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Waste to Watts and Water

Enabling Self-Contained Facilities Using Microbial Fuel Cells

Amanda Sue Birch, P. E.

Major, USAFR

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Wright Flyer Paper No. 37

Please send inquiries or comments to
Editor
The Wright Flyer Papers
Air Command and Staff College (ACSC/DEI)
225 Chennault Circle, Bldg. 1402
Maxwell AFB AL 36112-6426
Tel: (334) 953-6810
Fax: (334) 953-2269
E-mail: ACSC@maxwell.af.mil

AIR UNIVERSITY
AIR COMMAND AND STAFF COLLEGE

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Disclaimer

Foreword

It is my great pleasure to present another of the *Wright Flyer Papers* series. In this series, the Air Command and Staff College (ACSC) recognizes and publishes our best student research projects from the prior academic year. The ACSC research program encourages our students to move beyond the school's core curriculum in their own professional development and in "advancing air and space power." The series title reflects our desire to perpetuate the pioneering spirit embodied in earlier generations of Airmen. Projects selected for publication combine solid research, innovative thought, and lucid presentation in exploring war at the operational level. With this broad perspective, the *Wright Flyer Papers* engage an eclectic range of doctrinal, technological, organizational, and operational questions. Some of these studies provide new solutions to familiar problems. Others encourage us to leave the familiar behind in pursuing new possibilities. By making these research studies available in the *Wright Flyer Papers*, ACSC hopes to encourage critical examination of the findings and to stimulate further research in these areas.

JIMMIE C. JACKSON, JR.
Brigadier General, USAF
Commandant

Abstract

Lack of investment in future agile combat-support technologies could lead to a strategic surprise that diverts military attention and resources from critical air, space, and cyber operations. Looking to the national security environment in 2030, this research explores one technology—the microbial fuel cell (MFC)—that gives life to self-contained facilities decoupled from vulnerable supply lines and infrastructure networks. MFCs can dispose of waste (sewage, food scraps, gray water, etc.) while producing clean water (up to 70 percent of required volumes) and power (up to 600 watts per person). Using relevance tree methodology, the research concludes that USAF research and development investment alone will not bring MFCs to fruition. A successful strategy for MFCs will be collaborative, addressing not only the technological barriers but also the key social, industrial, and political hurdles to enabling this capability. Fully developed, this technology could save up to $50 million a day for a 150,000-person deployment. Beyond cost and mobility advantages, MFCs could enable homeland security against the terrorist threat and provide power, water, and sanitary waste disposal after wars or natural disasters. They could also bolster the legitimacy of stressed governments, offer security against chronic water and energy shortages, and function in isolated areas as well as urban centers. In addition to military uses, MFCs could become a diplomatic and economic tool to pursue a better state of peace by building a foundation for democratic and economic development.

Preface

Throughout my career in the United States Air Force, I have had the opportunity to see engineering technologies from two very different angles. I began my career as a research and development mechanical engineer at the Air Force Research Laboratory. I worked with technologies for the 30-year time horizon daily, which formed my ideas about strategic thinking for technology. Five years into my career, I became an Air Force civil engineer, responsible for operations, maintenance, and repair of facilities and infrastructure as well as future construction. Though innovators populate both career fields, Air Force civil engineers are generally more concerned about today's crises than future capabilities. The nature of our business forms us into loyal servants who always find innovative ways to "git 'r done." Furthermore, our operational pace leaves little opportunity to pontificate on capabilities for the 30-year horizon. This creates strategic vulnerabilities because we build our facilities and infrastructure to last, and they must enable air, space, and cyber power for nearly a century. I am thankful that I had an opportunity to begin to reconcile the differences in engineering thinking across these two career fields and merge the best characteristics into an idea that could contribute to national security.

I would like to thank Dr. John Ackerman and Dr. Glenn Johnson for their advice, enthusiastic support, and genuine interest in my research. Thanks also go to the Blue Horizons staff for providing a framework from which I could begin to shape an articulate argument. Col Rich Fryer, Maj Milt Addison, and the Air Force Civil Engineer Support Agency team also provided fantastic support for my research. Finally, I would like to thank God, the Ultimate Provider, who has blessed me with my dear husband. Paul, I thank you for your love and support during this year apart, but especially for your patience in allowing me to process aloud many random thoughts that eventually made their way into this product.

Introduction

The year is 2030. At a major US expeditionary base the power grid has failed, and limited fuel is available for purchase. Water reservoirs are nearly empty, and now fear is spreading that militants have contaminated available water resources. Health concerns take center stage as the sewage treatment plant and waste disposal systems stop working. Thankfully, the USAF has a powerful weapon that can save the day. After 20 years of research and development, the microbial fuel cell (MFC) gives expeditionary and home-station commanders a capability to produce clean energy and clean water while using only wastewater and other organic wastes as fuel.

Should the USAF bolster MFC research to give life to self-contained facilities decoupled from the infrastructure network? The USAF should invest in MFC research because this technology gives life to sustainable facilities decoupled from the infrastructure network, a key capability for national security in the 2030 environment. MFC capabilities, however, will not find success via research and development (R&D) investment alone. The USAF must collaborate within the Department of Defense (DOD) and beyond while taking a holistic systems approach to bring MFC capability to fruition. A successful strategy for MFCs will address not only the technological barriers but also the key social, industrial, and political hurdles that will bring about significant monetary and resource savings for the USAF.

The research methodology applied to capture all of these potential hurdles in MFC technology is the relevance tree. According to a report from the Futures Group International, this analytic technique ensures comprehensive exploration of a problem by breaking the system into increasingly smaller subsystems. The aim is to break the problem into enough detail that the issues can be resolved by exploring potential options at key nodes.[1]

Relevance tree methodology is a natural fit to explore future development and use of MFC technology. It allows consideration of a larger context than mere technical feasibility. Books such as Steven Schnaars's *Megamistakes: Forecasting and the Myth of Rapid Technological Change* and William Ascher's *Fore-*

casting: An Appraisal for Policy-Makers and Planners make it clear that technological feasibility alone plays only a small part in the adoption of new technologies; social, industrial, political, and economic factors often have the decisive role.

For a current example of why this systems approach is important to emerging technology analysis, look no further than biofuels. The European Union (EU) did not analyze biofuels using a systems approach prior to policy decisions. The EU issued policy "to replace 10 percent of transport fuel with biofuels . . . by 2020," but this "green" idea furthered global warming, deforestation, and food and water shortages.[2] If a relevance tree methodology had been applied to biofuels, the EU might have avoided a costly and embarrassing policy decision.

The relevance tree research methodology drives the structure of this paper. First, the relevancy of MFCs is established for airpower, national security, the 2030 environment, and applications outside primary DOD interest. After relevancy is established, the concept of self-contained facilities decoupled from the infrastructure network is explored. Since MFCs are a key capability that could enable self-contained facilities, the concept is explained from a technological perspective and then analyzed along with other relevant issues surrounding the technology using the relevance tree. Once the relevance tree is defined, key-node analysis in the technological, social, industrial, and political realms facilitates conclusions about the feasibility of a strategic plan to enable this capability to enhance US national security by the year 2030.

Who Cares?

The problem that MFCs address is defined by looking at their relevancy. Relevancy is first described in terms of air, space, and cyber power. Next, the research looks at the broader relevancy to national security, the 2030 environment, and beyond the DOD.

Relevancy to Air, Space, and Cyber Power

Facilities have evolved from mere shelters to force-projection platforms and command centers (such as the AN/USQ-163

Falconer Air and Space Operations Center weapon system) and will be critical to air, space, and cyber power as long as humans are involved with force projection.[3] What demands will be placed on future facilities as we enter the cyberage and beyond? Since current facilities must last *at least* 67 years, USAF leaders must define a strategic capabilities plan for future facilities that approaches the facility life cycle but is flexible enough to meet intermediate requirements.[4]

One capability the USAF will require in future facilities is the ability to operate apart from the infrastructure network and line of communications (LOC) in a clean and efficient manner, both in an expeditionary environment and within the United States. Today's facilities tie to a power grid, a water distribution system, and a wastewater disposal network, creating key nodes of vulnerability in both the physical and cyber realms.[5] Facility locations are limited to areas with developed infrastructure that exists or that must be built. What if a single technology could eliminate infrastructure dependency for all three of these services? MFCs hold this promise.

The MFC promise for the USAF extends beyond infrastructure decoupling both abroad and at home. For expeditionary facilities, airlift requirements are reduced for light, transportable, reusable, maneuverable cities that do not require heavy equipment to build, infrastructure to support, or fuels to sustain. Today's mobile electric power (MEP), for example, "requires . . . up to 4,000 gallons per day of fuel sustainment, placing a severe burden on an already stressed air fleet."[6] MFC technology's potential to reduce airlift requirements and build operating bases in any environment relates to the strategic principle of agility, as defined by the *National Military Strategy (NMS)*.[7] Additionally, fuel moving through ground LOCs creates exploitable vulnerabilities to equipment, supplies, and personnel that would be mitigated if facilities required less or no fuel and water to operate. For facilities in a homeland defense posture (which all USAF facilities must expect), decentralized utilities shift risks away from vulnerable physical and cyber infrastructure nodes, eliminating critical targets for the enemy.[8] This is important because the first national military objective defined in the *NMS* is to protect the United States, and the *National Strategy for Combating Terrorism* calls for "defense of potential targets of attack" to include critical infrastructure such as energy and water.[9] Furthermore, the synergy of using the same MFC technology at home and abroad will reduce training requirements for craftsmen while increasing their competence.

As a final note on MFC relevancy to the USAF, it is important to mention that the author narrowed the scope of this research to facility applications, but MFC significance is not limited to facilities alone. MFCs could be used in any application that requires clean energy, clean water, or organic waste disposal. Some obvious benefits beyond facilities include power for micro air vehicles and space assets; clean water, power, and waste treatment for aircraft latrines; power for ground vehicles; and clean, low-heat-signature generators for flight-line use.[10]

Relevancy to National Security beyond Air, Space, and Cyber Power

While the link between MFCs and air, space, and cyber power is clear, it is even more important to understand the broader link to US national security. This link will be discussed under four main topics: (1) reducing natural resource consumption, (2) eliminating spark points for world conflicts, (3) prioritizing stability, security, transition, and reconstruction (SSTR) operations, and (4) accomplishing tasks outlined in the *National Security Strategy* (*NSS*).

Reducing energy consumption and natural resource dependency is a national security issue. The Whole Building Design Guide Sustainable Committee notes that "with America's supply of fossil fuel dwindling [and] concerns for energy supply security increasing . . . it is essential to find ways to reduce load, increase efficiency, and utilize renewable fuel resources in federal facilities."[11] USAF lieutenant colonel John Amidon agrees: "The current world energy situation poses a national threat unparalleled in 225 years . . . [and] meeting this dilemma with a technical solution plays on America's greatest strengths, those of the inventor and the innovator."[12] The president codified this concern about natural resource dependency for both energy and water in Executive Order 13423, which requires agencies to reduce energy use by 3 percent a year (or 30 percent total) by 2015 and to reduce water consumption by 2 percent a year (or 20 percent total) by 2015.[13] The president launched goals that are even more aggressive in December 2007 by signing the Energy Independence and Security Act of 2007.[14] Considering that buildings in the United States consume 68 percent of electricity, facilities are a logical target to reduce natural resource dependency.[15] Former secretary of the Air Force Michael Wynn agrees with these goals: "The reliance on imported oil continues to threaten the economic, financial and physical security of the nation while the use of domestic fossil fuels contributes to nationwide pollution problems. The Air Force believes that development of renewable energy sources for facility energy is one important element of our comprehensive strategy."[16] The DOD also understands the link of energy to national security and to the military instrument of power. The Defense Science Board articulated this in a report linking fuel efficiency to six principles of war: surprise, mass, efficiency, maneuver, security, and simplicity.[17] Furthermore, a 2007 poll conducted for the Yale Center for Environmental Law and Policy shows that most Americans, 63 percent, also agree that energy is a national security issue by confirming that energy issues threaten the United States more than terrorists.[18] In summary, natural resource consumption is a national security concern acknowledged by the president, confirmed by the USAF, and linked to the principles of war. Facilities are a logical starting point for reducing resource consumption.

