison of the typical fuel cells to a DCFC. At high temperatures (>600 °C), this fuel is electro-oxidized to CO_2 at the anode compartment creating electricity.

The benefit of converting solid carbon directly to electricity enables the efficiency to be around 80 percent, which is about twice the efficiency of a conventional steam power plant. This increased efficiency results in a beneficial payoff for DCFC development, as well as a reduction of CO_2 emissions to about one-tenth of that of a coal firing power plant (Cao 2007).

As a fuel, charcoal produced from waste materials offers many benefits. It is inexpensive to produce from biomass, and easy to store. Charcoal is readily available to consumers worldwide from compacted beds with high-energy density particles. When combusted correctly, charcoal does not burden the atmosphere with CO_2 emissions, and does not contribute to climate change. In contrast with fossil fuels, charcoal has no mercury, almost no sulfur, low nitrogen, and produces very little ash. It has high electrical conductivity, a large surface area, and many bonds that enable it to be very reactive at relatively modest temperatures (Nunoura 2007).

Table 1. Operating characteristics of conventional fuel cells vs. DCFCs.

	PEMFC	PAFC	MCFC	SOFC	DCFC
Electrolyte	Polymer	Phosphoric acid	Molten carbonate salt	Ceramic	Fused KNO_3
Operating Temperature	80 °C (175 °F)	190 °C (375 °F)	650 °C (1200 °F)	1000 °C (1830 °F)	700 °C (1110 °F)
Fuel(s)	H_2 reformate	H_2 reformate	$H_2/CO/$ reformate	$H_2/CO_2/CH4$ reformate	Solid carbon
Reforming	External	External	External / internal	External / internal	Not necessary
Oxidant	O_2/air	O_2/air	CO_2/O_2/air	O_2/air	Humidified air
Efficiency (HHV)	30-35%	40-50%	50-60%	45-55%	80%

1.1.2 Motivation for Army Installations

Army installations are essential for the development of operational capabilities and readiness to serve and protect the nation and its interests. Installations are small cities with a full spectrum of facility types and utility requirements that use large amounts of energy. U.S. Army ERDC-CERL studied energy trends and their implications for Army installations (Westervelt 2005). The Army Assistant Chief of Staff of Installation Management (ACSIM) subsequently published the Army's Energy and Water Management Strategy for Installations (HQDA 2005). The Army has stated goals to minimize the net amount of solid waste generated by its installations by maximizing the amount of that waste that is recycled (Marelich 2006, HQUSACE 2002). Specific Army goals for reducing energy consumption at its facilities are to:

- eliminate energy waste in existing facilities
- increase energy efficiency in new construction and renovations
- reduce dependence on fossil fuels
- conserve water resources
- improve energy security (Fournier 2005).

The use of Direct Carbon Fuel Cells (DCFCs) to convert carbon-rich solid wastes to electricity can potentially address two of these goals—by reducing dependence on fossil fuels and improving energy security." DCFCs theoretically have the unique ability to convert the chemical energy in solid carbon particles directly to electricity in single cell systems with (an experimentally verified) efficiency of about 80 percent. This contrasts markedly with today's large scale pulverized coal-fueled combustion power plants, which convert the chemical energy contained in coal indirectly to electricity at 30–40 percent efficiency. That indirect method, which provides more than 50 percent of the electricity now generated in the United

States, first burns coal to produce heat, then uses that heat to produce steam, and finally passes that steam through a steam turbine to turn the shaft in an electrical generator to produce electricity. Biomass-fueled combustion power plants have even lower efficiencies, of about 25 percent, because of the high moisture content of the fuel compared to coal, and the low inherent efficiency of the overall steam cycle (EPRI).

The overall process of producing electricity in a DCFC from carbon-rich waste gains efficiency by its simplicity; it involves only two steps: (1) drying (and/or pyrolysis), [*] and (2) feeding the resulting fuel directly to the DCFC. Drying and/or pyrolysis of the waste fuels is required to create a carbon-rich particulate solid that can be fed to the DCFC fuel cell to produce power. The choice between drying or pyrolyzing the biomass before feeding it to the DCFC will depend on whether the energy contained in the waste gases resulting from pyrolysis of the dried biomass within the DCFC can be recovered efficiently, and whether the DCFC can be designed in a manner so that it is not fouled by the light gases and tars generated.

However DCFC technology is not yet a "mature" technology. It is at an early stage of development, and several vendors are currently exploring different technical approaches to implementing DCFCs. DCFC developers appear to favor fuels that are essentially pure carbon particles, with little inherent moisture, ash, sulfur, and nitrogen. Waste paper products, vegetation, structural wood, and a fraction of Municipal Solid Waste (MSW) can be converted into the type of fuel most highly valued by DCFC vendors by drying and pyrolysis of these waste materials.

The 10 largest Army installations in the United States are essentially small cities with total populations ranging from about 20,000 to 50,000 individuals including Army personnel, contractors, and civilian employees. Such large Army installations consume a substantial amount of electrical energy and produce a substantial amount of waste. This project focused on providing an initial assessment of the feasibility of converting the carbon-rich components in waste to a form that is feasible to feed to a DCFC to produce electricity. The quantities of solid waste material available at the 10 largest Army installations was estimated based on installation reports, data in the U.S. Army SWARS (Solid Waste Annual Reporting System) database, and other sources. The amount of electricity that could be gener-

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[*] Pyrolysis is loosely defined as heating in the absence of air.

ated from those wastes in DCFC then calculated and compared with the current average annual electrical loads at those installations.

1.2 Objectives

The objective of this project was to assess whether DCFCs have the potential to be used at large Army installations as part of a strategy to increase energy efficiency.

1.3 Approach

Key personnel from the vendor teams and R&D institutions that are currently developing DCFC technology participated in a workshop organized by Electric Power Research Institute (EPRI) in Palo Alto, CA on 29-31 August 2006. A technical panel evaluated each of the technology platforms and some of the highlights of this workshop are presented in this report.

In addition to collecting data from the U.S. Army Solid Waste Annual Reporting System (SWARS), several Army base personnel were contacted to gather information on the quantity of waste material available at each site. This information was used to estimate the amount of electricity that could be generated by using those wastes as an input fuel for DCFCs.

This study gathered information from reports generated by U.S. Army Installation personnel of the quantities of waste material available at the bases, from the U.S. Army SWARS (Solid Waste Annual Reporting System) data base, and extrapolated missing information to estimate the amount of electricity that could be generated from those wastes with DCFC technologies, then estimated and compared those amounts with the current average annual electrical loads at those bases.

1.4 Mode of Technology Transfer

This report will be made accessible through the World Wide Web (WWW) through URLs:

  http://www.cecer.army.mil

  http://dodfuelcell.cecer.army.mil/

2 Identifying Quantities and Composition of Wastes Typically Produced by Army Installations

2.1 Typical MSW Production Rates and Composition

The U.S. Environmental Protection Agency (USEPA) has estimated that the amount of solid waste generated in the United States averages about 4.5 lb (2.04 kg) of solid waste/person/day. In 2003, the solid waste produced amounted to about 250 million tons (226.8 billion kg) About 55.4 million tons (50.3 billion kg) was recovered for recycling and another 16.9 million tons recycled for composting (USEPA 2005). These totals amount to 1.04 lb/person-day (0.47 kg/person-day) for recycling and 0.15 kg/person-day (0.32 for lb/person-day) for composting.

The typical breakdown of the composition of this MSW is 35 percent paper, 24 percent yard trimmings and food scraps, 6 percent wood, 19 percent plastic, textiles, rubber, and leather, 10 percent metals and other inorganic materials, 5 percent glass, and 1 percent other. The components of MSW that are of most interest for conversion to carbon–rich particles are the 35 percent paper, 24 percent yard trimmings and food wastes, and 6 percent wood, totaling 65 percent of this waste. Table 2 lists the average carbon contents of these wastes streams along with other typical elemental compositions of these materials.

Table 2. Typical average data on the ultimate analysis of the combustible components in residual MSW (wt%, dry basis) (UCF)

Component	Carbon wt%	Hydrogen wt%	Oxygen wt%	Nitrogen wt%	Sulfur wt%	Ash wt%
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0

2.2 Base Military Population, Total Daily Base Population, and Base Land Areas

Because electricity consumption and waste generation rates for a given area are a strong function of population, this study focused on the 10 largest Army bases as measured by total population. Table 3 lists data that summarizes the military personnel on installation, total personnel on base, and the total installation land area.

2.3 Waste Production at Individual Army Bases

Army personnel at only five of the 10 bases contacted provided information on the annual rate of MSW produced. Since MSW could be a major source of carbon-rich materials for conversion to electricity, an estimate of the amount of MSW produced at each of the five bases that did not provide data was developed by the following procedure.

The USEPA value of 2.04kgs (4.5 lb) of MSW/person/day (USEPA 2005) was used to calculate a MSW value for each of the 10 bases. A comparison of the actual MSW generation rate obtained from each of the five reporting bases with the USEPA based rate indicated an average ratio of 0.52. The USEPA number calculated for each of the five bases that did not report their data was then multiplied by 0.52 to generate a calculated estimate of the MSW produced at each of those five non-reporting bases. Table 4 lists those values.

Table 3. Ten largest U.S. Army installations ranked by the total number of on-base personnel (DOD 2005).

Rank	Facility	Military Personnel	Total Installation Personnel	Total Acres
1	Fort Bragg, NC	43,890	52,367	152,922
2	Fort Hood, TX	42,391	50,215	214,778
3	Fort Campbell, KY	28,753	33,395	35,985
4	Fort Benning, GA	27,627	32,600	171,873
5	Fort Lewis, WA	21,893	27,932	86,041
6	Fort Leonard Wood, MO	21,873	26,247	62,911
7	Fort Jackson, SC	22,351	26,076	52,301
8	Fort Sill, OK	18,735	22,796	93,831
9	Fort Knox, KY	15,359	20,135	109,054
10	Fort Stewart, GA	13,628	19,317	279,271

Table 5 lists the actual waste production numbers reported by base personnel, values obtained from SWARS, and estimates of the missing data for MSW. Unfortunately because of the multiple sources of data that were used there may be some double counting involved in summing up these numbers. There is also data that was not provided or estimated. As a result, the numbers derived later in this report should be looked at as rough approximations of the amount of carbon available and the resulting electricity that could be produced from that carbon.

Table 6 lists the power consumption data reported by seven of the bases. The raw data was used to calculate values OF peak kW demand per person, which was 1.53 kW per person with a range from 1.09 to 2.01 and a ratio of annual average to summer peak demand, which was 0.60 with a range of 0.54 to 0.75. These numbers were used to estimate the average annual demand for those bases that did not provide annual average power consumption data.

Table 4. Actual and estimated values of MSW generated at the 10 largest U.S. Army installations.

Rank	Facility	Estimated MSW Generated on Installation at 4.5 lb /person/day (USEPA Average Rate) tons/yr	MSW Reported by Installation Personnel	Ratio of MSW Reported by Installation Personnel to Estimate Based on USEPA Factor
1	Fort Bragg, NC	43,006	25000	0.58
2	Fort Hood, TX	41,239	20784	0.50
3	Fort Campbell, KY	27,881	11147	0.40
4	Fort Benning, GA	26,772	(13,900)**	(0.52)*
5	Fort Lewis, WA	22,939	(11,900)**	(0.52)*
6	Fort Leonard Wood, MO	21,555	(11,200)**	(0.52)*
7	Fort Jackson, SC	21,414	9588	0.45
8	Fort Sill, OK	18,721	(9700)**	(0.52)*
9	Fort Knox, KY	16,536	9600	0.58
10	Fort Stewart, GA	15864	(8200)**	(0.52)*

* 0.52 is the average ratio of the actual reported MSW data to the calculated (USEPA basis) MSW production rate for Fort Bragg, Fort Hood, Fort Campbell, Fort Jackson and Fort Knox.
** These numbers were calculated using the 0.52 ratio as an adjustment factor.

