Available for licensing

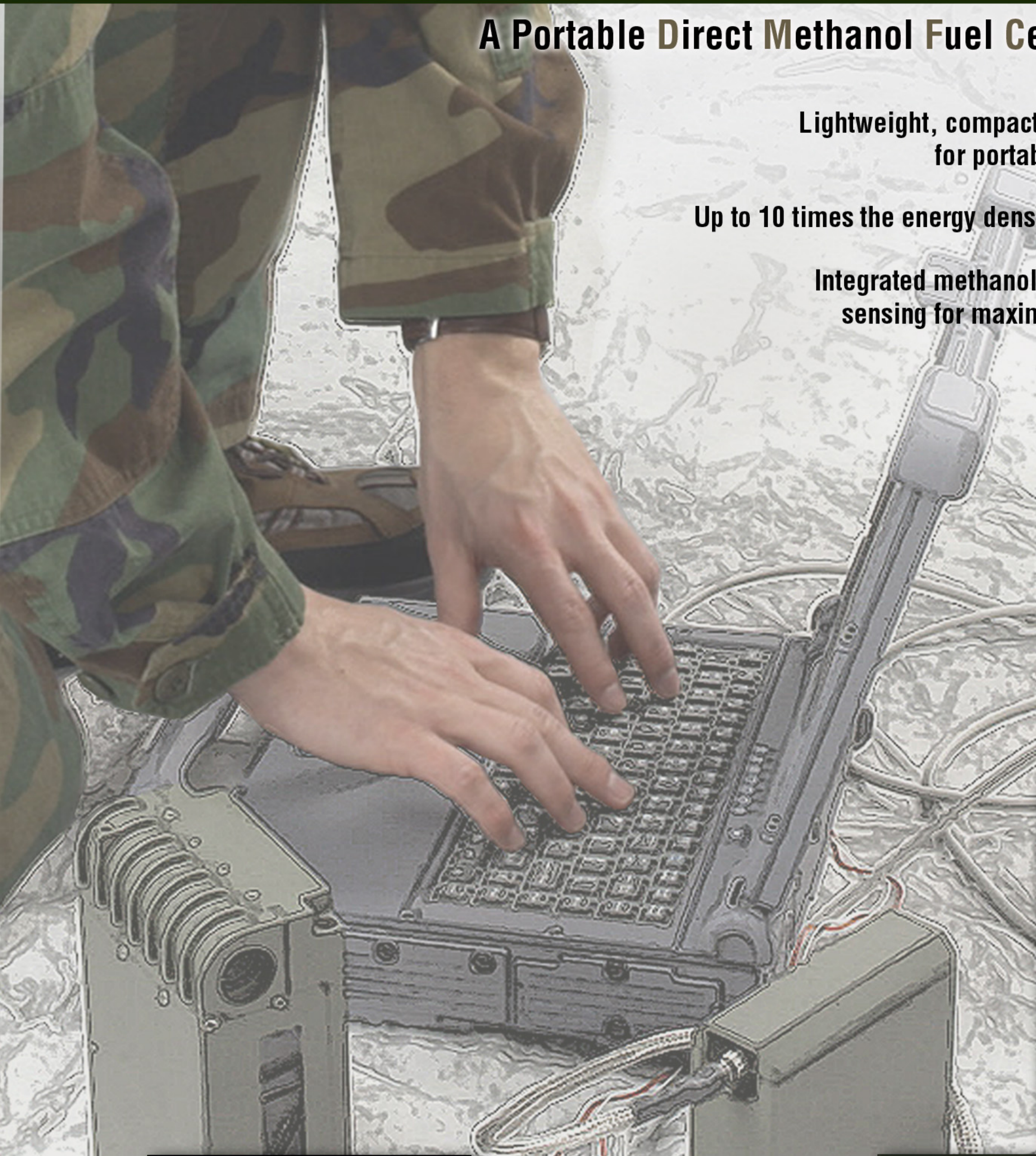
DMFC-20

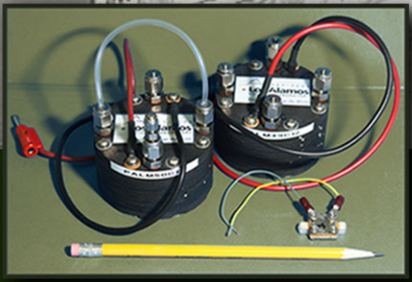
A Portable Direct Methanol Fuel Cell System

Lightweight, compact power supply for portable electronics

Up to 10 times the energy density of batteries

Integrated methanol concentration sensing for maximum efficiency





Los Alamos
NATIONAL LABORATORY

LAUR-05-7787

DMFC-20 Portable Power System

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ABOUT THE COVER

The DMFC-20, a portable direct methanol fuel cell system, efficiently and reliably delivers 20 watts of electric power to laptop computers, camping equipment (lantern), and other portable devices. The cover's main image shows the packaged DMFC-20 (left) and methanol cartridges enclosed in a case (right). The lower left inset depicts two individual methanol cartridges. The lower right inset shows the system's power supply—two small direct methanol fuel cell stacks. These stacks combine with other components to create a compact, lightweight, energy-efficient power source for applications with stringent size and weight requirements.