While the focus of this research is on US national security, technologies that reduce water and energy dependency could contribute to a reduction in armed conflicts throughout the world—conflicts that the United States often attempts to resolve. Since water and energy resources spark conflicts, alternative solutions to obtaining these natural resources would prevent conflicts.[19] Three examples come to mind. First, in the Future Capabilities Game 2007 (FG07), the scenario's conflict concerned natural resources. If the natural resource were available through MFCs or other technologies, could the conflict have been prevented? The second example concerns the peaceful split of the Czech Republic and Slovakia in 1993. Could the "velvet divorce" that resulted in peace and good governance have occurred if resources such as oil or water were at stake?[20] The final example is the Jordan River Basin, which includes Israel, Jordan, Lebanon, Syria, and the West Bank. Since 1948, 18 "extensive war acts causing deaths, dislocation, or high strategic costs" and dozens more hostile acts have occurred in this region.[21] Would these conflicts be less likely to start, or be more likely candidates for peaceful resolution, if water resources were available through a technological breakthrough? Critics will find that natural resource availability will not be a panacea for conflicts that also have deeper cultural roots. These examples establish the premise that water and energy resource availability, enabled by MFCs or other technologies, could contribute to future world stability by offering diplomats a tool to pursue a better state of peace.

The third link of MFCs to national security is in the growing priority of SSTR operations. Today such missions are not in vogue with the USAF's institutional infatuation with technology.[22] For the future, however, MFCs will provide capability useful in all four quadrants of military challenges shown in the 2006 *Quadrennial Defense Review* (*QDR*)—irregular, catastrophic, disruptive, and traditional challenges.[23] Additionally, MFCs will offer capabilities that are essential to all six operation plan phases as described in Joint Publication (JP) 3-0, *Joint Operations*.[24] The broad applicability of MFC capability allows this technology to fill a niche outside the "seize and dominate" phases and traditional security challenges where USAF technological innovation attention is typically focused.

MFC technology moves the USAF toward carrying out DOD Directive 3000.05, *Military Support*, that states, "Stability operations are a core US military mission. . . . They shall be given priority comparable to combat operations."[25] Since stability is key to transferring power to civil authorities, and since facility and infrastructure construction are a large component of stability, the United States could use MFC technology to expedite this transition in areas with damaged or absent infrastructure. New USAF irregular warfare doctrine acknowledges this mission by a call to civil engineers to implement it.[26] Another stabilization role the US military performs is humanitarian relief. "Humanitarian relief has long been recognized as a mission of the American armed forces," and the massive response to the "most destructive tsunami ever recorded" in Indonesia in 2004 is an example of the need for a capability to produce clean drinking water in the absence of operational infrastructure.[27]

Whether the military likes to acknowledge this aspect of its mission or not, SSTR operations are a core mission. While assigned to Iraq, Army captain John Prior captured the sentiment that is prevalent in today's writing on SSTR and counterinsurgency efforts. " 'Infrastructure is the key now,' Prior said more than once. 'If these people have electricity, water, food, the basics of life, they're less likely to attack.' Sewage, Prior realized, was the front line of nation-building."[28] The infrastructure provided by US military teams paves the way for winning the hearts and minds of the indigenous population by meeting its basic needs, which in turn adds legitimacy to stressed governments after war or disaster. In short, MFC technology adds capability across all phases of war and across all types of challenges.

Using the military instrument of power (IOP) for nation building is a possibility based on DOD Directive 3000.05, but the *NSS* links infrastructure development efforts to two essential strategic tasks that leverage the diplomatic and economic IOPs as well. The two essential tasks outlined in the *NSS* that relate to MFC technology are (1) to "ignite a new era of global economic growth through free markets and free trade," which includes "secure, clean energy development," and (2) to "expand the circle of development by opening societies and building the infrastructure of democracy."[29] The US Department of State (DOS) could support both objectives by helping developing nations become stable democracies using technology such as MFCs that enable modular, cost-effective, resource-savvy, low-maintenance, infrastructure-free facilities, especially in remote and impoverished areas. Furthermore, using MFC technology in impoverished areas provides clean water, combats disease, and helps states integrate impoverished nations lacking infrastructure into the global economy.[30] Nongovernmental organizations (NGO) could use MFCs in a similar manner to further these *NSS* objectives, but they could also use the technology as a baseline for establishing or supporting refugee camps or humanitarian relief efforts. The DOS and

NGOs could use MFC technologies to accomplish essential strategic tasks specified in the *NSS*.

To recap, MFCs could enhance national security beyond air, space, and cyber power in four ways: (1) reducing natural resource consumption, (2) eliminating world conflict spark points, (3) prioritizing SSTR operations, and (4) accomplishing essential tasks outlined in the *NSS*.

Relevancy to the 2030 Environment

The relevancy of MFC technology for air, space, and cyber power and the larger national security context in today's environment is evident, but that relevancy will grow even more as we approach the year 2030. MFCs will be a key defense capability regardless of which future threat dominates in 2030. Four main threat scenarios could depict the 2030 environment, and each of these scenarios needs MFC technology to enable national security. If the United States faces a *conventional, major-theater* enemy in 2030, MFCs will be needed to enable expeditionary and homeland facilities from which to project traditional air, space, and cyber power. If the *terrorist threat* to the homeland dominates in 2030, MFCs will be needed to eliminate key nodes of vulnerability in the homeland infrastructure (such as the power-grid, water, and wastewater systems). If *counterinsurgencies, small wars, and humanitarian crises* (such as those faced over the past 50 years in Vietnam, Iraq, and Afghanistan) characterize the next century, MFCs will be needed to provide critical infrastructure to "win hearts and minds" and legitimize nascent governments. If *energy and water shortages* or environmental concerns are the biggest national security concern in 2030, MFCs will be needed to provide green power and clean water.[31] No matter which scenario strategic planners assume is most important for 2030, MFCs could reduce the probability of strategic surprise if R&D investment begins now.[32]

The argument that follows looks more closely at the fourth scenario, energy and water resource shortages. Steven Schnaars, a marketing professor who specializes in future technologies, observes that "forecasters are imprisoned by their times."[33] Humans tend to look at today's crisis and project it into the future. Conventional threats;

terrorism; and small wars, insurgencies, and humanitarian crises are today's discernable threats covered extensively in the literature and the Air Command and Staff College curriculum. Energy and water resource shortages are tomorrow's strategic threats that are often overlooked, creating strategic risk. Therefore, this discussion focuses on this fourth scenario.

Energy will continue to be a concern in 2030. In 2007 the United States Department of Energy (DOE) forecast international power demand to double by 2030.[34] Today's energy crisis is well recognized and built into future national security strategy.[35] Projects are under way to reduce consumption and to transition to green power sources. The projected crisis for power, then, is not likely to be quantity and sources but availability.

Today's facilities depend on a power grid. Power grids have both physical vulnerabilities (enemy actions, natural disasters, and demand saturation) and cyber vulnerabilities (control software). Distributing the network into smaller pieces reduces risk, with an ultimate goal of individual self-contained facilities with collocated production and consumption. Besides reducing risk, after initial capital investment, power costs would drop since 30 percent of most electric bills is for transmission costs, and 10 percent of electricity is lost in transmission.[36] Self-contained facilities would be more likely to survive physical or cyber terror attacks as well as natural disasters.[37] Consumers could also reduce vulnerability to brownouts that threaten productivity and the economy.[38] Self-contained facilities address the nonavailability threat.

Water availability, on the other hand, will be a bigger natural resource crisis in 2030 than decision makers grasp today. Planning failures for this emerging shortage will result in a strategic surprise, forcing crisis action or emergency responses that will divert attention from the USAF's main goals.[39] A potential water shortage in 2030 is well documented, and the USAF must begin to prepare for it. Water shortage forecasts are available, for those willing to heed them, in future scenarios, futurists' predictions, and mainstream media.

Four credible future scenario projects highlight a future water shortage. First, the United Nations Millennium Project scenarios lend credibility to the prediction of a global water shortage in the 2030 time frame. In its product, *2007 State of the Future*, "providing sufficient clean water for everyone, without conflict" is one of the "15 Global Challenges" that needs to be addressed "to improve prospects for humanity."[40] These futurists observe that today "more than 1 billion people do not have access to safe drinking water" and that "by 2025, 1.8 billion people could be living in water-scarce areas desperate enough for mass migrations, and another 3 billion could live in water-stressed areas."[41] They also note that "80% of diseases in the developing world are water-related. Many are the result of poor management of human excreta. About 2.6 billion people lack adequate sanitation."[42] MFCs would address the water and sanitation challenges forecast by the United Nations Millennium Project.

Second, the Nobel Prize–winning Intergovernmental Panel on Climate Change predicts that by 2020 as many as 250 million Africans could experience water stress.[43] Third, Air Force planners looking at scenarios for 2025 also expect future water shortages. The King Khan scenario forecasts that "clean drinking water [will be] scarce and competition over water rights [will] become a source of conflict in Africa and Southwest Asia."[44] Finally, FG07 also reflects this same natural resource shortage. Future water shortages consistently appear in strategic planning scenarios.

Individual futurists also agree about the scarcity of future water. Peter von Stackelberg highlights the need for future water technology by surmising that "water is becoming increasingly scarce. . . . By 2025, about 3.4 billion people will live in regions that are defined by the UN as water-scarce."[45] The *Futurist*'s May 2008 magazine cover claims that "global demand for water has tripled in the past half century." The article's author expects this trend to continue and projects that since 70 percent of water consumption is for agriculture, water shortages will also lead to food shortages.[46] Professional futurists expect to see a water crisis by 2030.

Even popular media, which are generally not future-focused, are reporting on the likelihood of water scarcity in 2030. Starting in 2009, the government estimates that the demand for water will outstrip supply in La Paz-El Alto, Peru.[47] Even more surprising, the predicted water shortage in 2030 is not limited to places outside of the United

States. The main water source for Phoenix and Las Vegas, Lake Meade, "has a 50 percent chance of becoming unusable by 2021."[48] Both cities host military bases threatened by the absence of water. The threat of a water shortage is on the horizon, not just in the Middle East but also in the Western Hemisphere.

Natural resources will be scarce in 2030, and networked infrastructure will carry unnecessary risks. Scenario planners, futurists, and popular media have issued the warnings—water and energy shortages will characterize the world, including the United States, in 2030. Sustainable technologies that minimize natural resource losses while producing beneficial by-products will be necessary to project air, space, and cyberspace power, regardless of the most likely threat.

Relevancy beyond the Department of Defense

While this research focuses on the applicability of MFCs to national security through the military IOP, MFCs also enable the diplomatic and economic IOPs. Understanding the larger impact of this technology allows the USAF to identify R&D partners. This study also paints a picture of how important MFCs could become for 2030. Figure A.1 shows application and benefit areas, and table A.1 details a starting point for establishing collaboration partners.