Table 5. Summary of estimated carbon-rich waste available at the 10 largest U.S. Army installations (SWARS Data Sheets 2005 and 2006).

Rank	Facility	SWARS Corrugated Containers, High-grade Paper, Newspaper, tons/yr	SWARS Mixed Paper tons/yr	SWARS Vegetation, tons/yr	Individual Quantities Reported by Base Personnel during Interviews, tons/yr*
1	Fort Bragg, NC	1337	NR**	67,114	25,000 MSW
2	Fort Hood, TX	4475	830	1377 + 3397 of compost	2760 wood; 20,784 MSW
3	Fort Campbell, KY	2882	153	1543	785 wood; 11,147 MSW
4	Fort Benning, GA	248	92	2300	(13,900 MSW)
5	Fort Lewis, WA	2334	468	1499	(11,900 MSW)
6	Fort Leonard Wood, MO	1580	12	358	(11,200 MSW)
7	Fort Jackson, SC	1921	119	2627	360 wood 9,588 MSW
8	Fort Sill, OK	2031	413	1526	(9700 MSW)
9	Fort Knox, KY	3,149	296	8	9,600 MSW
10	Fort Stewart, GA	2152	0	0	(8200 MSW)

* Estimated values are shown in parentheses.
** Not reported.

Table 6. Estimated annual average electricity demand at the 10 largest U.S. Army installations.

Rank	Facility	Average Annual Demand	Summer Peak Electricity Demand	Minimum Demand	Peak kW/ Base person	Annual Average/ Summer Peak
1	Fort Bragg, NC		100-110 MW peak going to 150 MW		2.01	
2	Fort Hood, TX		99 MW		1.98	
3	Fort Campbell, KY	~30 MW	48-56 MW (32-38 MW winter peak)		1.56	0.58
4	Fort Benning, GA					
5	Fort Lewis, WA	27 MW	36 MW		1.29	0.75
6	Fort Leonard Wood, MO					
7	Fort Jackson, SC	~ 20 MW	31 MW summer peak, 23 MW winter peak		1.18	0.64
8	Fort Sill, OK	19.4 MW	36 MW	8-10 MW winter night	1.58	0.54
9	Fort Knox, KY		22.36 MW		1.09	
10	Fort Stewart, GA					
Averages					*1.53*	*0.60*

3 Review of Approaches to Biomass Pyrolysis

The general definition of pyrolysis is the heating of a material to a high temperature in the absence of air or oxygen. Most of the recent research work on biomass pyrolysis has focused on its use as part of processes to maximize the recovery of energy from biomass in the form of gaseous and liquid fuels. In general, the combination of higher temperatures (800–1000 °C) and very short residence times (less than 1 minute) maximizes the production of liquids, while the combination of higher temperatures (>1000 °C) and longer residence times maximizes the production of gases. In the case of applications where maximization of char production is the objective, relatively low temperatures and residence times of several hours are preferred. This last set of conditions is of interest for application as a way to prepare an appropriate feedstock for DCFC.

The most common commercially successful approach to biomass pyrolysis involves charcoal production. It has been practiced for thousands of years beginning with very simple batch systems to produce charcoal for cooking fires. In their earliest embodiments, it is likely that these operations were carried out in something that is probably close to the type of pits and mounds that are still used today by primitive peoples. Industrial charcoal production today is done in both batch ovens and continuous multiple hearth furnaces.

One typical batch system, the Missouri type charcoal kiln (Figure 1) takes a charge of about 16,300 kg (18 tons) of wood and requires about 3 weeks for the complete cycle of manual loading, heating the kiln, carrying out the carbonization over the temperature range of 260–370 °C (500–698 °F), cooling and manually unloading the kiln. In contrast, the continuous multiple hearth kiln (Figure 2) produces about 2495 kg/hr (2.75 tons/hr) of charcoal.
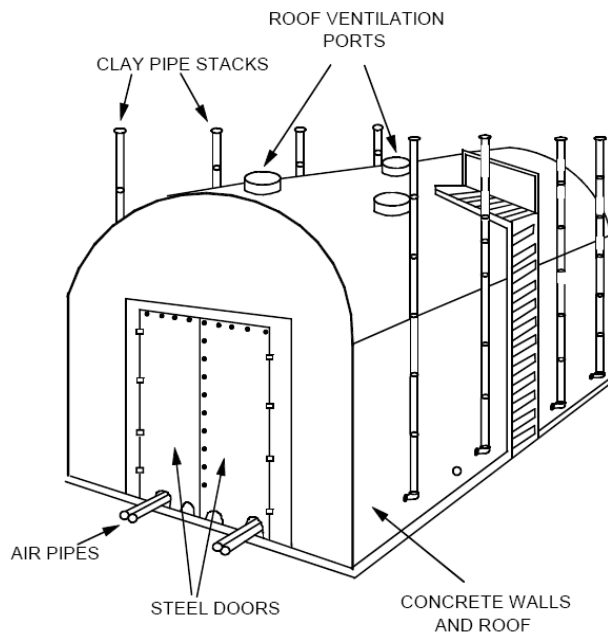
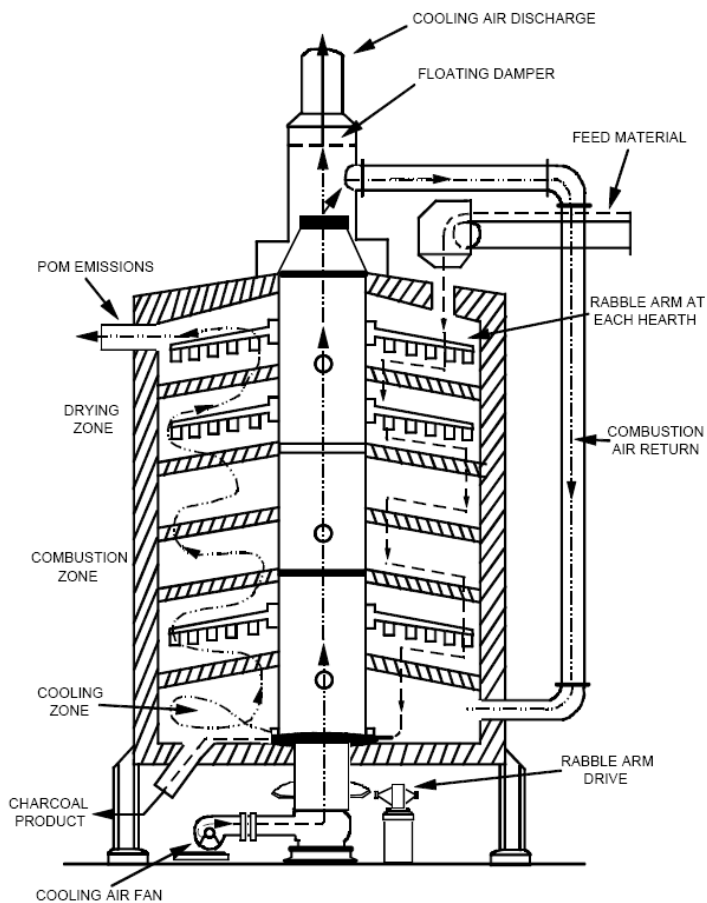**Figure 1. Missouri type charcoal kiln (USEPA 1995).**

Figure 2. Continuous multiple hearth kiln for charcoal production (USEPA 1995).

Professor Michael Antal of the University of Hawaii has developed a patented Flash Carbonization process (U.S. Patent #6,790,317, 14 September 2004) to markedly reduce the time required in a batch reactor to convert biomass into charcoal and to obtain yields of charcoal that are close to the theoretical maximum yield of about 30 weight percent of the biomass fed to the Flash Carbonization reactor. Figure 3 shows an illustration from the patent. Figure 4 shows the theoretical yields obtained by pyrolyzing cellulose, one of the major components of biomass (along with lignin and hemicellulose), at 400 °C and various pressures.

The only significant products of the pyrolysis reaction are C, H_2O, CO_2, and CH_4. The mixed gas stream of H_2O, CO_2, and CH_4 contains a significant amount of the chemical energy originally present in the cellulose. At 1 atm. pressure, about 62.5 percent of the energy in the cellulose is found in the C or char product, 19.5 percent is in the CO_2 product, and 18 percent is in the CH_4 (methane) product. This means that 55–66 percent of the dry feed is retained in the charcoal. The yield of charcoal (carbon) is enhanced by carrying out the reaction at pressures of up to 2.533 MPa (25 atm.), at conditions that allow some slight exothermic oxidation to occur, and with low sweep gas rates. Antal (2006) expresses the cellulose pyrolysis reaction as:
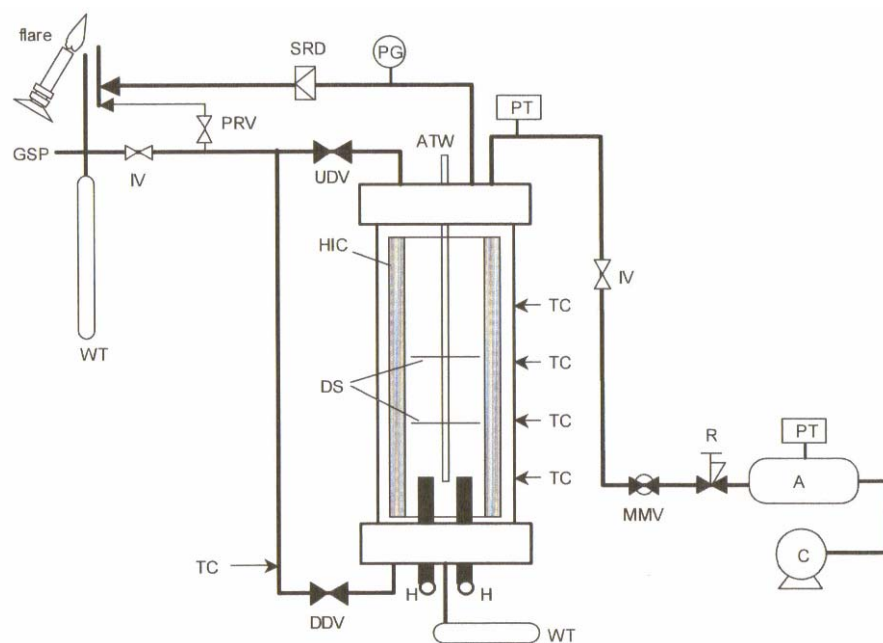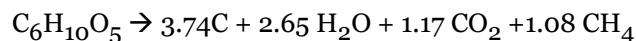
$$C_6H_{10}O_5 \rightarrow 3.74C + 2.65\ H_2O + 1.17\ CO_2 + 1.08\ CH_4$$

Figure 3. Flash carbonization process for charcoal production (U.S. Patent #6,790,317, 14 September 2004).
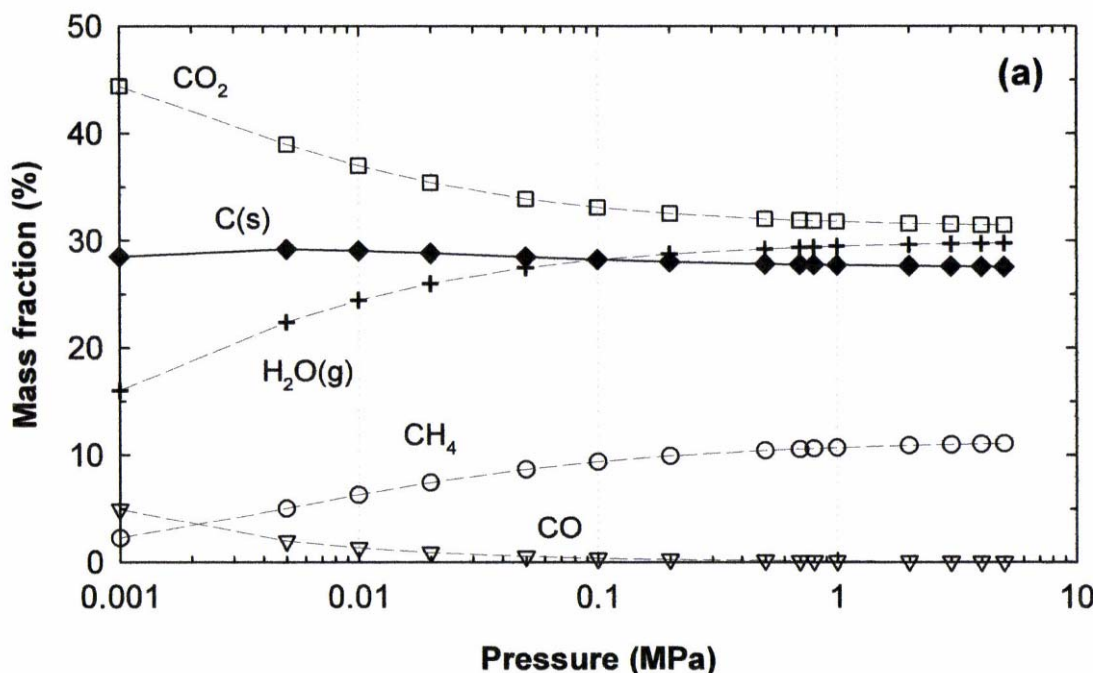
Figure 4. Thermochemical equilibrium predictions for the products of cellulose pyrolysis at 400 °C (Reprinted in part with permission from Industrial & Engineering Chemistry Research, No. 42, pp 3690-3699 [copyright 2003, American Chemical Society]).