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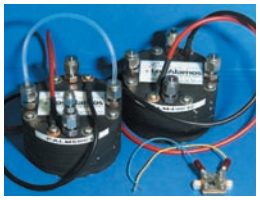


Executive Summary

DMFC-20 Portable Power System

Features

The DMFC-20 is a compact, highly energy efficient, direct methanol fuel cell power system that is designed to deliver 20 watts of electric power for use in portable military applications. Portable devices are also in great demand in the civilian sector, and potential industrial partners are interested in moving the DMFC-20 to the commercial market. When operated for a month, the DMFC-20 can provide up to 10 times the energy density (or specific energy) of batteries. A lightweight, integrated methanol sensor ensures that the DMFC-20 operates with maximum fuel-conversion efficiency. The DMFC-20's high specific energy and very efficient fuel conversion distinguish our system from other direct methanol fuel cells.

Applications

Commercial applications (given proper licensing):

- portable electronics
- battery chargers
- household tools
- long-operating air-quality sensors (e.g., carbon dioxide sensors)
- remote road signs
- camping equipment
- electric scooters (hybrid systems with rechargeable battery)
- forklifts (hybrid systems with rechargeable battery)

Military applications:

- auxiliary power
- battery chargers
- deployed field sensors

Benefits

- Compact and lightweight for portable applications
- Up to 10 times the specific energy of batteries
- High fuel-conversion efficiency
- Integrated methanol concentration sensing for maximum efficiency

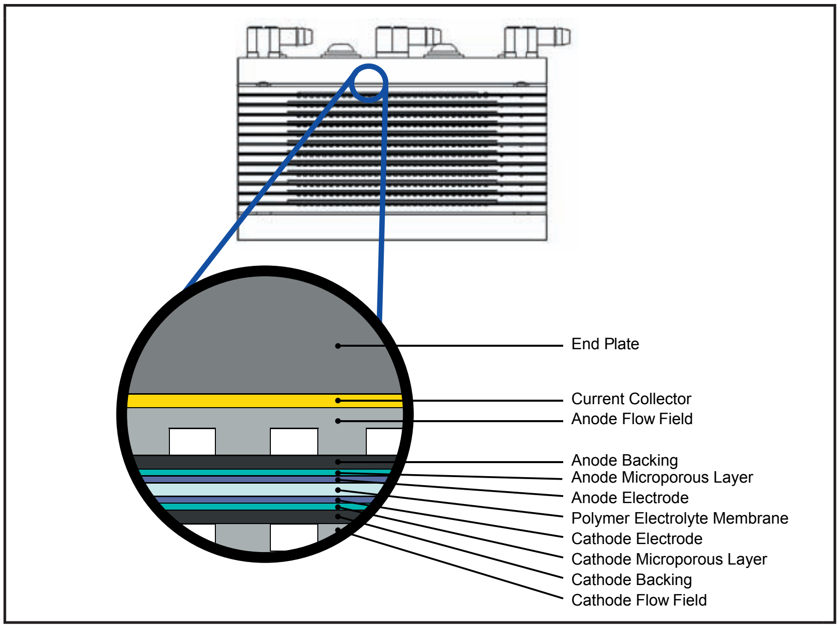
Overview

U.S. ground troops face a serious weight problem. Today's soldier must carry not only a weapon but also a vast array of electronic equipment, along with batteries to power that equipment, throughout a mission's duration. A soldier's gear can weigh close to 100 pounds, which is an extremely taxing burden for ground troops. A primary goal of the U. S. Army's Objective Force Warrior program is to lighten this load to about 40 pounds within a decade. The DMFC-20 Portable Power System offers a potential solution to the military's weight problem.

Our direct methanol fuel cell (DMFC) power system is designed to reliably and efficiently deliver 20 watts of electric power for use in portable military applications—in a compact, lightweight package that will not hamper a soldier's mobility. The Defense Advanced Research Projects Agency (DARPA) considers the DMFC-20 a promising portable power source for soldiers, and the U. S. Army has begun to evaluate its potential. Our system is also of interest in the commercial sector, where power requirements for portable electronic devices are rapidly outpacing the capabilities of today's batteries.

The primary components of the DMFC-20 are two small 12-cell DMFC stacks. Supporting components include a system controller, anode and cathode fluidics modules, a methanol cartridge, and an integrated methanol concentration sensor, all designed to minimize space requirements and keep weight as low as possible. The combination of effective system integration with an innovative stack technology makes the DMFC-20 an attractive power source for portable applications.