Understanding Microbial Fuel Cell Technology

With the relevancy of the research established, this section explains MFC technology. First, the research explores the self-contained facilities concept and how MFCs enable it. Next, an overview of MFC components and their interaction provides a foundation for further analysis. Additionally, a short section addresses what MFCs are not. Finally, with technical details in hand, the last section summarizes the technology's maturity.

Self-Contained Facilities Concept

The genesis of this research is the self-contained facilities concept. A self-contained facility moves services and connections from outside infrastructure into the footprint of the building. Examples of infrastructure that facilities connect to include electricity, natural gas, water, wastewater, solid sanitary waste disposal, and roads. Ideally, self-contained facilities would also include self-maintenance, or at least self-monitoring, capabilities such as remotely adjustable climate controls, self-repairing wall and roof materials, and drain-clearing capabilities. Furthermore, self-contained facilities should be light, reconfigurable, reusable, and maneuverable cities that do not require heavy equipment such as bulldozers and well-drilling rigs to build or sustain. These facilities leave no footprint when moved.

Since the topic of self-contained facilities is broad, this research focuses on the one technology that offers the most capability toward self-contained facilities—MFCs. MFCs are the most promising technology to explore for the self-contained facilities concept because they fold in several infrastructure and LOC dependencies—power, water, wastewater treatment, and waste disposal. For 2030's threats, self-contained facilities enabled by MFCs can reduce infrastructure and LOC vulnerabilities for facilities at home and abroad.

Microbial Fuel Cell Technology Overview

An overview of MFC technology is the starting point for exploring what MFCs can provide and the best way to move toward that goal. A brief study of figure 1 offers the best way to gain a basic understanding of MFC technology. Following the pictorial overview is a summary of how MFCs work as well as a description of the salient technology components for a more in-depth understanding of MFCs.

One kind of biological fuel cell, the MFC, uses living microbes as a catalyst for an electrochemical reaction that can convert waste to power and water.[49] Microbes metabolize waste products in a process that frees electrons. This idea is not new. Wastewater treatment plants use microbes to degrade organic matter. The new twist is capturing released electrons as power. "Normally the electrons power . . . the bacterial cells. However, by depriving the bacteria of oxygen . . . the electrons can be wrested . . . and used to power a circuit."[50] Wastewater is cleaned, as it is in wastewater treatment plants today, and the by-products of the reaction are clean water and power.

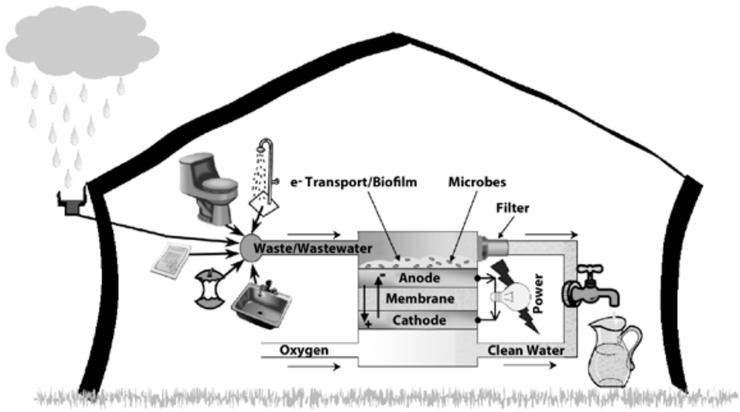


Fig. 1. Microbial fuel cell technology overview

With this understanding, the stage is set to discuss the primary components.[51]

Fuel. Fuel is the substrate in which the microbes act. Examples of fuels for MFCs include wastewater such as gray water, black water, and storm water; kitchen scraps; industrial waste streams; agricultural waste streams; sugars such as glucose, fructose, lactose, and mamose; algae; or any other kind of carbon-rich waste product such as wood, paper, or plastic.[52] The ideal mixture of the substrate is a key investigation area.[53]

Electrodes. Microbial fuel cells have an anode and a cathode. Flow of electrons between these two electrodes through an external resistance yields power. Electrode materials dictate how well electron transport can occur.[54] Electrode surface area also governs waste processing speed and power output density.[55]

Catalyst. Catalysts start the electrochemical reaction. They are necessary at both electrodes. A traditional fuel cell uses platinum as the catalyst, but in MFCs "bacteria on the anode . . . can act as the catalyst instead."[56] The catalyst governs the reaction speed at both electrodes and therefore becomes a variable that dictates the speed of power and clean water production.[57] A robust mixture of microbes, such as *Geobacter* and *Shewanella*, in the anode chamber catalyzes the reaction and allows for fuel flexibility.[58] Several microbiologists are studying the genetic engineering involved with optimizing microbes for MFCs.[59]

Membrane. A membrane separates the two electrodes and allows protons to pass from the anode to the cathode. It also allows anions to pass from the cathode to the anode. This proton exchange creates a potential across the two electrodes that pulls electrons from the anode to the cathode, thus generating electricity. The protons then combine with the oxygen at the cathode to produce water. Proper design of the membrane is important because this exchange controls the potential available across the electrodes (which equates to power) and the rate at which the reactions can occur at both electrodes.[60] Membranes are a current research topic, and recent publications suggest that Nafion membranes should be replaced with a nanoporous filter or "fast proton conducting ceramic membranes" to optimize power output and reliability.[61]

Electron Transport. Mediators help move electrons in the anodic chamber to the electrode so that they can be captured to produce electricity. Many MFC publications report supplementing the solution around the anode with mediators that are toxic chemicals, such as methylene blue.[62] Microbes, however, synthesize and excrete mediators as they "breathe."[63] This natural method of transporting electrons to the anode, often referred to as a mediatorless MFC, allows electrons to be passed to the anode via direct contact between the microbe and the electrode surface. Two examples of mediatorless electron transfer appear in the MFC literature—nanowires and biofilms. Nanowires are hairlike appendages that bacteria use to move electrons to the electrode surface.[64] Biofilms enable electron transport by orienting cell surfaces so that the electron-transporting proteins are a certain distance from the electrode, allowing electron hopping.[65] Biofilms coat the anode and grow on a carbon-based fiber.[66]

What Microbial Fuel Cells Are Not

With these main components defined, it is now possible to refine the definition of MFCs by understanding what MFC technology is not. Since many competing and complementary alternative energy projects are in the spotlight, it is important to understand what differentiates these technologies. Some technologies that should not be confused with MFCs are biofuels and biomass, hydrogen fuel cells, protein- or enzyme-based fuel cells, solar power, wind power, and desalination plants. A brief explanation of these technologies is included in appendix C. Future MFC applications will likely be coupled with some of these complementary energy and water technologies to build fully self-contained facilities.

Microbial electrolysis cells (MEC), on the other hand, are a kind of MFC, but they are not the focus of this research. MECs use an additional small voltage input (which could be provided by another MFC) to drive hydrogen production at the cathode. This hydrogen then drives a traditional fuel cell. MECs are more complex than the basic MFC idea explored here. Dr. Bruce Logan's group at Pennsylvania State University is researching this conceptualization.[67]

Technology Maturity

With a basic understanding of the concept of MFCs, how mature is the technology? Using MFCs on a large scale to dispose of wastewater, to clean water, and to generate electricity is a futuristic idea. Dr. Glenn Johnson, an MFC expert at the Air Force Research Laboratory, assessed MFC technology readiness level (TRL) as "two," which means that the basic concept or idea has just been formed.[68] In Dr. Johnson's assessment, in 10 years leaders will talk about MFCs as frequently as they discuss ethanol today.[69] Derek Lovley, an MFC researcher at the University of Massachusetts–Amherst, put it this way: "One way to think of this technology is that it is currently at the state of development that solar power was 20 to 30 years ago—the principle has been shown, but there is a lot of work to do before this is widely used."[70] MFC technology is still in its formative stages—the perfect time for the USAF to envision future uses for this emerging technology and shape the research to meet that vision.

Microbial Fuel Cell Relevance Tree: A Systems Analysis Framework

With a basic understanding of MFC relevancy and technology, analysis is now appropriate. MFCs could make a significant contribution toward self-contained facilities, but how could they contribute, and what must be addressed to achieve this goal? To answer these questions, this research used a relevance tree systems analysis. The relevance tree was first defined and then analyzed at key nodes. From this process, some capabilities and limitations emerged. Finally, a brief cost analysis showed the practical feasibility of implementing MFCs.

Defining the Microbial Fuel Cell Relevance Tree

A relevance tree breaks the problem into successively smaller parts so that individual issues can be identified and addressed. A graphical representation of this research is presented in appendix B and shows what it will take to move MFC technology from concept to capability.

Key-Node Analysis

The MFC relevance tree is a detailed, systematic sketch that captures the salient concerns surrounding MFC R&D and implementation. Because the tree has over 100 branches, this research cannot detail concerns at each node. The key-node analysis, therefore, seeks to highlight the most important nodes that leaders must address to advance MFC technology. This analysis looks at four tree branches: technological, social, industrial, and political challenges.

Key Technological Nodes. The first of these branches has three main categories (or nodes): basic science, engineering, and military suitability. This analysis highlights the biggest challenges in each of these areas.

Basic science challenges exist for all the major MFC components: fuels, electrodes, catalysts, membranes, and electron transport. Fuel mixtures and sources must be determined.[71] Electrode size, shape, and materials must be optimized.[72] Catalytic microbes must be better understood to determine power output limits and optimal mixtures for fuel flexibility.[73] Nanotechnology breakthroughs will enable high-integrity membranes that transport protons quickly without fouling.[74] For electron transport, hairlike structures on the microbe surface that form nanowires must be investigated.[75] Finally, microbiologists must advance biofilms to learn the mixtures, inoculation methods, and the best materials to grow microbial catalysts.[76]

Beyond these challenges, engineering issues must be identified early and addressed in parallel with the basic science. Configuration issues such as modularity and stacking, energy storage, and coupling with other power- and water-generation equipment must be considered now.[77] Manufacture will also bring challenges. Scaling laboratory experiments up to full-size systems capable of producing hundreds of thousands of watts of power and thousands of gallons of water will likely be problematic.[78] Mass manufacturing nanomembranes will also chart new territory. Of course, manufacturing puzzles are solvable if the physics are possible, but they may drive costs, size, or weight of the final product.

The final technological area is military suitability. Like any biological system, microbes are fragile. On the positive side, they can thrive in a broad range of environments and can adapt to any niche over time.[79] They exist in permanently frozen lakes (though water flow stops in frozen conditions) and in high-temperature sea vents.[80] On the negative side, living organisms may not have a shelf life and may require lead time to form productive populations.[81] If addressed early in R&D, a procedure could be developed for "seed" generation. For example, inoculums could be introduced and begin colonizing the system en route to an expeditionary location. Simple work-arounds exist for the first few hours or days until the systems are fully operational and stable. For more details about the technological challenges, see appendix B.

Key Social Nodes. The social aspect is the second branch that leaders must consider to advance the MFC concept. The three key social nodes are operational transparency, resistance to change, and cost.

The first key social node is operational transparency. In facilities, technologies that do not require occupants to change their lifestyle or business model will be most successful, so MFCs designed to be compatible with today's facilities are more likely to see widespread adoption.[82] For example, it would be easier to design technologies that capture household organic waste than to train a whole society to feed sorted kitchen scraps into an MFC in the basement. Others might resist the change if they knew their toilet water was cleaned and recycled to their kitchen sink. Of course that is what happens today, but it is at a distant treatment plant rather than in the crawl space at home.