Figure 5 shows a batch unit that takes a charge of about 1 ton of biomass (contained in the cylindrical basket at the rear left of the photograph). That basket is lowered into the pressure vessel at the right rear of the photograph. The reaction of biomass to charcoal is complete after ½ hr at elevated temperature and pressure. This particular unit was built over a number of years at a reported cost of $200,000 for the major equipment items only, and does not include an appropriate material handling system consistent with a commercial operation.

If the unit were run for the maximum possible number of cycles in a continuous period of 24 hrs/day, Antal (second from the right in the photograph) claims that it would have an output of about 9072 kg (10 tons) of charcoal for that period. Based on his estimate of the capital cost and labor, he estimated that this system had the potential to produce charcoal from agricultural waste, supplied to the process at zero cost, at a production cost of about $4/MMBtu. Typically the process yields 25–30 weight percent of charcoal, about 30 weight percent methane, with the balance being water and carbon dioxide, consistent with the theoretical predictions shown in Figure 4.

Figure 5. Batch flash carbonization reactor.

4 Review of DCFC Technologies Currently Under Development

4.1 DCFC Background Issues

Some aspects of DCFC technology still need to be tested. One such aspect is the mechanism of electrochemical oxidation of carbon to analyze the anodic process at the molecular level. Impurities often exist in inexpensive and readily available carbon fuels. These fuels should be analyzed to determine their effect on the carbon electro-oxidation rate, electrolyte, anode current collector, and other fuel cell component materials. This will show the amount of pretreatment needed for each fuel and its relationship to the DCFC lifetime. For example, raw coal should not be used directly since its impurities tend to decrease cell performance and shorten the cell life, although cleaning of the coal increases the cost of the electricity generated by DCFC power plants.

The electrochemical oxidation of carbon is performed at high temperatures in molten salt electrolytes. At polarizations over 0.1V and temperatures above 700 °C the main product from this reaction is CO_2. As the density increases, the resulting ratio of CO to CO_2 increases. It has been proven that it is possible to achieve complete electro-oxidation of carbon to CO_2, and that it is possible to avoid the formation of CO at the polarized condition. The reactivity of carbon is affected by many properties, such as crystallization, electrical conductivity, surface area, and particle size. The carbon electrochemical reaction greatly benefits by using carbons with good electrical conductivity, i.e., lower ohmic polarization (Cao 2007).

Thus far, researchers have encountered more specific details including:
- the need for feedstock de-ashing and/or pyrolysis prior to introducing the feed material to a DCFC
- removal of contaminated molten anode materials from the system at 740-900°C, removing coal mineral matter from the molten anode materials and then recycling purified melt to the anode chamber
- lack of sustained single cell operation to date
- lack of any cell stack construction and operation
- absence of component manufacturing and assembly experience
- lack of available test components with desired characteristics at reasonable cost.

4.2 DCFC Types[*]

4.2.1 DCFC with a Molten Carbonate Electrolyte

Molten carbonate electrolytes are very good for DCFCs because they are highly conductive, have good stability when CO_2 is present, and have an appropriate melting temperature for this application. The cell voltage is formed at the anode side and consumed at the cathode side, and there is an influence on the cell voltage by this partial pressure. Simulations have given results showing the system to be able to reach a net electrical efficiency of up to 78 percent.

4.2.2 DCFC with a Molten Hydroxide Electrolyte

Molten hydroxides are very beneficial as electrolytes. They have a higher ionic conductivity and a higher activity of the carbon electrochemical oxidation. This results in a lower overpotential and a higher carbon oxidation rate, as well as a much lower operation temperature of about 600 °C. This decreases the cost as it allows the use of less expensive materials.

During carbon electro-oxidation in this type of fuel cell, there is the formation of carbonates. They undergo both a chemical process and an electrochemical process. This fuel cell uses a pure graphite cylindrical rod, which acts as the anode and the fuel. It is immersed into molten sodium hydroxide and is served at the same time as the cathode. The cell is fed humidified air through a gas distributor in the bottom of the container.

To optimize the performance of the cell, one must look at the cathode material, air flow rate, operating temperature, and fuel cell scale. They system can be further optimized by changing the cell design, the electrode material, and the operating conditions.

4.2.3 DCFC with YSZ-based Solid Electrolyte

The Yttria-Stabilized Zirconia (YSZ) design combines advances in the solid oxide and molten carbonate fuel cell technologies. Their components include a U-tube consisting of a metal mesh cathode current collector, a cathode layer, an electrolyte later, and a metal mesh anode current collector. This structure is immersed into a liquid anode made of a mixture of molten elements and carbon particles. When this mixture is stirred causing a flow mode, the fuel cell operates better since there is an increased

[*] Cao et al. (2007) provide more detailed information on the topics included in this section.

contact between the carbon particles and the anode current collector, which enhances mass transport.

4.3   DCFC Workshop

A number of vendor teams and R&D institutions are currently developing DCFC technology. The key personnel from each organization (listed in parentheses) participated in a workshop organized by EPRI and held during 29-31 August 2006 at EPRI in Palo Alto, CA The participants of the workshop included:

*   Akron University (Steve Chuang)
*   CellTech Power (Tom Tao, Jeff Bentley)
*   Contained Energy (John Cooper, Bob Polak, Kevin Berner)
*   Direct Carbon Technologies (Turgut Gur, Alvin Duskin)
*   SARA (Ned Patton)
*   SRI (Iouri Balachov, Larry Dubois, Steven Crouch-Baker)
*   University of Hawaii (Michael Antal).

4.4   Current DCFC Research and Development

The following sections summarize the technical status of each team's work.

4.4.1   Akron University

All of the work described to date has been carried out on button cells located in a tubular apparatus (Figure 6). Most of the effort has been to test various combinations of anode and cathode catalysts. Typical experiments consist of placing a small amount of either raw coal or devolatilized coal on the button cell and either heating it up or dropping coal directly into a preheated cell. Test temperatures are normally in the range of 750–850 °C.

Power densities in the range of 50–150 mW/cm² have been obtained during the relatively short test duration of a few hours. Ash build-up on the surface of the button cell reduces power density, but removing the loose ash from the cell surface and allowing fresh carbon to reach the surface restores power density to previous levels.
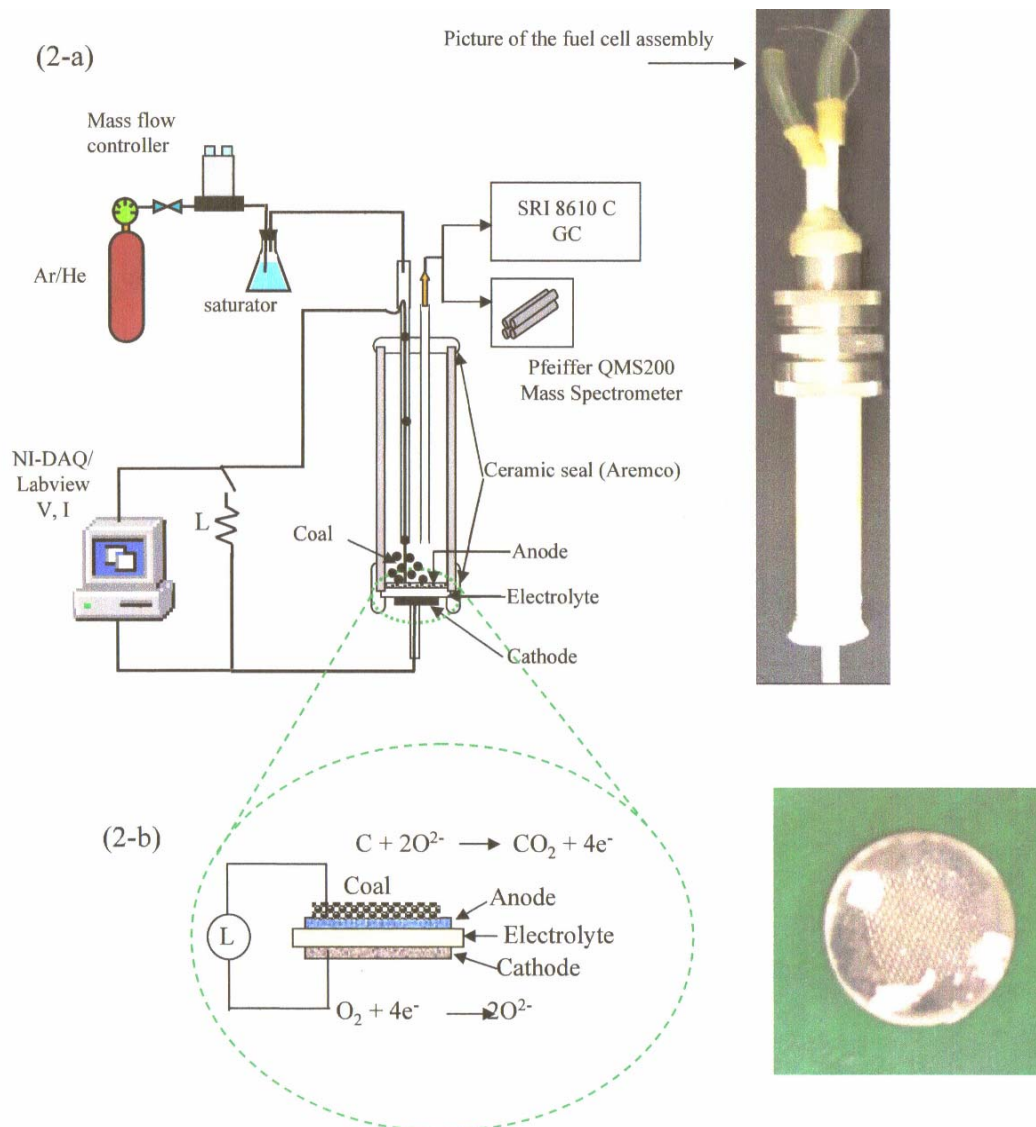
(2-a)

Picture of the fuel cell assembly

Mass flow controller

Ar/He

saturator

SRI 8610 C GC

Pfeiffer QMS200 Mass Spectrometer

NI-DAQ/ Labview V, I

L

Coal

Ceramic seal (Aremco)

Anode

Electrolyte

Cathode

(2-b)

$$C + 2O^{2-} \longrightarrow CO_2 + 4e^-$$

Coal

Anode

L

Electrolyte

Cathode

$$O_2 + 4e^- \longrightarrow 2O^{2-}$$

Figure 6. Akron University button cell test apparatus.