Like an ordinary battery, the DMFC-20 provides direct-current electricity from two electrochemical reactions that occur at the fuel cell's negative (anode) and positive (cathode) electrodes. However, unlike batteries, which are energy-storage devices, the DMFC-20 is an electrochemical energy converter, in which the chemical energy of methanol is directly converted into electricity. The DMFC-20 can generate power for as long as reactants are supplied to the electrodes. Methanol, a very high-energy fuel, is the anode reactant, and air is the cathode reactant.



Section diagram and detail of DMFC-20 stack.

Graphite plates at each end of a DMFC-20 stack (the end plates) provide structural support and compressive force distribution across the stack. Thinner, electronically conductive graphite plates, called bipolar plates, separate cells within a stack. These plates contain an anode flow field and a cathode flow field on opposite sides. Anode and cathode electrodes in each cell are in contact with opposite sides of a polymer electrolyte membrane, forming a membrane electrode assembly. A porous diffusion layer or "backing" placed between the flow fields and the electrode surface gives even reactant coverage across the electrodes. The accompanying section diagram shows the stack components.

Methanol diluted with water is fed to the anode feed manifold and distributed to each cell's anode flow field. The methanol then diffuses through the backing to the anode catalyst, where it reacts with water to form carbon dioxide, protons, and electrons. The membrane allows protons to pass through, while the electrons flow back through the backing, the bipolar plate, and an external electric circuit to the cathode. Carbon dioxide flows back through the backing to the anode flow field and then out of the stack.

On the cathode side of the system, filtered air is pumped to each cell. The air flows through the cathode flow field and diffuses across the backing to the cathode. At the cathode, oxygen from the air reacts with the protons and electrons to form water. This water then diffuses back through the backing, through the flow field, and out of the stack, where some of it is recovered to maintain water balance within the system. As a result of a difference in potential between the cathode and the anode, each cell in the stack generates a voltage. The sum of individual cell voltages gives the total stack voltage that drives electrons (current) through the external electric circuit.

The DMFC-20's system controller is a microprocessor that monitors the stacks and other system components and adjusts system operating parameters. Anode and cathode fluidics modules contain all the pumps, sensors, and filters required to direct impurity-free reactant streams to their respective electrodes. The disposable fuel cartridge, located external to the DMFC-20, is a lightweight and inexpensive lined aluminum can. The volume of the cartridge outside the liner is pressurized by a pump within the DMFC-20, ensuring that all methanol in the cartridge is extracted (in a fashion similar to that of a baby bottle).

The methanol concentration sensor accurately determines the amount of methanol in the feed stream in the presence of dissolved gases and trace organic or inorganic contaminants and under varying operating conditions, such as changing temperature and solution density. The sensor determines methanol concentration based on the rate of methanol diffusion through a polymer electrolyte membrane similar to that used in the stack cells. This diffusion is known as “methanol crossover.” The crossover rate is proportional to the methanol concentration in the anode feed stream; that is, as methanol concentration increases, the diffusion rate also increases. The diffusion current is measured over a suitable methanol concentration range at a fixed voltage (the “bias” voltage) applied between two sensor electrodes, which are separated by the methanol-permeable membrane. Methanol concentration data is fed to the system controller, which then determines how much pure methanol should be injected into the anode feed loop to maintain the target concentration.

The Appendix includes photos of the system, system specifications, and a detailed description of the system’s operation.

Competition

Batteries

- McDowell Research Corporation, lithium/sulfur dioxide primary (disposable) battery BA-5590
- Electric Fuel Corporation, zinc-air primary battery BA-8180

Other Portable-Power DMFCs

- Smart Fuel Cell A25
- Smart Fuel Cell C25—This DMFC system is more compact and lightweight than Smart Fuel Cell’s A25 system. Because the first C25 systems are just now being delivered for testing in the U. S., test data are not yet available. Therefore, the C25 is not included in the comparison matrix.
- Some companies, such as MTI MicroFuel Cells and Mesoscopic Devices, are developing DMFCs intended to deliver power at a scale similar to that of the DMFC-20. However, because these systems are not currently as developed as the DMFC-20, we have not included them in the comparison matrix. Likewise, although Toshiba announced a DMFC pack for powering laptop computers almost a year ago, it is not yet commercially available and therefore is not included in the comparison matrix.

Other Types of Fuel Cells

There are other fuel cell technologies under development today for portable applications, including the direct hydrogen fuel cell (DHFC) and the solid oxide fuel cell (SOFC). However, technical challenges with both technologies will prevent them from becoming viable alternatives to DMFC technology anytime soon, and we have therefore not included them in the comparison matrix. Storage is a major problem for all hydrogen fuel cells, and the extremely high operating temperatures of SOFCs are problematic for a power supply that will be carried by a soldier.