Operational transparency is related to the second key node—social willingness to change. In *The End of Oil*, Paul Roberts asserts that the success in hybrid vehicle sales might be an indicator of social readiness to accept revolutionary technologies that decrease dependence on traditional energy sources.[83] But social trends related to automobiles do not translate into a desire for change in American homes and businesses. Among other reasons, Americans change vehicles more frequently than homes.[84]

Second, modifying facilities built to last 100 years or more is different from changing features and infrastructure for vehicles that are replaced at least an order of magnitude more frequently. Roberts's book captures this idea:

> If the auto industry is ripe for an efficiency revolution, it's not clear whether that revolution can spread to other sectors. . . . Industrial nations currently waste an extraordinary amount of energy through poorly designed homes, office buildings, and factories—all of which could be redesigned for dramatic energy savings. Yet the daunting and hugely expensive task of reengineering such large pieces of infrastructure will require more than the kind of snappy ad campaign that has worked for hybrid cars.[85]

Beyond operational transparency and social willingness to change, MFCs will not see widespread adoption unless the advantages outweigh the costs. Even if two concepts provide the same service for the same cost, human habit will choose the old over the new. Slow adoption of photovoltaics is an example of consumers deciding that advantages do not yet outweigh costs.[86] Yet a deliberate or subconscious cost-benefit analysis is influenced by politics. For instance, government regulations implementing child-restraint seats and fire alarms changed the cost-benefit analysis because breaking the law is now a cost.[87] The same could become true for MFCs if policies on security, energy, or water change.

While social inertia is daunting, change is always possible. This change might be even easier in the civilian sector than within the bureaucracy of government. The question is whether incentives are needed to change the cost-benefit equation to bring the idea to reality in the desired time frame.

Key Industrial Nodes. The third branch essential to advancing the MFC concept is industry. Many industrial factors could affect MFC adoption and widespread use. This analysis considers two main industries: construction and utility. The construction industry, which accounts for 20 percent of the American economy, does not embrace innovation.[88] The United States Green Building Council (USGBC) observes that "the building industry is characterized by relatively slow rates of innovation due to its size, diversity, fragmentation, and low investments in research."[89] In *Megamistakes*, technological change expert Schnaars suggests that a precedent for lack of innovation may mean "leaders are napping."[90] This reflects a shortfall in government interest, investment, and incentive along with century-long facility life spans.[91] The utility industry may show similar resistance to adopting new sustainable technologies. Infrastructure such as high-voltage transmission lines, buried power lines, waterlines, and sewage pipes are costly investments that utility companies will not abandon quickly; however, the right incentives could allow innovative companies and municipalities to gracefully bridge a transition that could last as long as half a century. With the right leaders, R&D investment, and incentives, new technologies will be adopted.

Key Political Nodes. The final branch of the relevance tree to be analyzed is the political branch. Government investment, regulations, standards, taxes, and subsidies could all impact MFC success either positively or negatively. In fact, politicians wield the most power in shaping social and industrial demand for this capability. They even hold power over technology development since most academic R&D is funded through the government. If USAF leaders want MFCs for the future, the political machine must be a primary point of engagement. Specific recommendations follow in the conclusion.

Microbial Fuel Cell Key Capabilities and Challenges

The application relevance tree and the key-node analysis of the MFC relevance tree provided the framework to investigate MFCs systematically. Throughout this research, capabilities and challenges of MFCs emerged. Some key MFC capabilities and challenges from a USAF perspective are shown in appendix D.

Basic Cost Analysis

MFC capabilities and limitations are clear, but will it cost too much to replace, build, operate, and maintain MFC facilities? No! Appendix E makes some estimates for a 1,100-person base. This section investigates how operational cost savings would quickly pay for capital investments, briefly explores maintenance and operations requirements, and finally, highlights a few benefits that are difficult to translate into dollars.

Operations costs would quickly pay for capital investments. According to this research's calculations, organic waste has the potential to provide up to 25 percent of the power at an expeditionary base. While it is still uncertain how much of this potential energy MFCs could capture (alone or in combination with other technologies), scientists are optimistic that the technology would be much more efficient than combustion engines that peak at about 50 percent efficiency.[92] If MFCs and complementary technologies could capture 90 percent of the potential energy available (energy efficiencies have already been recorded at 65 percent and electron capture efficiencies at 96 percent), they could replace one of the four MEP-12 generators during a 1,100-person deployment.[93] *This will save $69,000 per day in fuel and fuel delivery costs at a single 1,100-person location* (see appendix E for details). Translated into major theater operations, during a 150,000-person deployment, MFCs could save as much as $50 million each day. The capital costs of an MFC (even if double the cost of today's generators) would quickly be recouped because of the reduced fuel requirements.

As a first step, if only the shower and latrine units became self-contained (power for lights, hot water, and water pump) using their own black water and gray water, the USAF would still save $2,500 per day at a single 1,100-person base. On top of these fuel cost benefits, the USAF would be able to capture and recycle 15,000 gallons of water each day at a 1,100-person installation. Even if MFCs cannot turn 90 percent of the potential energy of organic waste into energy, and even if significant R&D investments and capital costs are required, it is clear that the USAF would benefit from reduced costs and increased capabilities.

There would also be less need for maintenance. Microbial fuel cells do not have moving parts like gas-fired generators. Maintenance requirements would be similar to today's sewage treatment plants. Primary maintenance tasks include filter cleaning and periodic electrode replacement. Pumping sewage from expeditionary latrines and transporting it to the sewage treatment location can be eliminated, cutting maintenance hours, reducing truck traffic and inspections at base entries, and improving quality of life for both residents and craftsmen. Furthermore, personnel will not have to maintain fuel levels in storage bladders or bury as much infrastructure. Overall, maintenance requirements will be similar to or less than existing systems.

Beyond the cost savings, decision makers must also account for other benefits not reflected in this basic cost estimate. Because of the reduced airlift requirements for fuel and water, some mobility aircraft could be freed for other missions. Additionally, ground LOCs would become less burdened, minimizing improvised explosive device risk to personnel, equipment, and supplies. Similar benefits in reduced shipping requirements would ease the demand on sea LOC throughput as well. Although reduced LOC demand from a risk perspective is not quantitatively calculated here, the proposal to save lives and assets by reducing fuel and water demands during combat has merit.

This systems analysis quantified MFC capability and identified major obstacles in bringing MFC technology online. After building a relevance tree as an analysis framework, key technological, social, industrial, and political nodes emerged. Understanding these key issues resulted in conclusions about capabilities and limitations. After quantifying potential capabilities and limitations, a basic cost analysis revealed that MFCs could yield savings of up to $50 million per day in operating costs for a major deployment.

Conclusions

This research began by asking if the USAF should invest in MFCs. To answer this question, this research explored "who cares," explained the technical aspects of MFCs, and used relevance tree methodology to analyze capabilities, limitations, obstacles, and costs. With this analysis, the conclusion emerges: yes, the USAF should invest in MFC R&D, but investment alone is insufficient. This posture is substantiated by the following discussion of MFCs for self-contained facilities along with suggestions for strategy and future research.

Microbial Fuel Cells: The Grail for Green, Self-Contained Facilities?

MFCs hold great promise to meet future waste-disposal, water, and power requirements with significant cost savings, but they are a component required for success—not a panacea for all self-contained facility needs. MFCs are primarily a wastewater treatment capability and will likely meet 100 percent of that requirement. The fundamental capability that distinguishes MFCs from other sustainable facilities technologies is their ability to process sewage, kitchen scraps, and storm water for sanitary waste disposal and to restore water to potable quality. It is a bonus that MFCs also provide potable water and power as chemical reaction by-products.

While MFCs are likely to meet 100 percent of the waste disposal requirements, expecting MFCs to meet 100 percent of facility power and water requirements is unrealistic.[94] For power and water, MFCs must be coupled with demand reduction through both technology and conservation efforts. Roberts predicts that "no matter what energy technologies we end up using twenty or thirty years from now, we still won't have enough energy for everyone if we haven't found ways to use much less of it," and believes that "efficiency remains our greatest hope."[95] Even with increased efficiencies, MFC power densities will not meet forecasted power demand alone. MFCs may only meet 25 percent of full power requirements, so MFC technology should be coupled with other sustainable power sources such as hydrogen fuel cells, solar power, wind, and thermal technologies.[96] These are promising energy sources with capability gaps that MFCs could fill (for example, to produce hydrogen at night, on cloudy days, on low-wind days, or in places where thermal technologies are not viable).

For water supplies, MFCs can capture and recycle water, but the by-products of the chemical reaction will not produce large quantities of water itself. The main water benefit of MFCs is the ability to recapture the 70 percent of water used that now moves into the sewage treatment process and evaporates (in an expeditionary setting).[97] The stream of clean water produced at the anode combined with the trickle of clean water as a by-product of the reaction at the cathode will only partially meet water demand.[98]

MFCs are not a silver bullet, but they will fill gaps in existing sustainable technologies, and they provide power, water, and waste treatment while enabling self-contained facilities.

Strategy Recommendations and Future Research

Though MFCs cannot meet 100 percent of power and water requirements, they can augment production and dispose of all wastes while filling gaps in other power and water technologies. In light of the relevance tree analysis, this section recommends strategy and future research to address technological, social, industrial, political, and business-case considerations.

Technological Considerations. First, leaders must decide to invest in facility research and development, including MFCs. The USGBC points out that "the design, construction, and operation of buildings account for 20 percent of US economic activity and more than 40 percent of energy used . . . yet far less than 1 percent of the federal research budget is allocated to buildings."[99]

Next, the USAF must develop a road map for MFC technology to vector the R&D funds. The road map should include basic science milestones, but it should also outline envisioned systems, manufacturing techniques, and schemes for components working together up to the level of complete self-contained facilities. For example, if a target is expeditionary self-contained facilities, all component technologies such as MFCs, solar power, rainwater collection, and self-monitoring/self-maintaining systems must be identified, investigated, integrated, and set as deliverables. Deliverable interim milestones, such as an expeditionary self-contained shower and latrine facility by 2015, must be incorporated into the plan as well. Often systems engineering and manufacturing challenges are as difficult as basic science. Early conceptualization could identify the toughest obstacles that could be addressed in parallel with the basic science development to optimize research time and dollars. Appendix B is a starting point for science, systems integration, manufacturing, and military suitability challenges that should be addressed in the road map.

In addition to the road map, the technology investment strategy should be collaborative. Collaboration must first begin with USAF and DOD pursuit of academic partners, but it should ultimately become a cross-agency plan since this technology has the potential to contribute to areas of interest beyond the DOD (see fig. A.1). The DOD has initiated several notable energy projects, but no unified, concerted effort yet exists across the services.[100] A starting list of contacts for potential USAF, DOD, and academic collaborators is shown in table A.1.

The technology strategy and future research recommendations are (1) USAF R&D investment in MFC technologies, (2) development of a road map to spend those investment dollars, and (3) a collaborative technology approach.

Social Considerations. The social barriers to widespread use of MFCs are perhaps the most vexing challenges from the perspective of a USAF engineer.[101] Yet the impediments must be addressed because "enabling the rapid adaptation of new energy technologies to civilian use is required for the Nation's long-term physical and economic security."[102] Scientists and engineers can solve the technology problem, but if society does not adopt the technology, costs will increase, homeland security benefits will not be realized, and synergies between expeditionary and permanent facilities will be lost. Social obstacles must be the subject of further investigation. The USAF must hire outside expertise (like psychologists, consumer and marketing experts, or futurists), or rely on collaborative partners like the DOE, to gauge the magnitude of social challenges that might occur, possible solutions, and their impact on national security goals.