4.4.2 CellTech Power

CellTech Power is developing a technology that uses a liquid tin anode in a solid oxide fuel cell (Figure 7). This system oxidizes molten tin (Sn) to tin oxides (such as SnO_2) in the anode layer by oxygen ions produced in the cathode. The ions transit a typical Yttria-stabilized Zirconia (YSZ) electrolyte to reach the anode such that electrons are released. Electricity can be produced directly by oxidizing Sn like a battery. The SnO_2 can be reduced back to Sn by carbon-containing solids or any reducing gases consisting of carbon, hydrogen, oxygen, nitrogen, and sulfur that enters the anode. During the Sn regeneration, the device operates like a fuel cell. The Sn anode is not poisoned by sulfur. With a cell open circuit voltage (OCV) of 0.8V, the CO/CO_2 ratio is 0.2 in the anode effluent gas. Maintaining cell voltage

(OCV) above 0.8V keeps the dissolved SnO_2 concentration in the molten Sn at a level where precipitation of the oxide does not occur. This means that the CO-containing gaseous effluent that leaves the cell must be oxidized to complete the conversion of CO to CO_2.

Several years ago, with $15 million raised from venture capital and private sources, CellTech built two 1 kW Gen 2 units fueled by natural gas, which operated for more than 2000 hrs continuously. In those Gen 2 units, the natural gas was conditioned to a stream also containing CO and hydrogen and fed to the Sn anode. During 2005-2006, with Defense Advanced Research Projects Agency (DARPA) funding, CellTech developed Gen 3.0 cells and stacks allowing direct conversion of waste packaging materials and JP-8 into electricity. Before 2005, the key limitations of this system had been low power density (with levels of 40 mW/cm² with hydrogen fuel and 20 mW/cm² with carbon/JP-8 fuel) and difficulty in manufacturing. These power densities had been deemed too low for portable and mobile power generation. With support from DARPA/Army recently in place, CellTech is developing a Gen 3.1 (2007) cell architecture for direct JP-8 conversion with improved power density. They have modified the porous media to allow higher mass transfer rates of heavy fuel molecules flowing to the anode and are developing a high electrical conductance tubular cathode.

In 2006, CellTech demonstrated power densities of 160 mW/cm² for hydrogen and 80 mW/cm² for JP-8. The Gen 3.1 design is expected to provide approximately four times reduction in weight and volume over the previous Gen 3.0. Gen 3.1 is projected to become competitive for number of portable and mobile applications such as military field battery chargers. The mid-term power density target for direct JP-8 conversion is 200 mW/cm² (2008-2010); at this level the direct JP-8 conversion liquid Sn system becomes a formidable competitor for kilowatt or sub-kilowatt applications.

CellTech Power has several concepts of how to generate power from coal with this system, but has not completed a detailed flowsheet analysis. One approach involves feeding coal to a molten Sn bath anode to reduce SnO_2 to Sn, then transferring the molten Sn to the cell arrays for oxidation to SnO_2 and power production. Another concept is to use a fluidized bed of coal to take advantage of volatiles in coal, in which carbon in the coal is reacted with hot recycled CO_2 and water to produce a CO-rich gas, which is then fed to the cell array to produce power.
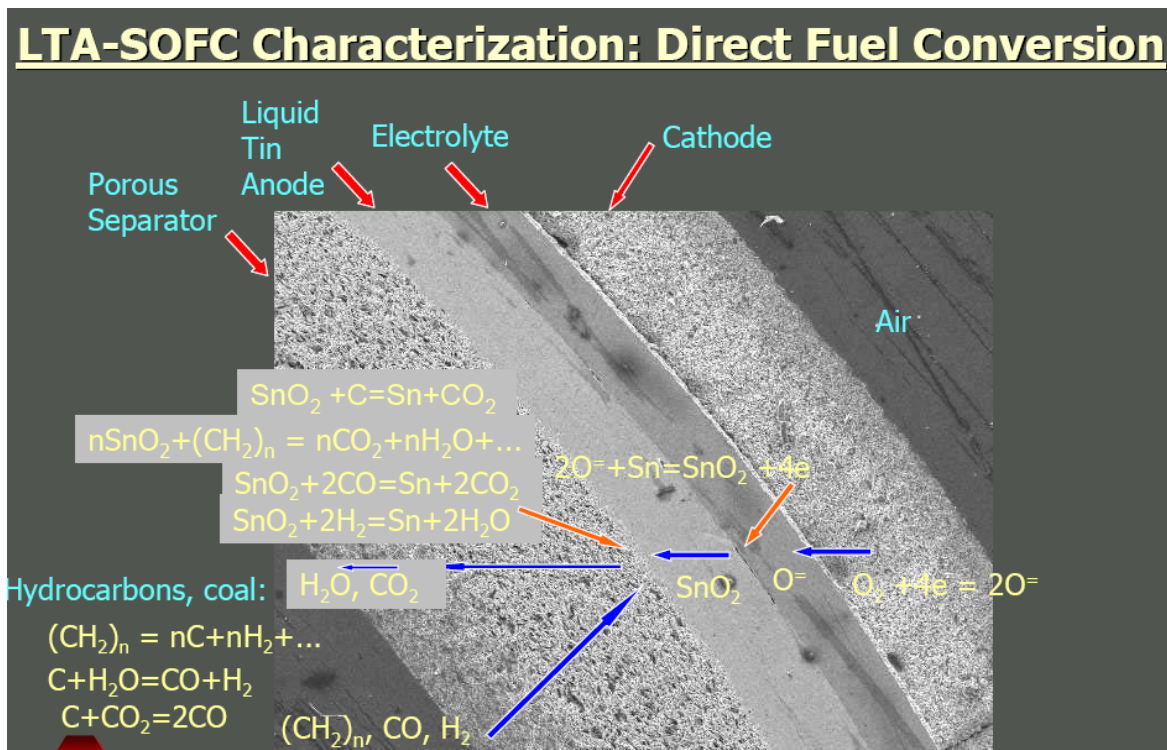
Figure 7. CellTech DCFC with a molten tin electrolyte layer.

4.4.3 Contained Energy

Contained Energy has exclusively licensed the DCFC technology developed by John Cooper at Lawrence Livermore National Laboratory (LLNL). The cathode in this technology is essentially a molten carbonate cathode, while the anode is a slurry of disordered carbon fuel and a carbonate eutectic. Under a Cooperative Research and Development Agreement (CRADA), Contained Energy engaged LLNL to develop the initial prototypes of its generation design; a single cell of 15W–30W output, and a five-cell bipolar stack of 75W–150W output. Figure 8 shows an early laboratory configuration of Contained Energy DCFC cells, and Figure 9 shows a Contained Energy single cell after assembly, and before loading into the furnace.

This design has an area-specific resistance (ASR) of 0.69 Ω/cm², which corresponds to a maximum theoretical power density for the cell of 280 mW/cm². However, with variances in individual cell performance in the stack, and with realistic losses from interconnects, Contained Energy is targeting a maximum gross power density of 140-200 mW/cm². Such a cell has operated for a period of 7 days.
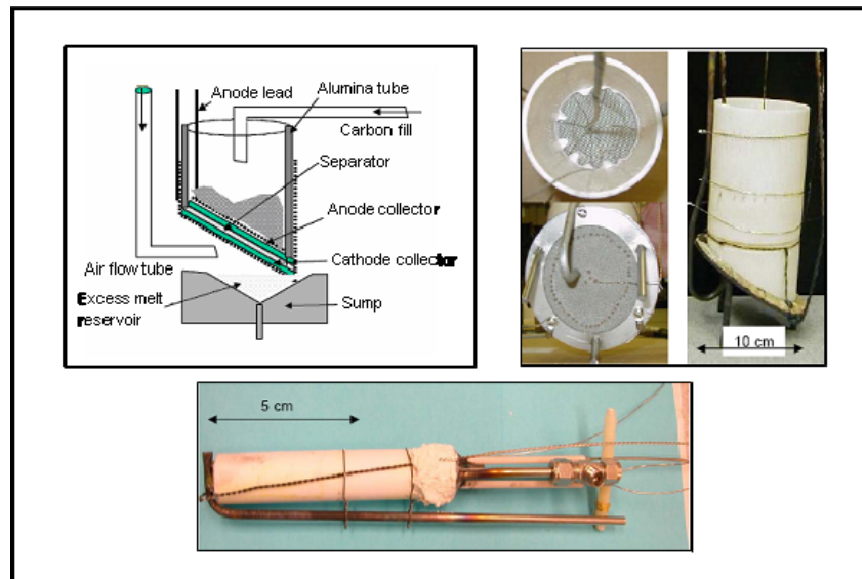
Figure 8. Contained Energy DCFC cells and stack concepts in the early laboratory scale configuration using 2 cm² and 60 cm² cells.
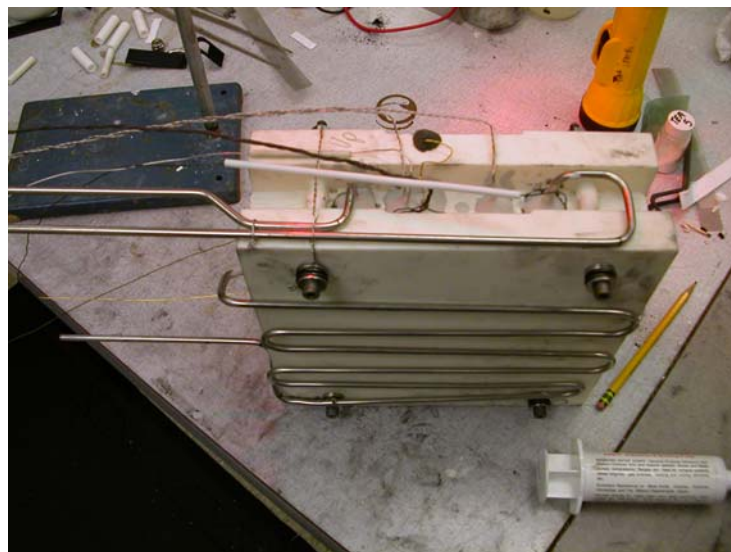
Figure 9. Contained energy DCFC single cell.

In early development work at LLNL, the cathode was identified as the rate limiting subsystem. Under the work during the CRADA, the cathode has been improved with new materials and a proprietary activation procedure. Having improved the cathode, the separator is now the limiting constraint in the system, apparently due to a change in the chemical composition of the fabric YSZ separator produced by the supplier. The supplier is working to correct the problem. Meanwhile Contained Energy is also developing alternative separators that should have the same or superior performance characteristics.

Contained Energy is transferring the results of this CRADA to their development facility in Cleveland, OH. Contained Energy is simultaneously developing a different design for mobile applications that can deliver energy density in the range of 1,000–2,000 Wh/kg.

4.4.4 Direct Carbon Technologies

The first experiments with a fluidized bed of solid carbon fuel (i.e., synthetic carbon, coal and almond shell) particles provided peak power outputs of 1-2 mW/cm² at 900 °C with a flowing CO_2 or He atmosphere. These experiments were done with an initial charge of 30 grams of solid carbon fuel and ran for more than 20 hrs. In some cases, erosion has been observed with delamination of the platinum anode. Figure 10 shows the Direct Carbon Technologies concept.