Comparison matrix

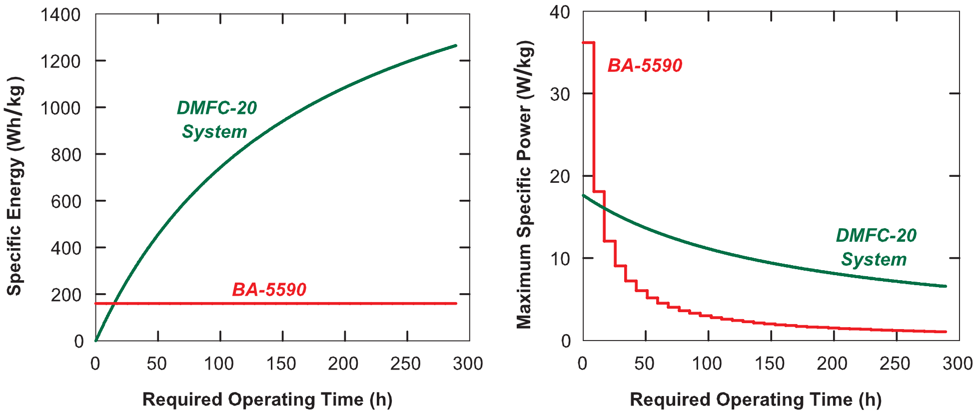
Parameters	**DMFC-20**	**Smart Fuel Cell A25 (with two fuel cartridges)**	**BA-5590 Lithium/Sulfur Dioxide Primary Battery (nine batteries)**	**BA-8180 Zinc-Air Primary Battery (three batteries)**	**Comments**
Nominal Power	20 W (at 33% efficiency)	25 W	≤ 38 W	≤ 48 W	Nominal power is the power of a continuously operating system. In the case of batteries, which are purely load-following devices, nominal power can be any power value between zero and the maximum power.
Maximum Power	~30 W	25 W	38 W	48 W	Maximum power delivery from Smart Fuel Cell's A25 system requires a 4 amp-hr battery buffer connected to the fuel cell stack (good for up to 80 W for as long as the battery remains charged).
System Efficiency	**33%** (at nominal power)	14% (at nominal power)	NA	NA	System efficiency is the ratio of electrical energy delivered by the system to the chemical energy of the fuel used. The term is applicable to fuel cells, which are energy-conversion devices, but not to batteries, which are energy-storage devices. **The DMFC-20's system efficiency is nearly 2.5 times that of Smart Fuel Cell's A25 system.**
Specific Energy	**0.55 kWh/kg**	0.12 kWh/kg	0.15 kWh/kg	0.18 kWh/kg	Specific energy is system energy content per unit mass (kWh/kg). The average specific energies given here are for 72 hours of continuous operation. **The DMFC-20's specific energy is between 3 and 4.5 times that of the other systems listed.**
Specific Power	**11 W/kg**	2 W/kg	4 W/kg	6 W/kg	Specific power is maximum output power per mass of the system with fuel cartridge(s) (W/kg); power is for 72 hours of continuous operation. **The DMFC-20's specific power is more than 5 times that of Smart Fuel Cell's A25 system and almost 2 times that of the BA-8180.**

Comparison matrix (cont.)

Parameters	**DMFC-20**	**Smart Fuel Cell A25 (with two fuel cartridges)**	**BA-5590 Lithium/Sulfur Dioxide Primary Battery (nine batteries)**	**BA-8180 Zinc-Air Primary Battery (three batteries)**	**Comments**
Cost	**$0.08–$0.16/Wh**	No data available	$0.70–$1.44/Wh	$0.15–$0.20/Wh	**The DMFC-20 delivers the least-expensive power.**
Robust	**Yes**	No	**Yes**	**Yes**	All power sources except for the Smart Fuel Cell A25 can withstand the rigors of military applications.
System Volume	**3.1 L**	24.3 L	7.9 L	10.3 L	Volume is for 72 hours of continuous operation, including fuel (in the case of the DMFC systems). **The DMFC-20's volume is from 2.5 to almost 8 times less than that of competitive power sources.**
Weight	**2.7 kg**	11.9 kg	9.5 kg	8.1 kg	Weight is for 72 hours of continuous operation. **The DMFC-20 system is from 3 to more than 4 times lighter than competitive power sources.**

Advantages

The main advantage of the DMFC-20 over lithium/sulfur dioxide and zinc-air primary batteries is its use of methanol, a very high-energy fuel (6.1 kilowatt-hours per kilogram at 25° Celsius). Thanks to the unique membrane electrode assembly and stack technology developed at Los Alamos, as well as the expert system-integration approach by an industrial collaborator, we have already demonstrated the DMFC-20's tank-to-user (fuel conversion) efficiency to be at least 33 percent. For a typical military or civilian "mission" lasting three days (72 hours), 33-percent system efficiency translates into an average specific energy (energy capacity per unit mass) of 0.55 kilowatt-hour per kilogram. This average is almost four times that of the BA-5590 battery—used by the military today—and three times that of the BA-8180 battery.