Industrial Considerations. This research identified many industrial challenges in bringing MFCs to fruition; however, with a deliberate plan, these obstacles are surmountable. Incentives are powerful change agents, and specific recommendations should be the focus of future research. A good starting point for this research might be lessons learned from ethanol infrastructure.[103]

Political Considerations. First, policy makers must deliberately decide if a free market can effectively shape the future energy and water economy or if government intervention is necessary to protect the economy and ultimately national security. In *The End of Oil*, Roberts argues that a free-market economy could bring about a new energy economy if energy prices gradually increase, but he worries that world events could lead to catastrophic spikes in oil prices.[104] He contends that "improving efficiency . . . must begin in the political sphere with a new consensus by policy makers that the energy system must change in fundamental ways—and, above all, real leadership [is needed] to ensure that such change actually happens."[105] One of the primary functions of government is to provide collective security for the nation. Risks in today's energy volatility suggest that government intervention may be necessary. Ultimately, policy makers must decide if, when, and how to intervene, but the important thing is that they make an intentional decision to intervene or not intervene, rather than simply falling back to a default position resulting from indecision.

Second, policies must not dissuade military decision makers from doing the right thing when it comes to energy and water. Wing commanders, for example, see new technologies as risks without rewards since operational savings are not realized at the installation level. Furthermore, incentives such as tax credits or renewable energy credits penalize the government since no benefits can be gained. In his article "Energy and Force Transformation," Scott Buchanan advocates that "the Services, combatant commanders, research laboratories, and other major DOD organizations should be allowed to keep a portion of the savings from innovative initiatives in material, procedures, and doctrine that significantly enhance energy efficiency."[106] The USAF should engage its attorneys and policy makers to find creative incentives that reward decision makers for taking sensible risks to implement MFC technologies.

Beyond these two primary political recommendations, future research should investigate policies that could jeopardize or enhance bringing MFCs to fruition. Specific areas to address are investment policies and levels, incentives, regulations, standards, taxes, and subsidies. Future research should consider how decisions in these areas directly and indirectly affect the social, industrial, technological, and government realms.

Business Case. No investment strategy or policy decision is complete without a supporting business case. This research included only a cursory cost analysis focusing on a 1,100-person expeditionary base, which clearly showed the advantages of MFCs for remote and expeditionary facilities. Future research should expand this business case, especially for permanent facilities that would require more extensive investments to update building systems to accommodate MFC technologies and would have less organic waste (as a percentage of power required) on hand from which to generate power.

Summary

National security planners cannot know the exact threats for 2030, but the environment could be characterized by conventional, major theater threats; terrorist threats; small wars, insurgencies, and humanitarian disasters; or water and energy resource shortages. Which of these threats dominate the 2030 environment is irrelevant; they all require the capabilities that MFCs provide—distributed, secure, and sustainable power, water, and waste/wastewater treatment. MFCs are a guaranteed investment for the future. They are a flexible technology capable of enabling effects across the entire range of military operations and, as a bonus, they will also quickly pay for themselves.

The USAF should invest in MFC research because this technology allows development of self-contained facilities decoupled from the infrastructure network, a key capability for national security in the 2030 environment. The USAF must develop facility energy, water, and wastewater capabilities to ensure future combat effectiveness of air, space, and cyberspace forces that rely heavily upon facilities. Leaders cannot assume that these enablers will be available in the future; they must plan for them. Nevertheless, an MFC investment strategy must include more than R&D

funds. The USAF must pursue a collaborative approach that addresses not only the technological barriers at the scientific and systems integration level but also the key social, industrial, and political hurdles. Our national security depends on it!

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. This research methodology is described in detail in Futures Group International, "Relevance Tree and Morphological Analysis."

2. "Biofuels May Threaten Environment"; Harrabin, "EU Rethinks Biofuels Guidelines"; Biello, "Biofuels Are Bad"; and Rosenthal, "Biofuels Deemed a Greenhouse Threat."

3. Joint Publication (JP) 1-02 defines *facility* as "a real property entity consisting of one or more of the following: a building, a structure, a utility system, pavement, and underlying land." JP 1-02, *Department of Defense Dictionary*, 199. Throughout the rest of this paper, however, *facility* will refer to just the building or structure, while *infrastructure* will refer to the utility systems and pavement. The 2007 *Air Force Handbook* explains that the "AN/USQ-163 Falconer Air and Space Operations Center Weapon System (AOC-WS) is the senior element of the theater air control system. The joint force/combined force air component commander uses the system for planning, executing, and assessing theater-wide air and space operations. The AOC-WS . . . disseminates tasking orders, executes day-to-day peacetime and combat air and space operations, and provides rapid reaction to immediate situations by exercising positive control of friendly forces." The AOC-WS occupies approximately 70,000 square feet of space where 1,000 to 2,000 people work. United States Air Force, *Air Force Handbook 2007*, 64–65.

4. DuBois, *Defense Installations Strategic Plan*, 8.

5. The Whole Building Design Guide Sustainable Committee explains in "Optimize Energy Use" that "increased security of energy supply and distribution systems [has] become an important component of national security after the 9/11 terrorist attacks. Today, power generation is still mostly handled by massive centralized plants, which are inevitable targets, and electricity moves on vulnerable lines." The vulnerability of infrastructure to attack in the cyber realm was confirmed by the Department of Homeland Defense and is reported in Meserve, "Sources."

6. "Logistics Fuel Reformer/Processor."

7. "Agility is the ability to rapidly deploy, employ, sustain and redeploy capabilities in geographically separated and environmentally diverse regions." Myers, *National Military Strategy*, 6.

8. Facilities will increase in importance as force-projection platforms for space, cyberspace, remotely piloted vehicles, and long-range bombers operate from facilities that are not near the battlefield.

9. See Myers, *National Military Strategy*, 8; and Bush, *National Strategy for Combating Terrorism*, 13.

10. The Army has already developed fuel cells (but not MFCs) for silent, low-heat-signature generators. Holcomb et al., "Energy Savings for Silent Camp™ Hybrid Technologies," slide 20. Other examples of the low-heat-signature capability of fuel cells abound in the literature. See, for example, Lambert, "Fuel Cells."

11. Whole Building Design Guide Sustainable Committee, "Optimize Energy Use."

12. Lt Col John M. Amidon, "A 'Manhattan Project' for Energy," 76.

13. Bush, Executive Order 13423, Strengthening Federal Environmental, Energy, and Transportation Management.

14. "The Lighting Efficiency Mandate will phase out the use of incandescent light bulbs by 2014, and improve lighting efficiency by more than 70 percent by 2020. . . . The Federal Government Operations Mandate will reduce the energy consumption of Federal Government facilities 30 percent by 2015. Additionally, all new Federal buildings will be carbon-neutral by 2030." See "Fact Sheet: Increasing Our Energy Security."

15. Whole Building Design Guide Sustainable Committee, "Optimize Energy Use."

16. United States Air Force, "U.S. Air Force Renewable Energy Program," 3.

17. Defense Science Board Task Force, *More Capable Warfighting*, 10.

18. Glenn, *Worldwide Emerging Environmental Issues*, 7.

19. For evidence that resources are a source of conflict, see "Dark Side of Natural Resources"; Abbott, Rogers, and Sloboda, *Beyond Terror*, chap. 3; Klare, *Resource Wars*; and Renner, *Anatomy of Resource Wars*.

20. Morrison and Conway, *Kiss, Bow or Shake Hands*, 121.

21. Yoffe, "Basins at Risk," 197.

22. Carl Builder asserts that the altar of worship for the USAF is technology and that the enchantment with technological marvels, especially flying machines, characterizes USAF culture. Builder, *Masks of War*, 19.

23. Rumsfeld, *Quadrennial Defense Review Report*, 19; and *National Defense Strategy*, 2–3. This array of four challenges—traditional, irregular, catastrophic, and disruptive—originally appeared in this document.

24. The six plan phases are shape, deter, seize the initiative, dominate, stabilize, and enable civil authority. JP 3-0, *Joint Operations*, IV-26.

25. DOD Directive 3000.05, *Military Support*, 19.

26. Air Force Doctrine Document 2-3, *Irregular Warfare*, 42–43.

27. Elleman, *Waves of Hope*, v.

28. Packer, "Letter from Baghdad"; and Meserve, "Sources."

29. Bush, *National Security Strategy*, 25–27, 31–34.

30. Logan, "Energy Diversity Brings Stability," 5161. Logan states that "modern wastewater treatments have accomplished more to protect human health and our environment than perhaps any single technology" (ibid.).

31. For a thorough analysis of environmental threats to national security and a sustainable security strategy, see Ackerman, "Climate Change," 56–96.

32. In his recent White Paper, Gen T. Michael Moseley emphasizes that future fights will not be the same as today's fights and that the USAF must

look ahead to make proper assumptions about the future to avoid unnecessary risk. Moseley, *Nation's Guardians*, 9.

33. Schnaars, *Megamistakes*, 63.

34. Energy Information Administration, *International Energy Outlook 2007*.

35. See, for instance, National Energy Policy Group, *National Energy Policy*.

36. Col Elwood Amidon, briefing, subject: Needed Now, slide 44.

37. Ibid.

38. Many power systems "have become overburdened in recent years, illustrated by the California energy brownouts in 2001." United States Green Building Council, *Building Momentum*, 10.

39. Martino, "Technological Forecasting," 14.

40. Glenn and Gordon, *2007 State of the Future*, 10.

41. Ibid., 14.

42. Ibid.

43. Intergovernmental Panel on Climate Change, *Climate Change 2007*, 11.

44. Engelbrecht et al., *Alternate Futures for 2025*, 76.

45. Water technology is one of 12 technologies von Stackelberg highlights as essential to the future in "Future of Universal Water."

46. Brown, "Draining Our Future," 16.

47. "Loss of Andes Glaciers."

48. Barnett and Pierce, "When Will Lake Mead Go Dry?" 1.

49. The other type of biological fuel cell is an enzyme or protein fuel cell. These are explained in appendix C.

50. Biever, "Plugging into the Power of Sewage."

51. Wastewater treatment efficiency will be less than current wastewater treatment plants because energy that would normally allow the microbes to metabolize more of the waste is being captured to produce electricity. Logan et al., "Microbial Fuel Cells," 5189.

52. Rodrigo et al., "Production of Electricity," 198; "Project to Turn Beer Wastewater into Power," 11; Yokoyama et al., "Treatment of Cow-Waste Slurry," 634; Catal et al., "Electricity Production from Twelve Monosaccharides," 196; Rabaey et al., "Microbial Fuel Cell Capable of Converting Glucose," 1531; and Hatcher, "New Sources of Biomass Feed Stocks."

53. The maximum power density from MFC fuel found to date is one kilowatt of power per cubic meter of waste. Fan, Hu, and Liu, "Enhanced Coulombic Efficiency," 348.

54. Logan et al., "Graphite Fiber Brush Anodes," 3341.

55. Top power output based on electrode surface area is 5.8 watts per square meter. Rosenbaum et al., "Interfacing Electrocatalysis and Biocatalysis," 6658.

56. Angenent, "Microbial Fuel Cells Turn on the Juice."

57. Microbes are typically not used at the cathode, but the cathodic catalyst is still an important variable in power and water output. See Cheng, Liu, and Logan, "Increased Performance of Single-Chamber Microbial Fuel Cells," 493; and You et al., "Microbial Fuel Cell Using Permanganate," 1409.

58. Lovley, "Bug Juice," 501–2.

59. See Biffinger et al., "Biofilm Enhanced Miniature Microbial Fuel Cell; and Logan and Regan, "Electricity-Producing Bacterial Communities," 517.