Benchmarking experiments done for comparison reasons with gaseous fuels (3% H_2 and 100 percent CO) in the absence of solid fuel in the bed and using the same cells similarly gave peak power densities of 1-2 mW/cm². In both solid and gaseous fuel cases, the fuel cell behavior was dominated by ohmic loses due mostly to the high resistance of the thick partially stabilized zirconia (PSZ) tubular electrolyte employed in these experiments.
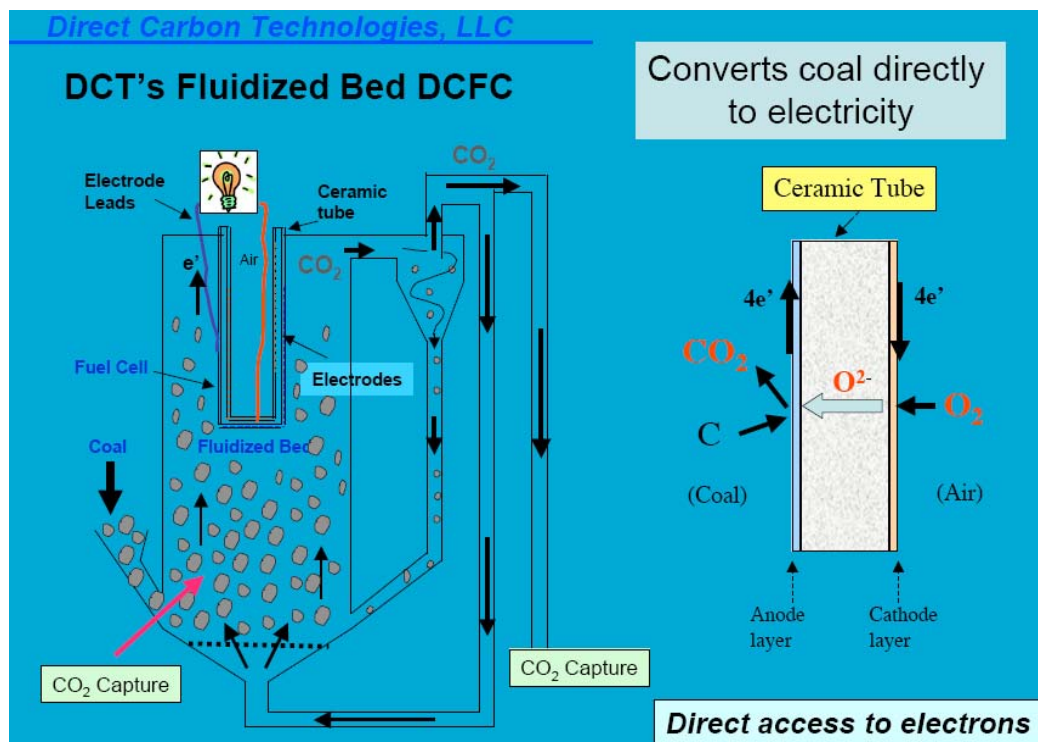

Figure 10. Direct Carbon Technologies fluidized bed DCFC concept.

In contrast, experiments at those same conditions in the tubular reactor, with the synthetic carbon placed on button cells (featuring thin yttria stabilized zirconia ([YSZ] electrolyte wafers with Ni/YSZ cermet anodes) provided by Ceramatec (Salt Lake City, UT) and agitated by a flowing CO_2 stream produced a peak power density in excess of 140 mW/cm², which deteriorated in time due to sulfur interaction with the Ni anode. Similar experiments using fluidized coal (Lower Kittanning, PA) in flowing He gas with other button cells gave peak power densities in excess of 40 mW/cm² (Figure 11), which also decayed in time. Again, benchmarking tests on these same button cells using gaseous fuels only gave comparable power densities. These results pointed to the importance of the microstructure, stability, and catalycity of the anode and its impact on cell performance.

In all cases, gas analyses of the reaction products verified oxygen balance around the cell (Figure 12), and indicated that all oxygen, supplied electrochemically through the solid electrolyte into the solid fuel bed, is accounted for in the form of CO and CO_2 in the flue stream. These preliminary results demonstrated for the first time that one can electrochemically convert solid carbonaceous fuels into electricity in a single step inside a fluidized bed reactor.

4.4.5 SARA

After several prior embodiments of this technology, which used a carbon rod inserted into a molten sodium hydroxide bath, SARA has evolved a new concept that uses different salts in two chambers separated by a porous separator plate (Figure 13).
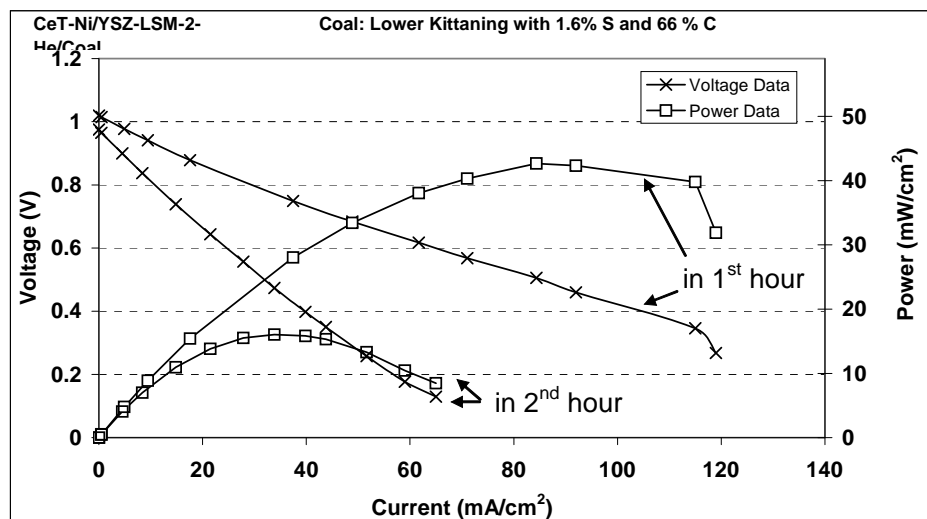
Figure 11. Polarization curves for DCT fuel cells.
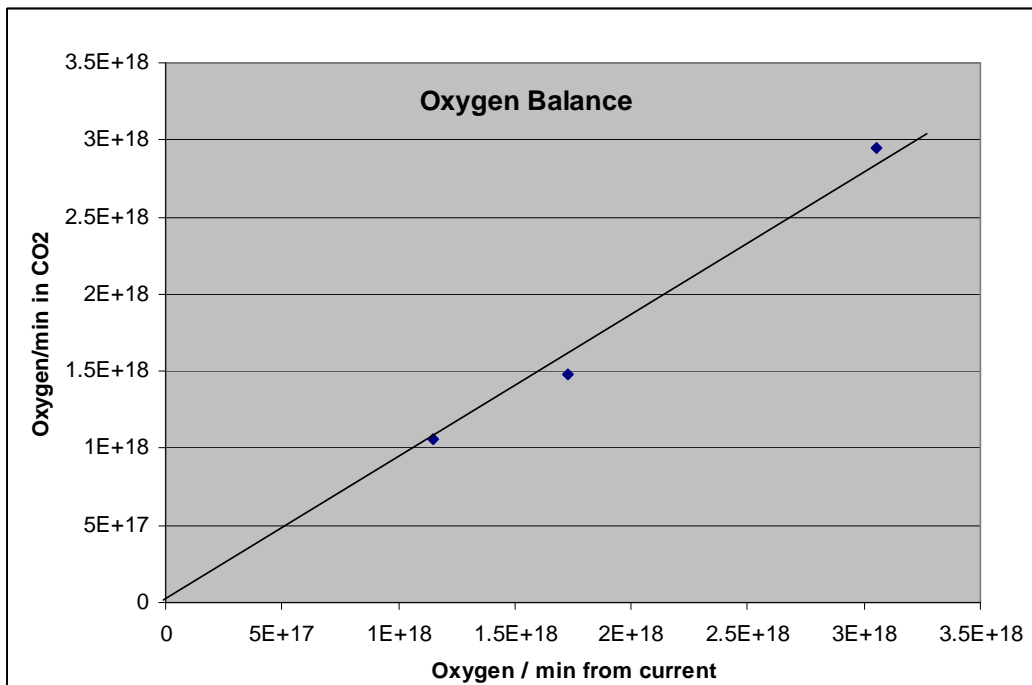
Figure 12. Oxygen balance in Direct Carbon Technologies DCFC ratios for DCT fuel cell.
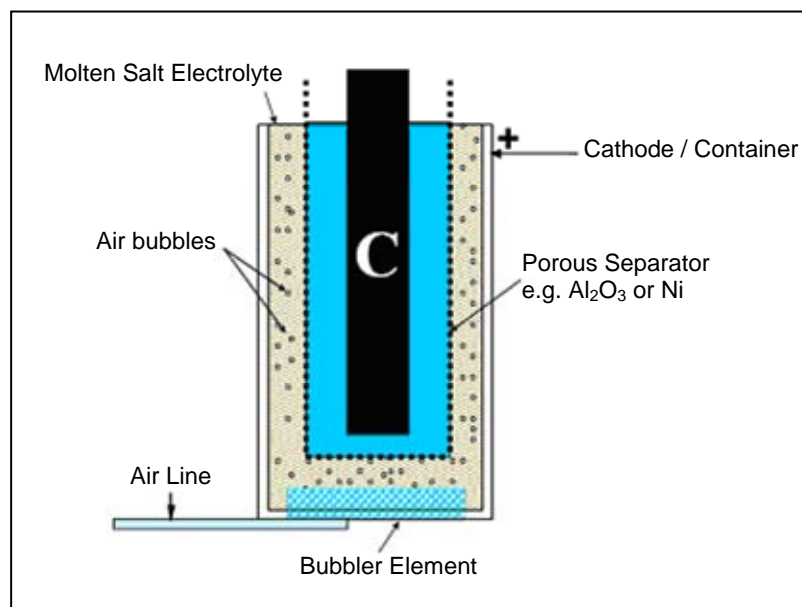
Figure 13. SARA annular molten salt bath DCFC.

The cathode chamber contains molten potassium (KOH) or sodium hydroxide (NaOH). Better results have been obtained with KOH. Moist air is bubbled into this chamber where the oxygen picks up electrons, resulting in the formation of OH⁻ ions, which then transport through the separator membrane to enter the anode chamber. A basket of solid fuel particles is

suspended in molten metal carbonates in the anode chamber. The OH^- ions react with the solid fuel to produce CO_3^{-2} ions and electrons. The CO_3^{-2} ions also react with the coal to produce CO_2 and electrons.

SARA recently observed that the electrolyte was stable over the course of a 500-hr experiment. A stackable design concept has been developed. They stated that the major challenges are the separator material and design, corrosion, and operating temperature. Power density numbers for this system are difficult to compare to the other systems reviewed because those numbers are based on the area of the separator rather an anode or cathode area.

4.4.6   SRI

The SRI concept is to feed coal (as well as other carbon sources such as tar, biomass and waste paper/plastic) as a carbon rich solid fuel to a flowing molten salt, such as alkali metal carbonates. That mixture forms an electrically conducting anode when the carbon concentration reaches a value between 30 and 40 percent. Air is fed to a conventional SOFC cathode (typically strontium-doped lanthanum manganite [LSM]) which provides the oxygen ions that migrate through a solid oxide electrolyte (typically YSZ) and react with the solid fuel to produce electricity and CO_2. SRI currently is operating a batch system which has up to six cathode/electrolyte tubes inserted into a single molten salt bath. Three types of tubes are being used: simplified, sub-scale, and full-scale (Figure 14).

For the experiments conducted to date, the solid fuel is mixed with salt powder and the dry mixture is then dropped into the apparatus, which is then heated to its operating temperature of 800-950 °C. Power densities of approximately 300 mW/cm² have been achieved. Lifetimes in excess of 1200 hours have also been demonstrated. A design for a 40 kW power system has been completed.