DMFC-20 and BA-5590 specific energy (left) and maximum specific power (right) curves as a function of operating time.

Thus, with the fuel cell technology described here, a user in need of a 20-watt power source for 72 hours is offered a choice between a battery pack and a DMFC system with one-fourth the weight. (The latter weight factor depends on the mission duration; it will go down for shorter missions and up for longer missions.)

The figure shows that for a 288-hour (12-day) mission, the specific energy of the DMFC-20 is approximately 8 times that of the BA-5590 battery. The factor increases to more than 10 times that of the BA-5590 after 28 days of operation. In general, the longer the required usage, the clearer the DMFC-20 advantage becomes.

While system efficiency and specific energy set DMFCs apart from primary batteries, the DMFC-20 also stands out among other DMFCs in the portable power category. First, the DMFC-20 has already been packaged into a functioning prototype. Its design is robust enough for military use, and the fuel cell is currently being prepared for field testing. The U. S. Army has ordered eight DMFC-20 systems, for which delivery is planned in April 2004.

Second, the DMFC-20's fuel-conversion efficiency is higher than that of other DMFC systems. In theory, fuel-conversion efficiencies could be as high as 80 to 83 percent. In reality, however, the efficiency of a DMFC system at a high voltage, such as 0.55 volt per cell used by the DMFC-20, is expected to be between 36 and 40 percent. Fuel losses from diffusion crossover and evaporation, activation and concentration polarization overpotentials at electrodes, and ohmic (electrically resistive) losses may all contribute to reductions in fuel-conversion efficiency. The DMFC stacks developed at Los Alamos, especially the proprietary membrane electrode assemblies used in the cells, are designed specifically to deliver high performance at high voltage, reducing losses and increasing efficiency.

Third, the DMFC-20's specific energy has distinguished it among other DMFC systems. Reduced part count, enhanced materials, function integration, and improved fabrication tolerances have reduced the DMFC stack mass. Engineering efforts at an industrial collaborator have reduced the mass of individual system components without impairing overall robustness. Smart Fuel Cell's A25 system is much larger and heavier than the DMFC-20.

Applications

Principal commercial applications (given proper licensing) include using the DMFC-20 as a power source for

- portable electronics (laptop computers, personal digital assistants, portable radios and televisions),
- battery chargers, and
- camping equipment.

Military applications involve soldiers using the DMFC-20 as a portable power source to

- provide auxiliary power,
- recharge batteries, and
- power deployed field sensors.

Other applications

The DMFC-20 can also be used to power the following:

- Household tools (e.g., nonpolluting power push mowers, cordless vacuum cleaners)
- Long-operating air-quality sensors (e.g., carbon dioxide sensor)
- Remote road signs
- Electric scooters (hybrid systems with rechargeable battery)
- Forklifts (hybrid systems with rechargeable battery)

Summary

The DMFC-20 system demonstrates the potential that fuel cells have in powering portable and mobile electric and electronic devices. Our compact, lightweight DMFC system stands out among other portable DMFC systems because of its high fuel-conversion efficiency, excellent specific energy, market readiness, and robust packaging for military and outdoor civilian use.

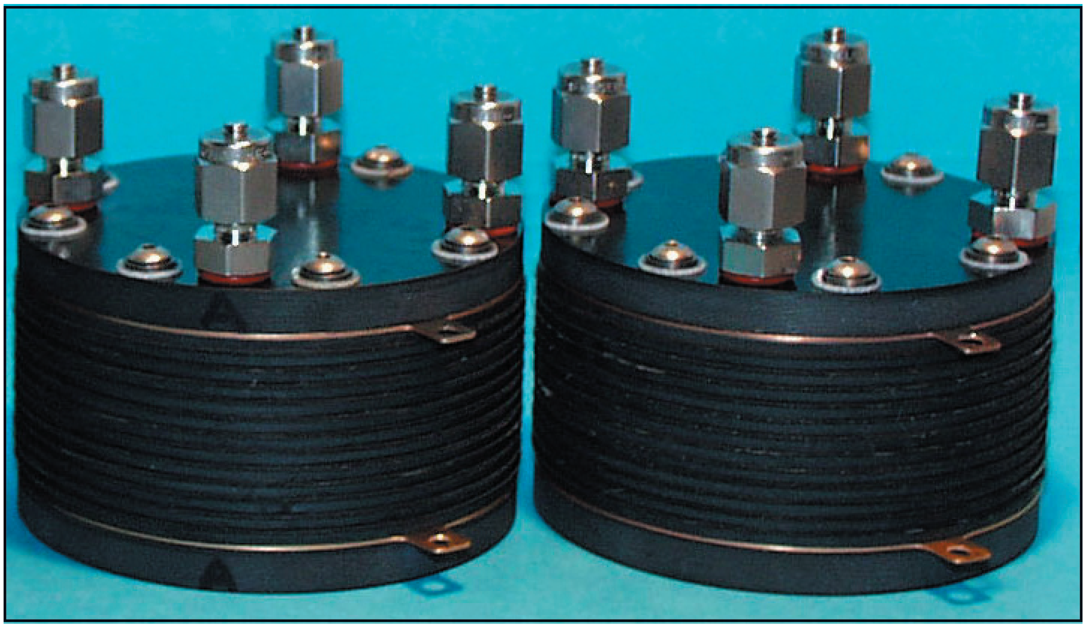
Successful military implementation and development will help drive down fuel cell costs, making the system very appealing to industrial partners.