60. Proton exchange is governed by the surface area of the anode and the membrane. Oh and Logan, "Proton Exchange Membrane," 162.

61. Biffinger et al., "Diversifying Biological Fuel Cell Designs," 1448; and Tsui and Wiesner, "Fast Proton Conducting Ceramic Membranes," 79.

62. Walker and Walker, *Biological Fuel Cell*, 12.

63. Many microbes synthesize and excrete soluble redox-active molecules to enable anaerobic respiration. Stams et al., "Exocellular Electron Transfer," 371.

64. Gorby et al., "Electrically Conductive Bacterial Nanowires," 11358; and Reguera et al., "Extracellular Electron Transfer," 1098.

65. Biffinger et al., "Biofilm Enhanced Miniature Microbial Fuel Cell," 1675.

66. Angenent, "Microbial Fuel Cells Turn on the Juice."

67. For a nontechnical explanation of this concept, see Logan, "Overview: Microbial Electrolysis Cell Research." For a recent scientific publication on this configuration, see Cheng and Logan, "Sustainable and Efficient Biohydrogen Production."

68. TRL is a measure of the maturity of an emerging or desired technology. See Deputy Under Secretary of Defense for Science and Technology, *Technology Readiness Assessment (TRA) Deskbook*, ES-1, III-1–III-3; and Johnson, "Microbial Fuel Cell for Remote Power Generation," 5. The *TRA Deskbook* goes on to point out that in TRL 2 "invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies" (III-2).

69. Glenn R. Johnson and Robert Diltz, in discussion with the author during visit to Air Force Research Laboratory, Tyndall AFB, FL, 6 February 2008.

70. Biever, "Plugging into the Power of Sewage."

71. For a summary of different fuel sources matched with different microbes, see Kim, Chang, and Gadd, "Challenges in Microbial Fuel Cell Development," 487.

72. The "high surface-area-to-chamber volume ratio utilized in the mini-MFC enhanced power density when compared to output from similar macroscopic MFCs." Ringeisen et al., "High Power Density," 2629. For cross section and area matter, see Ringeisen, Ray, and Little, "Miniature Microbial Fuel Cell," 591. Angenent is studying "anode-cathode shapes, surfaces areas and distances to both increase power and reduce the resistance in the system so that less power is lost as it runs." "Fuel Cell Generates Electricity," 3.

73. Many microbes may still be awaiting discovery. Lovley, "Bug Juice," 506.

74. Biotechnology and nanotechnology are closely linked for MFC research. For an example, see Morozan et al., "Biocompatibility Microorganisms," 1797–803.

75. For a visual depiction of biological nanowires from pili, see fig. 4 in Gorby et al., "Electrically Conductive Bacterial Nanowires," 11361.

76. “Power Boosted 10-Fold,” 7; Ghangrekar and Shinde, “Microbial Fuel Cell,” 8; and Logan et al., “Microbial Fuel Cells,” 5184. Rabaey et al. note that “multiple populations within microbial communities can cooperate to achieve energy generation.” “Microbial Ecology Meets Electrochemistry,” 9.

77. Aelterman et al., “Continuous Electricity Generation,” 3393.

78. MFCs show promise in the lab, but substantial additional optimization will be required for large-scale electricity production. Lovley, “Microbial Fuel Cells,” 327.

79. Rittmann et al. explain that “the numbers of different microbial strains are enormous—de facto infinity. Furthermore, only a tiny fraction of the strains have been cultured and characterized. Second, microorganisms can evolve rapidly.” “Vista for Microbial Ecology,” 1102.

80. Johnson and Diltz, discussion.

81. “Electricity generation in a MFC was obtained after a short acclimatization period of less than 10 days.” Of course, this is only the beginning of MFC research, so these numbers could go down. See fig. 2 in Rodrigo et al., “Production of Electricity,” 200.

82. Schnaars, *Megamistakes*, 117.

83. An Internal Revenue Service report indicates that Toyota alone has sold more than 60,000 hybrid vehicles in the United States, ending a federal tax credit incentive program for purchasing that company’s hybrid vehicles. “2008 Hybrids Certified as Tax Credit”; and Roberts, *End of Oil*, 338–39.

84. The average American driver purchases a new vehicle every three to five years. Jones, “What Is a Hybrid Vehicle?”

85. Roberts, *End of Oil*, 338–39.

86. Schnaars, *Megamistakes*, 118.

87. Ibid., 121.

88. United States Green Building Council, *Building Momentum*, 4.

89. Ibid., 17.

90. Schnaars, *Megamistakes*, 153.

91. A lasting effect of the Cold War was a diversion of funds and intellectual talent away from “civil research and development and into military programmes.” Abbott, Rogers, and Sloboda, *Beyond Terror*, 59.

92. Lindeburg, *Mechanical Engineering Reference Manual*, 29-11.

93. Energy efficiency measures how much of the energy input can be converted to output. Rabaey et al., “Microbial Fuel Cell Capable of Converting Glucose,” 1533. The 96 percent electron capture efficiency is a Coulombic efficiency measurement. It indicates how many of the electrons produced in the anodic chamber can be captured by the electrodes. Rabaey et al., “Tubular Microbial Fuel Cells,” 8077.

94. “Electricity generation from wastewater will not by itself solve the need for power in the U.S. The energy in human, animal, and food-processing wastewater alone can provide at most only 5% of our current electricity needs and thus a small percentage of our total energy use. MFCs are just one part of a needed transition to a more diverse and stable energy portfolio.” Logan, “Energy Diversity Brings Stability,” 5161.

95. Roberts, *End of Oil*, 338.

96. For estimate calculations, see appendix E, "Basic Cost Analysis"; for potential synergistic technologies, see appendix C, "Competing and Complementary Microbial Fuel Cell Technologies."

97. See estimates calculated in appendix E.

98. Simonite, "Dew-Harvesting 'Web.' "

99. United States Green Building Council, *Building Momentum*, 2.

100. James, "Sierra Bravo."

101. Even experienced forecasters find social trends the most difficult aspect of future technologies to predict. Schnaars, *Megamistakes*, 100.

102. Buchanan, "Energy and Force Transformation," 54.

103. Johnson and Diltz, discussion.

104. Roberts, *End of Oil*, 340.

105. Ibid., 339.

106. Buchanan, "Energy and Force Transformation," 53–54.

Appendix A

Applications and Collaboration Partners

Microbial fuel cells (MFC) have many potential applications within the Department of Defense (DOD) and beyond. Figure A.1 lists some applications and the agencies that are potential collaboration partners.

Because of the broad applicability of MFCs, collaboration could provide synergy in bringing MFC capabilities to fruition. This research identified some of the main players within the DOD and academia. Table A.1 serves as a starting point to identify potential collaboration partners. The Web site http://www.microbialfuelcell.org also provides an overview of research groups currently investigating MFCs.

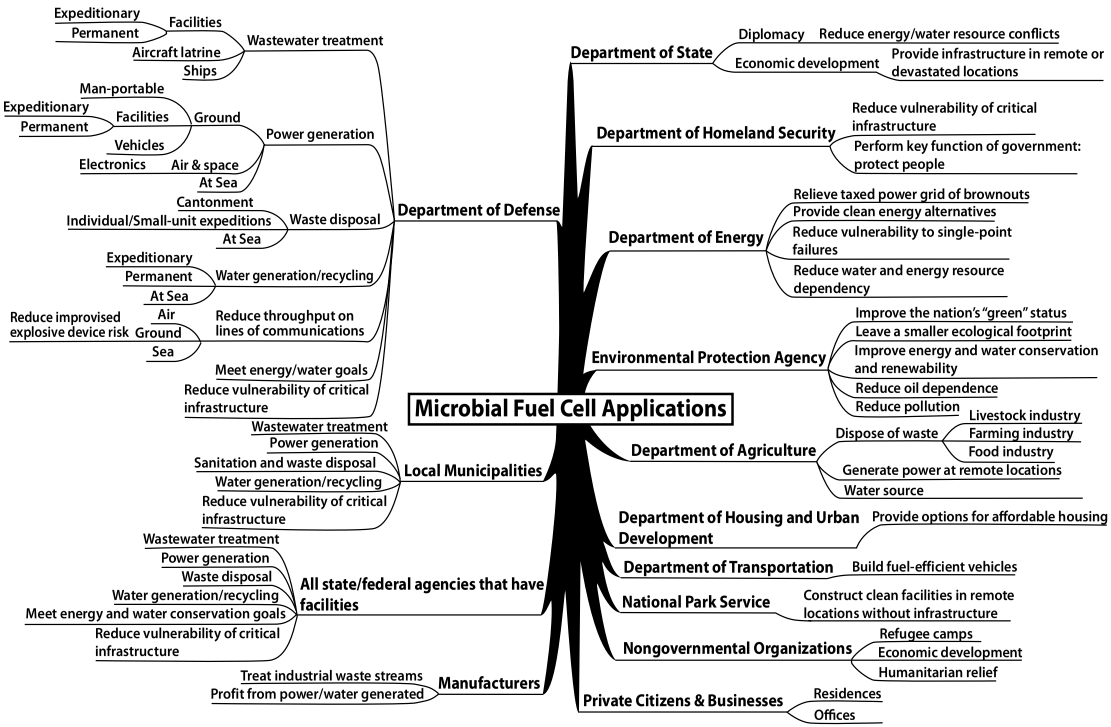


Figure A.1. Application relevance tree

Table A.1. Potential collaboration partners

Organization	*Contact*	*Research Interest*
AF Advanced Power Technology Office (APTO)	Mike Mead 478-222-1827 (DSN 472) mike.mead@robins.af.mil	Identify, assess, transition, and integrate advanced power and alternative-energy and fuel technologies into the USAF's inventory of ground vehicles, support equipment, base expeditionary airfield resources (BEAR), and fuel-cell equipment/ applications
Air Force Civil Engineer Support Agency (AFCESA)/CC	Col Richard Fryer 850-283-6101 (DSN 523) richard.fryer@tyndall .af.mil	Commander, AFCESA
AFCESA/CEN	Maj Milt Addison 850-283-6139 (DSN 523) milton.addison@tyndall .af.mil	Engineering, management, and legal services to support energy and water usage reduction initiatives, renewable development, commodity acquisition, capital program management, and utility privatization
AFCESA/CEX	Mr. Rod Fisher 850-283-6127 (DSN 523) rod.fisher.ctr@tyndall.af.mil	Expeditionary equipment requirements and development; looking at future expeditionary latrine already
AF Office of Scientific Research (AFOSR)	Maj Jennifer Gresham 703-696-7787 (DSN 426) jennifer.gresham@afosr .af.mil	Enzyme/protein/microbial fuel cells for air and space vehicle applications
AF Research Laboratory (AFRL)/RXQ	Reza Salavani Dr. Aly Shaaban 850-283-3702 (DSN 523) aly.shaaban@tyndall.af.mil	Future deployed energy and utility systems
AFRL/RXQL	Dr. Glenn Johnson 850-283-6223 (DSN 523) glenn.johnson@tyndall .af.mil	Biological (microbial and enzyme) fuel cells