4.4.7   University of Hawaii

Charcoal has been used as the feedstock for a low temperature aqueous carbonate fuel cell that has operated as high as 245 °C (Figure 15). At this temperature the cell offered an open circuit voltage of 0.57 V and a short circuit current of 43.6 mA/cm². At 220 °C, the power density was 6.3 mW/cm². One possible explanation for the relatively low open circuit voltages resulted from the formation of carbon oxides on the anode that were accompanied by the release of CO_2.
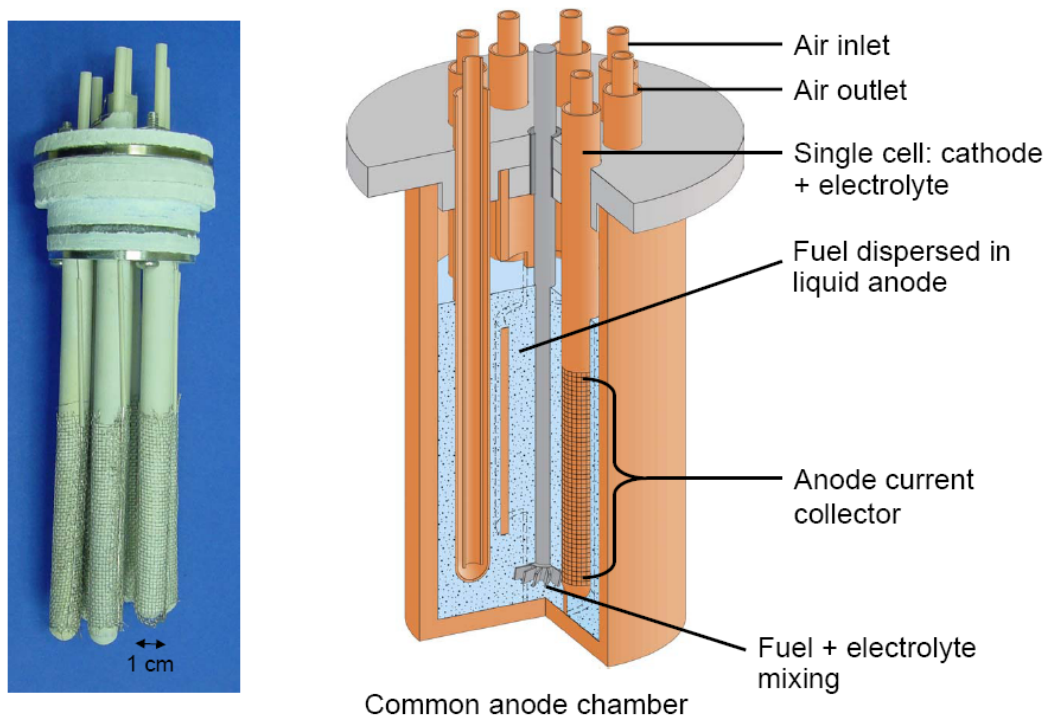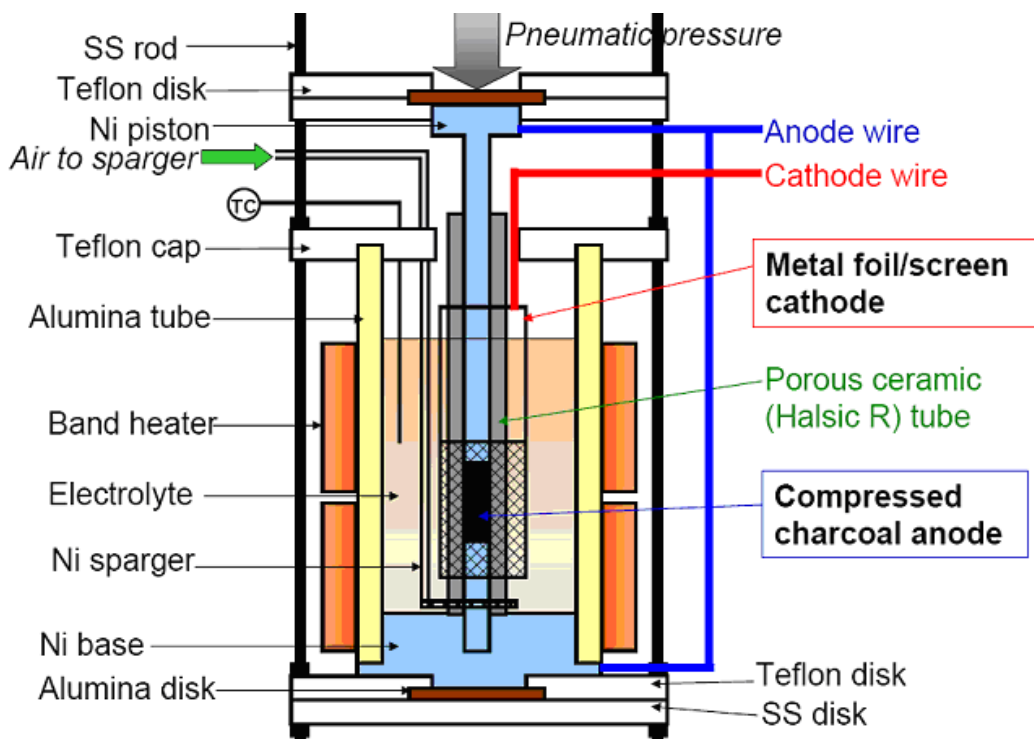
Figure 14. SRI multiple tubular DCFC stack prototype.

Source: Antal (2006); used with author's permission.

Figure 15. University of Hawaii low temperature aqueous carbonate fuel cell.

Thermodynamically, oxygen reduction at the cathode is more favorable at temperatures below 200 °C, however, improved anode performance could result from a higher temperature that could combust the carbon oxides accumulated on the bicarbon anode material. Therefore, performance could be markedly improved if a split cell could be developed in which the cathode could be operated at below 200 °C and the anode at above 240 °C (Nunoura 2007).

4.5   General Summary of the Direct Carbon Fuel Cell Industry

The data in Table 7 briefly describe the status if the Direct Carbon Fuel Cell industry.

4.6   Conceptual Process Options for Heat and Mass Integration of DCFC Systems

Chapter 3 has discussed several techniques for the production of a solid, carbon-rich, particulate fuel from various carbon-rich waste steams, including paper products, wood, and vegetation. Chapter 4 discusses a variety of approaches to DCFC system design that could be used for electricity production. The issue is whether to integrate these two operations into a continuously operating system or to disperse the fuel preparation and electricity production functions to separate locations.

Table 7. Summary dcfc technology.

Vendor	Contained Energy	SRI	SARA	CellTech Power	Direct Carbon Technologies	Akron University	University of Hawaii
Fuel	De-ashed and devolatized coal	Raw coal	Devolatized coal	Raw or gasified coal	Raw coal	Raw coal	Biomass char
Anode	Solid fuel particles coated with molten carbonate	Raw coal in flowing molten carbonate (currently carbonate)	Metal basket containing raw coal particles suspended in molten carbonate bath	Sn/SnO_2 melt	Currently Pt for experimental convenience	Ni or Cu	Compressed charcoal
Electrolyte	Molten carbonate	Yttria-stabilized Zirconia (YSZ)	Ni with 2% Ti cathode melt container	YSZ	YSZ	YSZ	Aqueous KOH
Cathode	Lithiated NiO	LSM* or other SOFC type	Metal vessel containing molten alkali	LSM*	LSM* or other SOFC type	LSM* / YSZ	Silver for experimental convenience
Current R&D Status	Assembling 5 cell stack at 100 watts	Unit with six cathode tubes in molten carbonate	Single 2-chamber cell with different electrolytes	Concepts for coal use	Single tubular cell with fluid bed of carbon	Single button anode in tube	Single KOH cell operating at ~220 °C
* strontium-doped lanthanum manganite							

In the integrated case, it is necessary to transport the fuel to a central location and then transmit and distribute electricity from that location to a variety of users. The integrated approach offers an opportunity for maximum energy efficiency as a result of integration between the fuel preparation and fuel consumption operations as well as the opportunity to use that waste energy (thermal and methane) in other buildings or processing plants that could be co-located with the integrated unit. This point will be discussed in later paragraphs.

Figure 16 shows a system with the potential for the highest energy efficiency and best opportunity for energy integration with co-located facilities. In this concept, feed material is dried at about 149 °C (300 °F) to drive water off from the wet biomass/MSW feed material. The dried feed is then pyrolized at 371 °C (700 °F) to drive off methane and carbon dioxide and produce char which is fed to the DCFC. Hot, CO_2-rich anode product gas is recycled from the DCFC to the fuel dryer and pyrolyzer to provide the heat energy needed for those operations.

Excess energy in the pyrolyzer waste gas and in the CO_2 rich anode-off gas can be used for steam generation and perhaps used in co-located energy consuming facilities. Currently, waste heat generated by 200–250 kW Phosphoric Acid Fuel Cell (PAFC) and Molten Carbonate Fuel Cell (MCFC) units provide waste heat for hot water and energy to drive absorption chillers for cooling.

If no attractive opportunities exist for energy savings as a result of energy integration with other co-located facilities, then the separate drying and pyrolysis would probably not be cost effective. Figure 17 shows a system that is simpler than the highly integrated system should in Figure 16 with the pyrolyzer (which includes the required drying operation) integrated with the DCFC. Energy to drive the pyrolysis reaction is obtained by recycling a fraction of the hot, CO_2-rich, anode product gas to the pyrolyzer. The methane-rich product gas from the pyrolyzer is then available for use as a combustion fuel for space or hot water heating.

There may be situations where it is economically undesirable to integrate the feed preparation equipment (pyrolyzer and/or dryer). For example as will be discussed in Chapter 7, "Electricity Dispatch Options" (p 36), the capacities of the two systems may be deliberately mismatched, so that electricity generation is only done during peak demand hours.
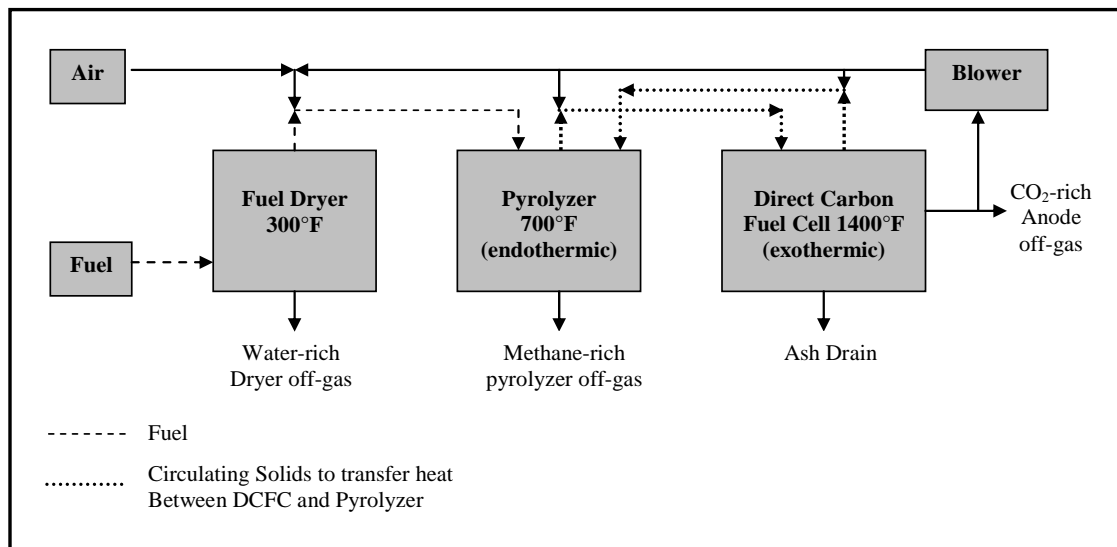
Figure 16. Highly integrated dryer/pyrolyzer/DCFC system for maximum efficiency.
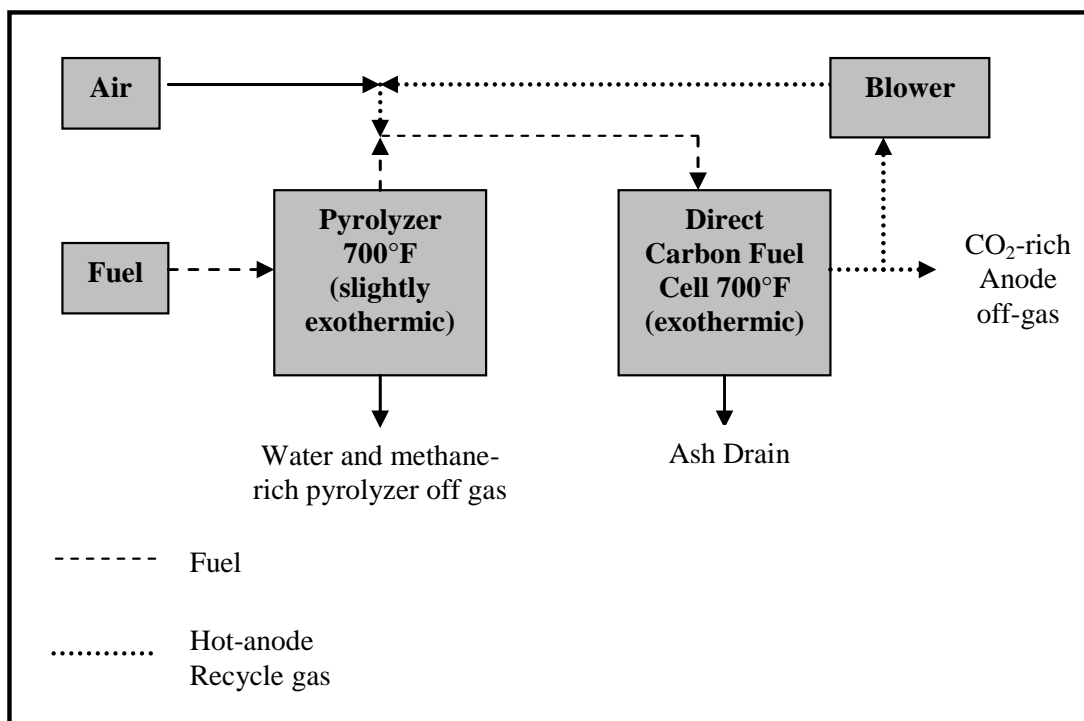
Figure 17. Integrated pyrolyzer/DCFC system for high efficiency.