Weight reduction efforts planned for the next year will make our system even more attractive to the military and commercial sectors. Our goals are to reduce stack weight from 650 to 250 grams and weight of the supporting components from 975 grams to 800 grams. These reductions should increase the system's specific energy to at least *0.78 kilowatt-hour per kilogram* (for a 72-hour mission), *5 times* the specific energy of a BA-5590 lithium/sulfur dioxide primary battery.

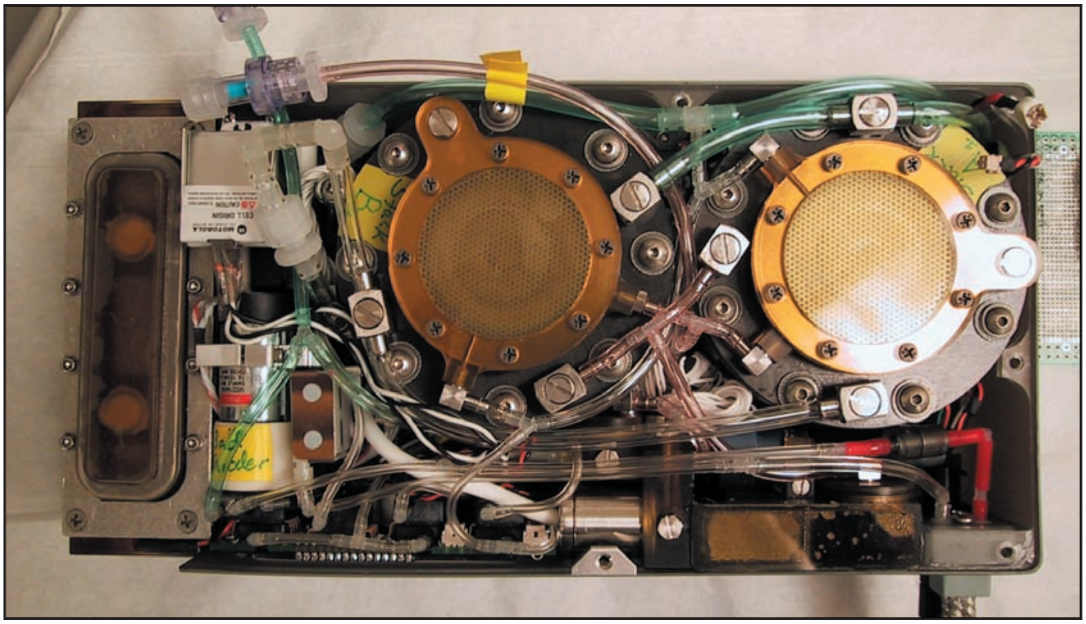
Appendix

Photographs of DMFC-20
DMFC-20 Specifications
DMFC-20 Operation

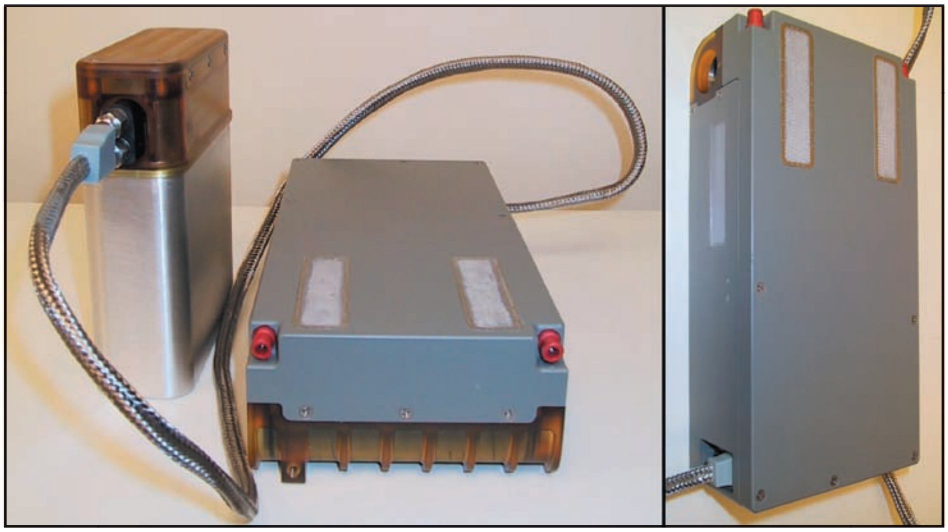
Photographs of DMFC-20



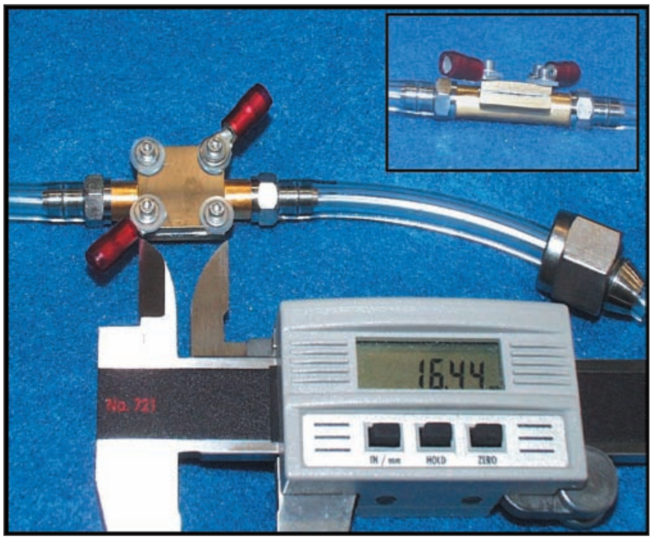
A pair of Los Alamos stacks used in the DMFC-20 power system



Complete DMFC-20 (two stacks) with top cover removed



DMFC-20 with methanol cartridge on the left



Methanol concentration sensor developed and built at Los Alamos. The sensor is integrated into the DMFC-20 system as a key control element.

DMFC-20 Portable Power System Specifications

Continuous net power	20 W (load following)
DC voltage	12 V
Warm-up time	10 min (maximum)
Energy yield from fuel	2.0 kWh/kg
Fuel-conversion efficiency	33%
Converter weight	1.7 kg
System specific energy for 72-hour mission	0.55 kWh/kg (current) 0.78 kWh/kg (future)
Current technology readiness level (TRL)	6 (estimated)

DMFC-20 Operation

The DMFC-20 is a portable, compact, and lightweight system, designed to deliver 20 watts of electric power efficiently and reliably. The primary components of the system are a pair of direct methanol fuel cell (DMFC) stacks, which serve as the power supply. Supporting components include a system controller, anode and cathode fluidics modules, a methanol cartridge, and an integrated methanol concentration sensor.