Table A.1. Potential collaboration partners *(continued)*

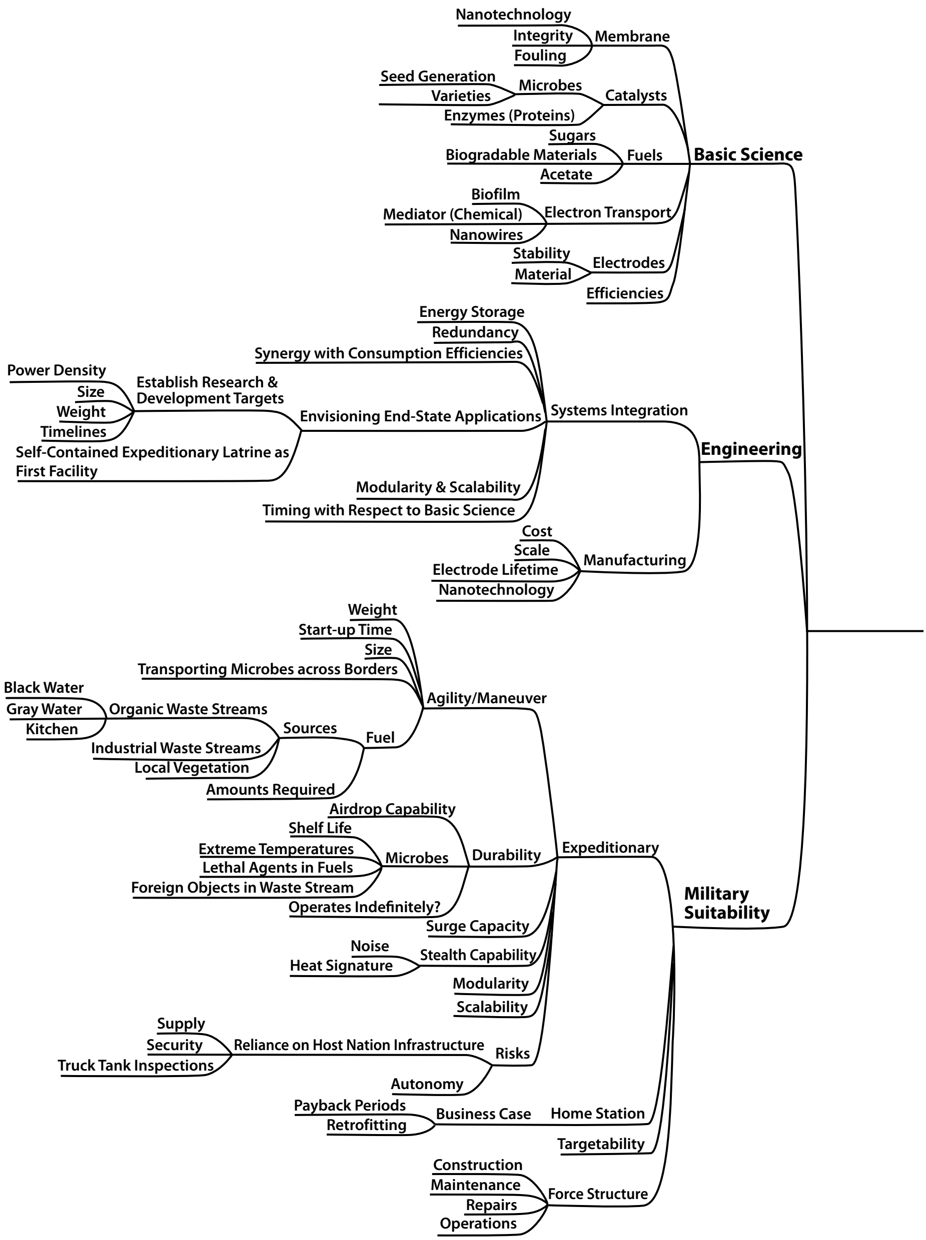
Organization	*Contact*	*Research Interest*
Defense Advanced Research Projects Agency (DARPA)	Ms. Sharon Beermann-Curtin 571-218-4935 sharon.beermann-curtin@darpa.mil	Mobile integrated sustainable energy recovery, integrated high-energy dense capacitors, micropower sources, nanocomposite optical ceramic, robust portable power
US Army Corps of Engineers (COE) Communications Electronics Research, Development and Engineering Center (CERDEC)	Pavel Fomin 703-704-1027 (DSN 654) armypower@conus.army.mil	Soldier and man-portable fuel cells
US Army COE Construction Engineering Research Laboratory (CERL)/ Engineer Research and Development Center (ERDC)	Franklin H. Holcomb 217-373-5864 franklin.h.holcomb@erdc.usace.army.mil	Wastewater treatment plant with MFC for hydrogen infrastructure
US Army Research Laboratory	Dr. Kurt Preston 919-549-4234 (DSN 832) kurt.preston@us.army.mil	Environmental sciences, US Army base camps
US Army Research Laboratory	Charles W. Walker Alyssa L. Walker 301-394-0306	Biological fuel cells, sensors and electronic devices, soldier-portable power
US Naval Research Laboratory (NRL)	Brad Ringeisen Justin Biffinger 202-767-0719 bradley.ringeisen@nrl.navy.mil justin.biffinger@nrl.navy.mil	Biofilms, anoporousmembranes, microbe adaptation
Arizona State University	Dr. Bruce Rittmann 480-727-0434 rittmann@asu.edu	Microbiology, biofilms renewable resources

Table A.1. Potential collaboration partners *(continued)*

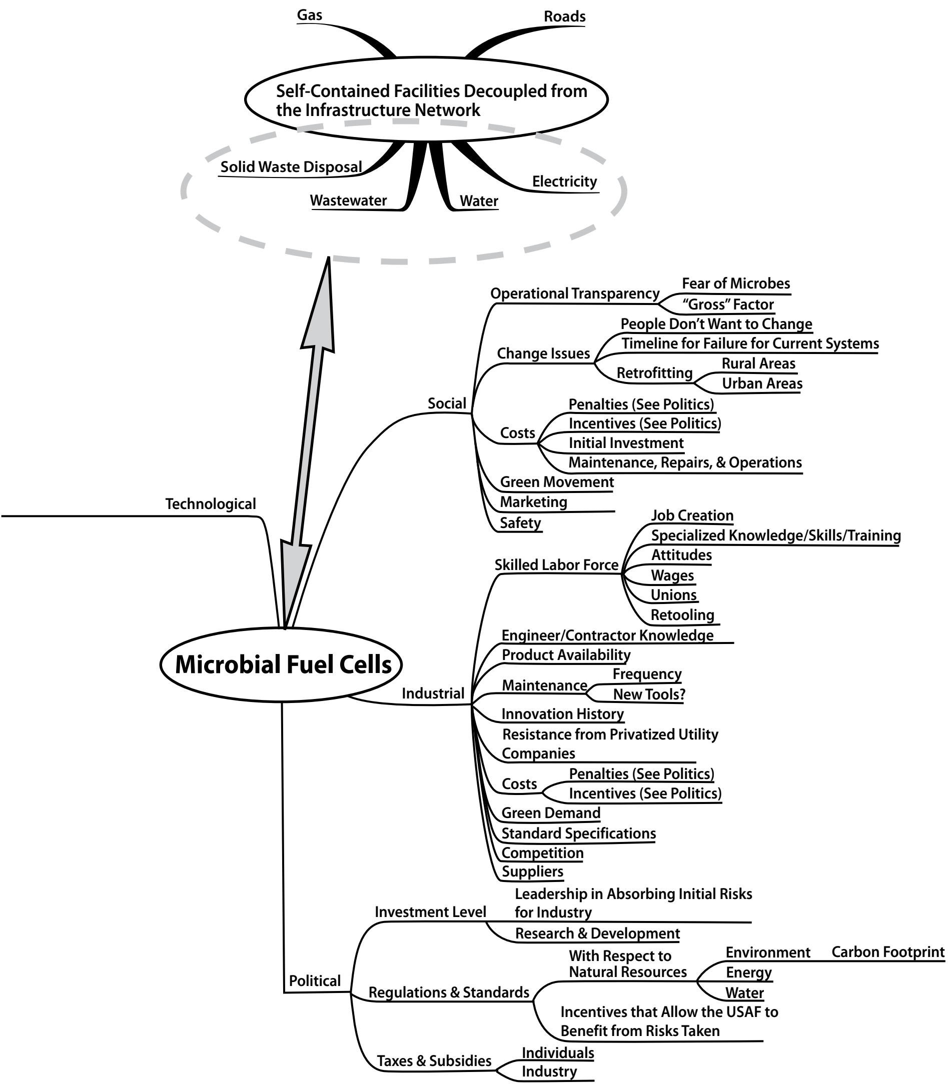
Organization	*Contact*	*Research Interest*
Pennsylvania State University	Dr. Bruce Logan 814-863-7908 blogan@psu.edu	Technologies for a sustainable water infrastructure, energy production from waste
Florida International University (FIU)	Applied Research Center Jerry Miller, Colonel, Retired 305-348-6623 jerry.miller@arc.fiu.edu	Self-contained facilities, Western Hemisphere Information Exchange (WHIX) Program—includes FIU, US Southern Command (USSOCOM), US Army
University of Massachusetts, Amherst	Derek Lovley 413-545-9651 dlovley@microbio.umass.edu	MFCs, microbiology, microbial nanowires, biofilms
University of Minnesota	Dr. Daniel R. Bond 612-624-8619 dbond@umn.edu	MFCs, microbiology, biofilms
University of Queensland, Brisbane (Australia)	Dr. Korneel Rabaey k.rabaey@uq.edu.au	Wastewater management, industrial waste streams, microbiology
University of Southern California Multi-University Research Initiative	Dr. Kenneth Nealson 213-821-2271 knealson@usc.edu Yuri Gorby (J. Craig Venter Institute) ygorby@venterinstitute.org Steven Finkel, Florian Mansfeld Andreas Lüttge (Rice Univ) Byung Hong Kim (Gwangju Institute of Science and Technology, Korea) Bruce Logan (Penn State) Shana Rapoport	Microbiology, chemistry, electrochemistry, engineering, modeling
Washington University, St. Louis	Dr. Lars Angenent 314-935-5663 angenent@seas.wustl.edu	MFCs to dispose of waste in the food and agriculture industries

Appendix B

Microbial Fuel Cell Relevance Tree



Basic Science
Membrane
Nanotechnology
Integrity
Fouling
Catalysts
Microbes
Seed Generation
Varieties
Enzymes (Proteins)
Fuels
Sugars
Biogradable Materials
Acetate
Electron Transport
Biofilm
Mediator (Chemical)
Nanowires
Electrodes
Stability
Material
Efficiencies
Engineering
Systems Integration
Energy Storage
Redundancy
Synergy with Consumption Efficiencies
Envisioning End-State Applications
Establish Research &
Development Targets
Power Density
Size
Weight
Timelines
Self-Contained Expeditionary Latrine as
First Facility
Modularity & Scalability
Timing with Respect to Basic Science
Manufacturing
Cost
Scale
Electrode Lifetime
Nanotechnology
Military
Suitability
Expeditionary
Agility/Maneuver
Weight
Start-up Time
Size
Transporting Microbes across Borders
Fuel
Sources
Organic Waste Streams
Black Water
Gray Water
Kitchen
Industrial Waste Streams
Local Vegetation
Amounts Required
Durability
Airdrop Capability
Microbes
Shelf Life
Extreme Temperatures
Lethal Agents in Fuels
Foreign Objects in Waste Stream
Operates Indefinitely?
Surge Capacity
Stealth Capability
Noise
Heat Signature
Modularity
Scalability
Risks
Reliance on Host Nation Infrastructure
Supply
Security
Truck Tank Inspections
Autonomy
Home Station
Business Case
Payback Periods
Retrofitting
Targetability
Force Structure
Construction
Maintenance
Repairs
Operations


Gas
Roads
Self-Contained Facilities Decoupled from the Infrastructure Network
Solid Waste Disposal
Electricity
Wastewater
Water
Operational Transparency
Fear of Microbes
"Gross" Factor
People Don't Want to Change
Change Issues
Timeline for Failure for Current Systems
Retrofitting
Rural Areas
Urban Areas
Social
Penalties (See Politics)
Costs
Incentives (See Politics)
Initial Investment
Maintenance, Repairs, & Operations
Green Movement
Technological
Marketing
Safety
Job Creation
Specialized Knowledge/Skills/Training
Skilled Labor Force
Attitudes
Wages
Unions
Retooling
Engineer/Contractor Knowledge
Microbial Fuel Cells
Product Availability
Maintenance
Frequency
New Tools?
Industrial
Innovation History
Resistance from Privatized Utility Companies
Costs
Penalties (See Politics)
Incentives (See Politics)
Green Demand
Standard Specifications
Competition
Suppliers
Investment Level
Leadership in Absorbing Initial Risks for Industry
Research & Development
With Respect to Natural Resources
Environment
Carbon Footprint
Energy
Political
Regulations & Standards
Water
Incentives that Allow the USAF to Benefit from Risks Taken
Taxes & Subsidies
Individuals
Industry

Appendix C

Competing and Complementary Microbial Fuel Cell Technologies

Biofuels and Biomass

Microbial fuel cells (MFC) are not fed by biofuels or biomass. MFCs can digest organic materials, some of which could be called biomass, but the primary purpose of an MFC as envisioned today is to treat wastewater and capture electrons as microbes digest the carbon-rich fuels. While tailored MFCs could probably digest harvested biomass, they are meant to dispose of organic waste rather than create demand for plant life to be used as fuels. In addition, unlike biofuels, MFCs do not convert biological material into synthetic fuels or gas to be used to fuel other systems such as vehicles. MFCs directly convert nuisance waste into useable power.