Another situation where non-integration may be economically preferred is where the biomass source is remote from the electrical demand area. In that case, it might be cheaper to transport a much lower weight of particulate fuel product compared to the high moisture vegetation/MSW components to the generation site located near the demand center (Figure 18).

Figure 18. Non-integrated Pyrolyzer and DCFC system for maximum flexibility.

5 Preliminary Estimation of Overall Process Efficiency

Certain simplifying basic assumptions are required to calculate the overall efficiency of the process to go from raw carbon-rich, waste-fuels to electricity. Since the work of all the teams involved in developing DCFC technology is at very early stages of development, it is not likely that a fully integrated stack and fuel cell power plant will achieve the maximum the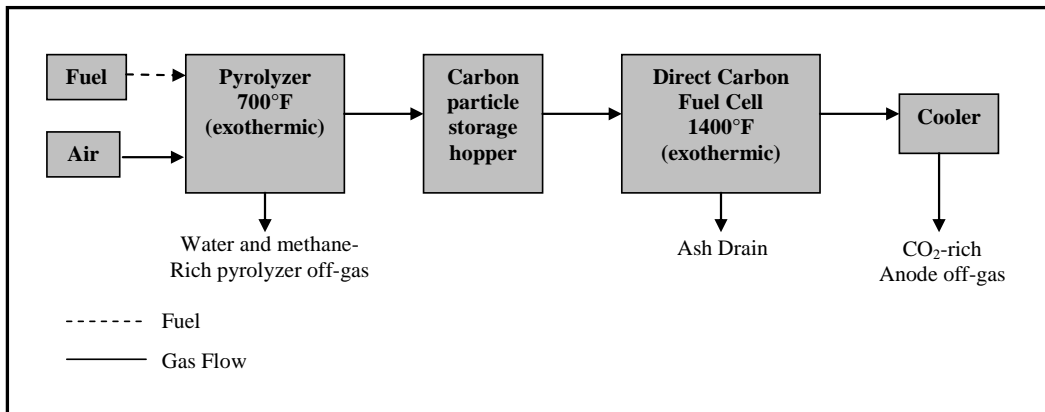oretical efficiency of 80 percent that occurs in a single cell. This exercise assumed that the efficiency of converting the chemical energy (Higher Heating Value or HHV basis) in the dry carbon in the fuel to AC electricity in the DCFC is 65 percent. For reference, typical pulverized coal power plants convert the chemical energy in coal (on the same HHV basis) to electricity at 30–35 percent efficiency.

Wood received in a power plant is assumed to contain 45 percent moisture. The typical carbon composition of dry-wood is assumed to be 50 percent, as listed previously in Table 2. The heat of combustion of carbon when CO_2 is the only product is 14,087 Btu/pound (Perry 1973). Therefore the amount of pure carbon required to produce 1 MWH of electricity is 372 lb. This was calculated as:

> (3412 Btu/kWh) x (1/.65)
>> =5250 Btu/kWh for electricity production
> (5250 Btu/kWh) x (1/14087 Btu/pound carbon) x (1000 kWh/MWH)
>> = 372 lb of carbon/MWH

If dry wood contains 50 percent carbon, then 372 lb of carbon is contained in 744 lb of dry wood (372/0.5 = 744).

Assuming that wet-wood contains 45 percent moisture, then the amount of wet wood required for 168.7kg (372 lb) of carbon or 337.5kg (744 lb) of dry wood is 613.7kg (1353 lb). It follows that the amount of water contained in the wet wood is 276.2kg (609 lb). Drying wood by evaporation requires approximately 1000 Btu of heat per pound of water evaporated. Removing 276.2kg (609 lb) of water from wet wood requires 642.5MJ (609,000 Btu) of energy.

Converting 168.7kg (372 lb) of carbon into 1 MWH of electricity in a DCFC liberates 1,939 MJ (1,838,000 Btu) of waste heat in the fuel cell, calculated as:

Fuel required to produce 1 MWH of electricity
= (5250 Btu/kWh) x (1000 kWh/MWH)
= 5,250,000 Btu * 1.055056kJ/1BTU = 5,539,044 kJ

The amount of energy contained in 1 MWH of electricity is:

3412 Btu/kWh x 1000kWh/MWH= 3,412,000 Btu * 1.055056kJ/1BTU
= 3,599,851 kJ

It follows then, that the waste heat available is:

5,250,000 − 3,412,000 = 1,838,000 Btu/MWH * 1.055056kJ/1BTU
= 1,939,192.9 kJ/MWH

To maintain the fuel cell at its constant operating temperature of approximately 760 °C (1400 °F), this waste heat must be removed from the DCFC system both by heating up the reactants that are fed to it, and cooling and recycling the gas product from the cell.

The waste heat available of 1,939 MJ/MWH (1,838,000 Btu/MWH) is far more than the 642 MJ/MWH (609,000Btu/MWH) required for wet wood drying. It can therefore be used to supply the heat needed for evaporation of the water from the wet wood.

In general, it is prudent at this stage of development of DCFC to plan to use a feedstock to the DCFC stack system that is as free of sulfur, chlorine, and metal contaminants as possible, to minimize potential problems with anode poisoning. For example, pyrolized wood, consisting almost exclusively of carbon, would likely be preferable as DCFC feedstock over wet wood. High moisture levels in the DCFC may lead to embrittlement of fuel cell component materials and should be avoided.

The pyrolysis step also liberates a significant amount of methane. A reasonable assumption is that 10 percent of the mass of dry wood fed to a pyrolysis reactor will be produced as methane. Therefore, 613.7kg (1353 lb) of wet wood containing 744 lb of dry wood will yield about 33.7kg (74.4 lb) of methane. This amount of methane contains about 2,110 MJ (2,000,000 Btu's) of energy, which could be used for drying or pyrolysis, or which could be exported for external uses.

6   Estimates of On-Base Potential Electricity Production from Wastes

Carbon-rich wastes produced at U.S. Army bases include various types of paper products (including corrugated containers, high-grade paper, newspaper, and mixed paper), wood, vegetation, and MSW. The carbon contents of the raw wastes vary as a function of the amount of water and other components in the waste steam and the elemental composition of the carbon containing materials. The following assumptions were made to allow a simplified approach to the calculation of the amount of carbon that was present in the waste streams that could be used for power generation.

Paper products and dry wood were both assumed to contain approximately 50 percent carbon. Therefore the total quantities of paper products and dry wood were multiplied by 0.50 to estimate the fraction of available carbon in paper products and dry wood (Table 9).

Vegetation was assumed to be equivalent to wet wood which contains 55 percent dry wood, of which 50 percent is carbon. Therefore the quantity of wet wood was multiplied by 0.5 times 0.55 (=0.275) to estimate the fraction of available carbon in vegetation (EPA 2005).

MSW was assumed to consist of 65 percent of materials that were equivalent to vegetation (EPA 2005). Therefore the quantity of vegetation was multiplied by 0.65 X 0.55 x 0.50 (=0.179) to estimate the fraction of available carbon in MSW.

The following equations were used to calculate the amount on annual average MW that could be generated at each of the 10 Army bases studied.

- From Paper and Wood (where Paper includes Corrugated Containers, High-grade Paper, Newspaper, Mixed paper); (p+w):

    Potential Annual MW (p+w) =
        (Paper and wood total from Table 6, tons/yr) x
        (0.5 tons of carbon/ton of paper and wood) x
        (1 MWH/0.186 ton carbon) x (1 yr/8760 hrs)

- From Vegetation(v):

    Potential Annual MW (v) =
    (Vegetation from Table 6, tons/yr) x (o55 tons of dry wood/ton of wet wood) x
    (0.5 tons of carbon/ton of drywood) x
    (1 MWH/0.186 ton carbon) x (1 yr/8760 hrs)

- From MSW (m)

    Potential MW capacity (m) =
    (MSW from Table 6, tons/yr) x (0.65 tons of wet wood equivalent/ton MSW) x
    (o55 tons of dry wood/ton of wet wood) x (0.5 tons of carbon/ton of drywood) x
    (1 MWH/0.186 ton carbon) x (1 yr/8760 hrs)

Table 8 summarizes the estimated amount of electricity that could be produced from paper, vegetation, and waste, respectively.

Table 9 lists the data used to compare the total power production to the average annual demand at each base. With the exception of Fort Bragg, where the estimate for production is 33 percent of demand, the other bases fall with in the range of 8–15 percent with an average of 12 percent.

Table 8. Estimated power production from waste at the 10 largest U.S. Army installations.

Rank by Population	Facility	Annual tons Paper and Wood (p+w)	Annual Tons Vegetation (v)	Annual Tons MSW (m)	Power MW from Paper (MW)	Power from Vegetation (MW)	Power MW from MSW (MW)	Total Potential (MW)
1	Fort Bragg, NC	1337	67,114	25000	0.4	11.3	2.7	14.4
2	Fort Hood, TX	8065	4774	20874	2.5	0.8	2.3	5.6
3	Fort Campbell, KY	3820	1543	11447	1.2	0.2	1.3	2.7
4	Fort Benning, GA	340	2300	13900	0.1	0.4	1.5	2.0
5	Fort Lewis, WA	2802	1479	11900				2.4
6	Fort Leonard Wood, MO	1592	358	11200	0.4	0.0	1.2	1.6
7	Fort Jackson, SC	2760	2627	9588	0.7	0.4	1.1	2.2
8	Fort Sill, OK	2444	0	9700	0.7	0.0	1.0	1.7
9	Fort Knox, KY	3445	8	9600	1.1	0.0	1.0	2.1
10	Fort Stewart, GA	2152	0	8200	0.6	0.0	0.8	1.5

Table 9. On-installation power demand that could be produced from current waste streams at the 10 largest U.S. Army installations.