Unlike batteries (which are energy-storage devices), the DMFC-20 is an electrochemical energy converter, in which the chemical energy of methyl alcohol (methanol) is directly converted into electricity. Combustion engines (another form of energy converter) are limited in their energy-conversion efficiency because some heat energy must always be rejected (Carnot thermal engine). In a fuel cell, the efficiency is not limited in this way, and the efficiency may be much higher (depending on operating temperatures) as a result. In theory, fuel cell efficiencies could be as high as 80–83 percent. In reality, however, the efficiency of a DMFC system with 0.55 volt per cell is roughly 40 percent. Fuel losses from crossover and evaporation, activation and concentration polarization overpotentials at electrodes, and ohmic (electrically resistive) losses may all contribute to reductions in fuel cell efficiency.

A fuel cell, like an ordinary battery, provides direct-current electricity from two electrochemical reactions. The reactions occur at negative (anode) and positive (cathode) electrodes to which reactants are continuously fed. In the case of the DMFC-20, methanol is the anode reactant and air is the cathode reactant. Carbon dioxide and water are the byproducts of the two reactions.

In an individual fuel cell, the anode and cathode are in contact with opposite sides of a polymer electrolyte membrane, forming a membrane electrode assembly (MEA). Reactant is fed to the cell by means of serpentine channels, or flow fields, machined into electronically conductive graphite plates on the anode and cathode sides. The plates, called bipolar plates, separate one cell from another and contain an anode flow field and a cathode flow field on opposite sides. A porous diffusion layer or “backing” placed between the flow fields and the electrode surface gives even reactant coverage across the electrodes. Multiple cells connected in series form a fuel cell stack. The DMFC-20 uses two 12-cell stacks.