Rank by Population	Facility	Average Annual Demand Reported (MW)	Average Annual Demand calculated based on base population and 0.91 kW/person derived in Table 5 (MW)	Estimated Average Electricity production from Waste (MW)	Electrical Demand that Could be produced from Waste
1	Fort Bragg, NC		48	16.0	33%
2	Fort Hood, TX		46	6.8	15%
3	Fort Campbell, KY	~30		3.3	11%
4	Fort Benning, GA		30	2.4	8%
5	Fort Lewis, WA	27		3.1	11%
6	Fort Leonard Wood, MO		24	2.4	10%
7	Fort Jackson, SC	~20		2.8	14%
8	Fort Sill, OK	19.4		2.6	13%
9	Fort Knox, KY		18	2.7	15%
10	Fort Stewart, GA		18	2.0	11%

6.1 Suggestions for Additional Carbon Rich Fuel Production at Large Army Bases

Several of the Army installations considered in this work are located on very large expanses of land. One of the unique data points identified in this study was the very large amount of vegetation that was reported by Fort Bragg. This suggests that at least some of these bases could use a significant fraction of their land as an energy plantation to produce vegetation that could be harvested annually to produce carbon-rich solids for use in energy generation. The typical value cited in previous studies of energy plantation concepts is about 5 tons of oil-equivalent energy (equal to 2,110 MJ [200,000,000 Btu]) assuming that oil has an energy content of 46.5 MJ/kg (20,000 Btu/pound) per acre. At a heat rate for electricity production of 5.5 MJ/kWh (5250 Btu/kWh), about 250 acres of energy plantation would be required to produce 1 MW of electricity for 8760 hrs/yr. This calculation suggests an approach that could offer a long term solution to the security issue of electricity supply to individual bases. At this time, no computations have been made to estimate whether this approach could potentially be cost effective, especially in comparison to the price of electricity imported into the base.

6.2   Value of the Energy Produced

Figure 19 shows the estimated amounts of annual revenue that could be obtained by selling the power from a DCFC generating system at various annual average production capacities in MW and assumed power values in cents/kWh. For example, a constant production of 8 MW would have a value of about $5.6 million at 8 cents per kWh.

If it were assumed that the waste fuels were provided at no cost and that the operating expenses were 1 cent/kWh, then the net amount remaining to pay an assumed capital charge rate of 20 percent would be $4.9 million. This amount could justify a facilities investment of $24.5 million or $3063/kW. The various developer teams are targeting a DCFC plant price, exclusive of feed preparation, of $1500/kW. Note that, after more than three decades of efforts to lower their product prices, manufacturers of commercially offered PAFC and MCFC fuel cell power plants are currently offering their products at $3000–4000/kW. Thus it appears that the use of still-to-be developed DCFC could be feasible to produce competitive power if developers were able to meet their cost goals.
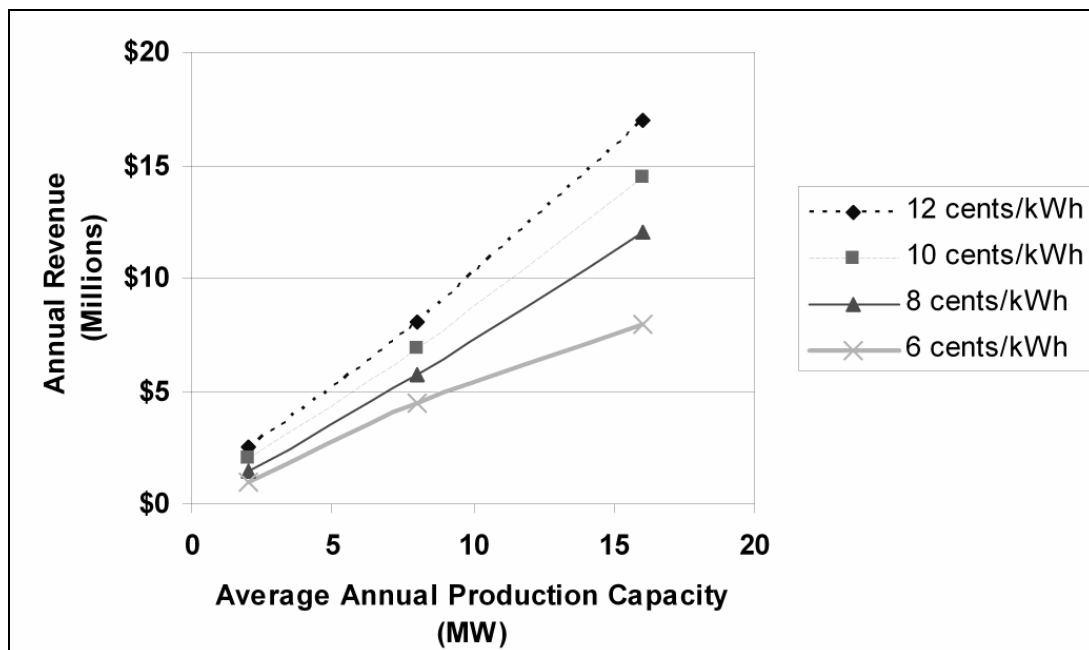

Figure 19. Estimated value of DCFC power production.

7 Electricity Dispatch Options

The production cost of electricity delivered by a generator to a customers' site varies throughout the day, as the local generating company continuously optimizes the combination of operating generating plants that are being used to meet instantaneous demand and power that can be purchased from the grid. Typically, the ratio of peak power demand to minimum power demand for individual customers is on the order of 2:1. Utility companies that supply electricity to a large number of diverse customers will typically keep those units with the lowest individual dispatch costs in service continuously. Instantaneous dispatch cost is almost totally a function of fuel cost. Therefore, the generating units in service during periods of lowest demand are those with minimum fuel cost, typically nuclear units followed by large, very efficient coal units. As demand increases, smaller, less efficient coal units are brought into service. At peak demand periods, usually corresponding to the late afternoon and early evening hours, combustion turbines fueled with relatively costly natural gas are brought into service. Many utilities base their rates to large customers in part on the amount of power required to meet peak demand requirements.

In those conceptual situations where an Army installation has been equipped with a combination Pyrolysis and DCFC system to produce some of its power from waste materials generated on base, the installation can use that system in a number of ways. The first and lowest cost approach from the standpoint of the capital investment requirement is to configure the system so that it operates with a steady flow and feed material to the pyrolysis section of the plant with all of the carbon-rich, solid fuel particles delivered continuously to the DCFC. This system will produce a constant amount of power through all periods, including minimum and maximum demand periods. It will also offer the minimum investment per unit of power delivered and the best opportunity for heat integration, and therefore maximum energy efficiency. (Figures 16 and 17 [pp 28, 28] show this system.)

At the other end of the spectrum is the approach of feeding the pyrolysis section continuously at a steady rate and delivering the carbon-rich, solid fuel product to a storage hopper. The stored fuel is then fed to the DCFC to produce power only during high demand periods. For example, a pyrolysis system designed to produce fuel to supply a 2 MW DCFC unit for 24

hrs/day could also supply the fuel required by a 6 MW DCFC unit that op-
erates only 8 hrs/day. This option has the disadvantage in that it requires
an additional investment for a carbon-rich particle storage system and a
much more significant additional investment for purchase of 4 MW of ad-
ditional DCFC capacity. (Figure 18 [p 29] shows this system.)

The economics of these cases depend very strongly on whether the local
rates for power from the grid differ significantly as a function of time of
day and whether there is a capacity charge for power that is based on peak
load use. Each Army base will have to determine if there is any potential
advantage in moving from a simple steady-state, continuously operating
system to one that is configured for intermittent power production.

8   Conclusions

This work concludes that DCFC technology offers a unique approach for the direct conversion of biomass-derived, carbon-rich solid fuel directly to electricity at very high conversion, likely to be over 80 percent with the production of a CO_2-rich flue-gas. This conversion rate surpasses the best overall efficiency anticipated for future biomass combustion plants, which is about 25–30 percent. (This estimate relates only to the particulate carbon supplied to the DCFC.)

In a well integrated system, the waste energy from the fuel cell would provide sufficient heat to perform the drying step, and the energy from the gas produced in the pyrolysis step would exceed the energy consumption for the pyrolysis operation. Note that pyrolysis technology is commercially available with at least one new approach, developed at the University of Hawaii, identified that has the potential for reducing production costs.

This work also concludes that the amount of waste available for conversion to electricity with a pyrolysis/DCFC system at nine of the 10 largest Army installations studied would support electricity production ranging from 8–15 percent (averaging 12 percent) of their annual average electricity consumption. The tenth Army installation studied, Fort Bragg, could produce 33 percent of its annual average electricity demand from installation-generated wastes. Furthermore, researchers noted that additional vegetation-based energy could be produced on installation land. However the economics of these "energy plantations" was beyond the scope of this study.

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Acronyms and Abbreviations

Term	Spellout
AC	alternating current
CERL	Construction Engineering Research Laboratory
DCFC	Direct Carbon Fuel Cell (DCFC)
DOD	Department of Defense
USEPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERDC	Engineer Research and Development Center
CERL	Construction Engineering Research Laboratory
ES	Electrical System
GA	Georgia
HHV	Higher Heating Value
HQ	headquarters
IL	Illinois
JP-8	JP-8 (Jet Propellant)
KOH	potassium hyroxide
MCFC	Molten Carbonate Fuel Cell
MSW	Municipal Solid Waste
MW	megaWatt
MWH	megawatt hour
PAFC	Phosphoric Acid Fuel Cell
SARA	Superfund Amendments and Reauthorization Act
SC	South Carolina
SF	square feet
SOFC	Solid Oxide Fuel Cell
TNT	trinitrotoluene
TR	Technical Report
UCF	University of Central Florida (UCF)
URL	Universal Resource Locator
USEPA	U.S. Environmental Protection Agency
WWW	World Wide Web
YSZ	Yttria-Stabilized Zirconia

Appendix A: Army Personnel Contacted

Rank	Facility	Personnel Contacted, Waste Information	Telephone Numbers
1	Fort Bragg, NC	Kristina Wilson	910-396-0011 910-432-8482
2	Fort Hood, TX	Jim Salmon Emily Silva	254-287-2131
3	Fort Campbell, KY	Mike Davis Doug Foster	270-798-2151 207-798-9767 207-798-3474
4	Fort Benning, GA	Dorinda Morpeth Ted Williams	706-545-2011
5	Fort Lewis, WA	Ron Norton Phil Crawford Jim Averamp	253-967-1110
6	Fort Leonard Wood, MO		573-563-4013
7	Fort Jackson, SC	Ed McDowerll George Dibb	803-751-1110
8	Fort Sill, OK	Steve Hankins Andrew Bennett	580-442-3608
9	Fort Knox, KY	Danny McGar	502-624-8186
10	Fort Stewart, GA	Denise Kelley	912-767-5027
	Army Environmental Center	Charles Harris	410-436-1224

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14. ABSTRACT

The U.S. Army has policies to minimize production of waste materials, maximize recycle of waste materials, and minimize energy consumption on its installations. A beneficial way to implement these policies is to convert paper, wood, vegetation, and Municipal Solid Waste (MSW) fractions into a carbon-rich feed stock by pyrolysis to fuel Direct Carbon Fuel Cells (DCFCs). DCFCs potentially offer a unique approach for the direct conversion of biomass-derived, carbon-rich solid fuel to electricity at very high conversion, with the production of a CO_2-rich flue-gas. This work gathered information on the quantities of waste material available at U.S. Army installations from installation reports and from the U.S. Army Solid Waste Annual Reporting System (SWARS) database, then estimated the amount of electricity that DCFC technologies could generate from those wastes, and finally compared those amounts with the current average annual electrical loads at the 10 largest Army installations.

15. SUBJECT TERMS

direct carbon fuel cells (DCFC)	fuel cells	energy efficient
electric power consumption	solid waste reduction	

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