An end plate at each end of a stack provides structural support and even compressive force distribution across the stack. The DMFC-20’s end plates also serve as current taps, where an external circuit may be connected to the stack. The end plates are made of graphitic materials, and each is machined on one side, with flow fields to supply reactant solution to the adjacent cells. The DMFC-20's negative (anode) end plate has ports through which anode and cathode reactants are fed into the stack. Methanol (the anode reactant) is a fuel with a high specific energy, or energy per unit mass, of 6.1 kilowatt-hours per kilogram at 25° Celsius. The cathode reactant is air drawn in from the atmosphere and filtered to remove particle contaminants. The reactants are distributed to the individual cells of a stack via manifolds within the stack assembly.

The methanol is fed into the system from an external cartridge and diluted with water recovered from the cathode reaction before being fed through the anode end plate to the anode feed manifold, where it is then distributed to each cell's anode flow field. From the flow field, the methanol solution diffuses through the backing to the anode catalyst, where it reacts with water to form carbon dioxide, protons, and electrons. The membrane is selectively permeable, allowing only protons to pass through, while the electrons flow back through the backing, the bipolar plate, and an external electric circuit to the cathode. The carbon dioxide flows back through the backing to the anode flow field and then out of the stack via the anode outlet manifold. Some methanol does not react at the anode and instead diffuses across the membrane and reacts with oxygen from the air at the cathode, driving down the cell's voltage. This phenomenon is called methanol crossover. Because the methanol fed into the stack is not consumed in one pass, the anode outlet is fed into a pair of gas separators that remove the carbon dioxide from the fluid stream; the stream then passes through an ion-exchange filter before being circulated back into the stack. An integrated methanol sensor monitors the methanol concentration of the anode feed stream, providing closed-loop feedback to the system controller, which determines how much pure methanol and make-up water are needed to maintain a constant anode feed concentration.

On the cathode side of the system, filtered air is pumped through the anode end plate and into the cathode inlet manifold, where it is distributed to individual cells. In each cell, air flows through the cathode flow field and diffuses across the backing to the cathode. At the cathode, oxygen from the air reacts with the protons (which have diffused across the membrane from the anode reaction) and electrons (which have conducted across the bipolar plate from the neighboring cell's anode reaction) to form water. This water then diffuses back across the backing, through the flow field and cathode outlet manifold, and out of the stack, where some of it is recovered in a condenser to dilute methanol in the anode feed loop. As a result of a difference in potential between the cathode and the anode, each cell in the stack generates a voltage, and the more cells there are in a stack, the higher the voltage that drives electrons through the external circuit.

The DMFC-20's integrated methanol sensor accurately determines methanol concentration in the presence of dissolved gases and trace organic and ionic contaminants and under variable conditions, such as changing temperature and solution density. Like the fuel cell stacks, the methanol sensor includes an MEA, backings, and gaskets. The sensor determines methanol concentration based on methanol crossover. The methanol crossover current is proportional to the methanol concentration of the anode feed steam. As methanol concentration increases, crossover current also increases. The methanol crossover current is measured at an applied voltage of 0.8 volt over a concentration range suitable for DMFCs. This information is fed to the DMFC-20 system controller, which then determines how much pure methanol and make-up water should be injected into the anode loop to maintain the target concentration. If higher concentrations of methanol are desired (e.g., approximately 1 molar), it may be necessary to regulate the current drawn from the methanol sensor by restricting the sensor's active area.

The DMFC-20 stack would not be capable of delivering power without the other supporting components. For a system such as the DMFC-20, with stringent requirements for size and efficiency, designing and packaging these components is not at all trivial, requiring a very large investment of resources on the part of an industrial collaborator Aerospace and Technologies Corporation. All of the supporting components are designed to create as small a parasitic load as possible, while maintaining a very compact, space-efficient, and lightweight overall package. The result is a device that can supply a U. S. soldier in the field with reliable power without excess weight and bulk—no large numbers of heavy spare batteries, but only a couple of small, lightweight methanol cartridges and one DMFC-20 energy converter.

Perhaps the most critical supporting component is the system controller. This microprocessor monitors system and stack conditions and directs appropriate actions depending on system load and environmental conditions. The controller uses programmed control strategies to correctly respond to a variety of system conditions or failures.

Anode and cathode fluidics modules contain all the pumps, sensors, and filters required to provide anode and cathode reactant flow. The anode fluidics module contains all the components necessary to supply pure methanol and make-up water to the anode feed loop while removing ionic contaminants and carbon dioxide gases. The cathode fluidics module supplies the stack cathode with fresh air and recovers water from the cathode exhaust needed to replenish the anode make-up water supply. The condenser recovers water from the cathode exhaust stream and also rejects excess heat from the system. The cathode fluidics module then releases excess air, carbon dioxide, and water from the system.

The disposable fuel cartridge, located outside the packaged DMFC-20, is a lightweight and inexpensive lined aluminum can. The volume of the cartridge outside the liner is pressurized by a pump within the DMFC-20, ensuring that all methanol stored within the cartridge is extracted (in a fashion similar to that of a baby bottle).