Hydrogen Fuel Cells

MFCs are not the same as hydrogen fuel cells, though the technologies have parallel components. The basic setup of hydrogen fuel cells and MFCs is the same, but the fuels and catalysts are different. Hydrogen fuel cells must have hydrogen fuel, which is costly to produce and uses more energy to create the fuel than the fuel cell can output. In hydrogen fuel cells, platinum (which is also expensive), rather than microbes, serves as a catalyst to split the molecule and harvest the electrons. Both technologies consume fuel, which differentiates them from batteries, but the consumable fuels and the reaction catalysts are different.

Protein-Based (or Enzyme-Based) Fuel Cells

MFCs are not protein- or enzyme-based fuel cells. Both are biological fuel cells, but enzyme-based fuel cells use purified enzymes from reduction and oxidation reactions, rather than complete microbial cells, as the catalysts. Both technologies have characteristics that allow them to fill different niches. The microbial catalysts in the MFC could theoretically be sustained forever as they regenerate themselves. Different organisms could also be combined to allow fuel flexibility, which would be highly valued for ground applications. Unlike microbes, enzymes could theoretically allow more complete electron harvesting since living microbes consume some of the chemical energy to survive and reproduce. Enzyme fuel cells, therefore, could potentially be a more dense power source more suitable to air and space vehicle applications.[1]

Solar Power

MFCs are not solar power. They do not use photovoltaics, space-based power vectoring, or solar thermal energy. MFCs are a good candidate, however, to couple with solar power to fill existing limitations. The USAF already has prototype expeditionary, flexible facilities with integrated photovoltaics.[2]

Wind Power

MFCs are obviously not wind power. MFCs, however, are a good candidate to couple with wind power to fill existing limitations.

Desalination Plants

MFCs are not desalination plants, and they do not replace the reverse osmosis water purification unit (ROWPU) that the USAF currently uses in expeditionary settings. MFCs can operate in salt water to produce energy (often called sediment batteries), but they will not convert saltwater to potable water because the microbes metabolize carbon-based compounds, not salt.[3]

Notes

1. These ideas concerning differences and potential applications of the different types of biological fuels cells came from Maj Jennifer Gresham (Air Force Office of Scientific Research), phone interview with the author, 16 November 2007.
2. Keith, "BEAR Base Solar Power System."
3. Reimers et al., "Microbial Fuel Cell Energy."

Appendix D

Key Microbial Fuel Cell Capabilities and Challenges

Capabilities	*Challenges*
Within 48 hours, enables secure, basic ground services (water, electricity, and waste disposal) apart from the vulnerable infrastructure network, at both permanent and expeditionary locations, in a clean and efficient manner	Sufficient waste volumes Microbe vulnerability Social acceptance Reluctance to invest in facility technologies
Eliminates need for fuel and water to flow through lines of communication (reduces risks/vulnerabilities/costs)	Resistance from utility and construction industry Timeline to convert homeland infrastructure
Sanitarily disposes of 100% of sewage and other carbon-rich waste	Must be coupled with demand-reducing technologies (energy and water)
Reduces water requirement by at least 70%	
Generates 600+ watts of power per person—25% of an expeditionary base power requirement	
For a 150,000-person deployment saves • 2 million gallons/day of water • 180,000 gallons/day of fuel • $50 million/day in fuel operating costs (fuel price plus transport cost)	
Prevents natural resource conflicts	
Generates power with no heat/noise	

Appendix E

Basic Cost Analysis

This is a basic cost analysis for a 1,100-person expeditionary base and includes potential savings in both electrical power and water with implementation of efficient microbial fuel cell (MFC) systems.

Electrical Power

Table E.1. Organic power sources at 1,100-person expeditionary base

Potential Power Source	*MMBtu's[a]/day[b]*	*~ kW[c]*
Black/Gray Water	2+	30
Food Waste	4+	50
Paper/Cardboard	40	480
Wood	10	120
Total	56	680

[a]million British thermal units
[b]Waste characterizations for "00-Staff, 50-Hospital Bed Bare Bases" were provided in tables labeled "Battelle Report" and "ACC/WMO Report" from Johnson and Diltz in discussion with author.
[c]kilowatts

Mobile Expeditionary Power (MEP)-12A Generator[1]

Rated capacity: 750 kW
Actual output capacity: 625 kW
Fuel consumption rate: 1,320 gallons (gal) per day (568 watts [W]/gal/day)
Cost: $165,000
Weight: 25,000 pounds

Expeditionary Base Power Planning Factor

2.7 kW per person[2] (Four MEP-12s/1,100 people)

Impact

MFCs, therefore, could supply about 25 percent of the required base power and replace one of the four MEP-12A generators at a 1,100-person location if 90 percent of the waste's potential energy could be captured.

Fuel Costs (per gallon)

Standard cost: $3.04[3]
Delivered cost via USAF tanker: $52.50[4]
Delivered cost (conservative) to remote operating location: $300[5]

Amount Saved Daily by Substituting an MFC for One MEP-12A

Standard cost: $3.04/gal x 1,320 gal/day = $4,000 ($4K)/day
Cost for fuel delivered via USAF: $52.50 x 1,320 gal/day = $69K/day
Cost for fuel delivered to a remote operating location: $300 x 1,320 gal/day = $400K/day
Cost savings for 150,000-person deployment: $50 million/day

Amount Saved Daily by Substituting Gray/Black Water Only for 30 kW of Power

Gallons of fuel saved: 30 kW ÷ 568 W/gal/day = 50 gal/day
Standard cost: $3.04/gal x 50 gal/day = $150/day
Cost for fuel delivered via USAF: $52.50 x 50 gal/day = $2.5K/day
Cost for fuel delivered to a remote operating location: $300 x 50 gal/day = $15K/day

Water

Planning Factor

Water-use planning factor (expeditionary): 20 gal/person/day[6]
Water-use planning factor (permanent): 50 gal/person/day[7]
Wastewater planning factor: 14 gal/person/day[8]

Impact

The typical expeditionary plan calls for wastewater disposal via evaporation lagoons, so 14 gal/person/day is lost via evaporation that could be reclaimed with MFCs.

Savings

Water savings percentage: 14 gal/person/day ÷ 20 gal/person/day = 70%

Total water saved/day for a 1,100 person base: 14 gal/person/day x 1,100 people = 15K gal/day

Literature Estimates

Dr. Bruce Logan (see table A.1) estimates that "this system would produce 51 kilowatts on the waste from 100,000 people."[9] Logan's calculation only includes gray water and black water, and he predicts 0.5 W/person.

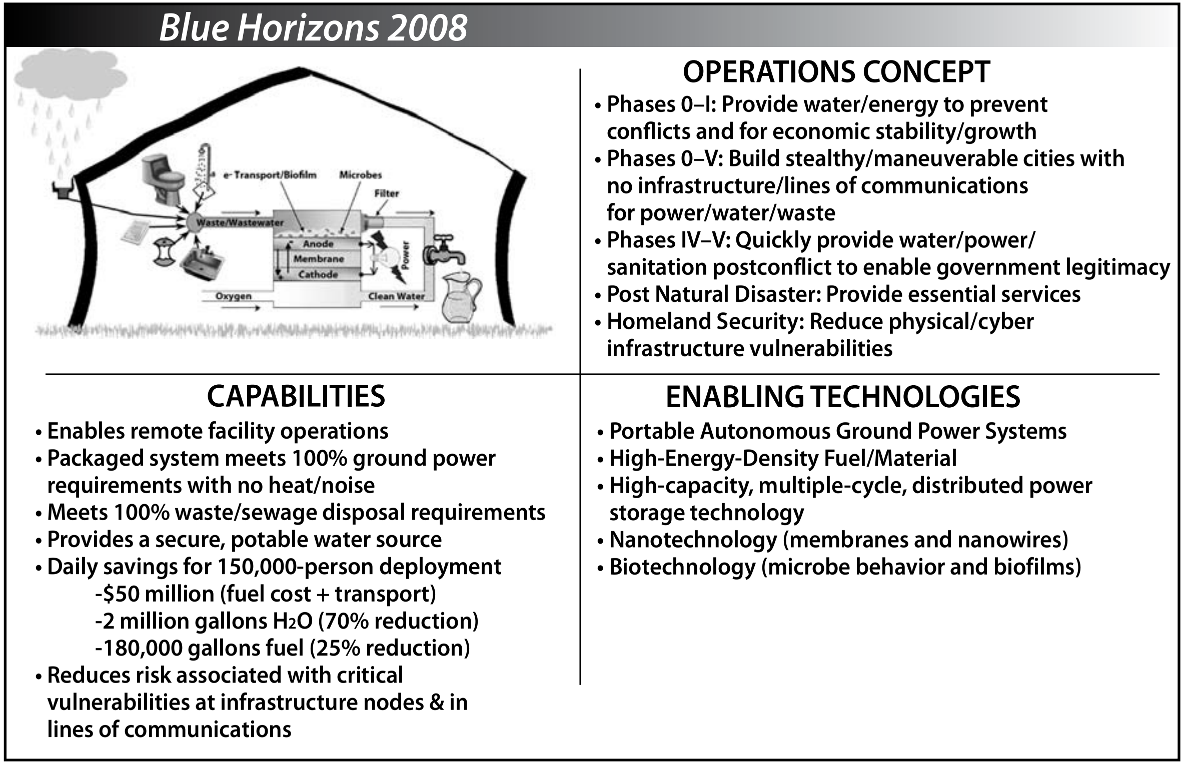
Notes

1. Air Force Handbook 10-222, vol. 10, *Guide to Harvest Falcon*; and vol. 2, *Guide to Bare Base Assets*, 34.
2. Ibid., vol. 2, *Guide to Bare Base Assets*, 75.
3. Grant, "Surging Oil Prices."
4. The 2001 delivered fuel cost was "$17.50 per gallon for USAF worldwide tanker-delivered fuel." Since the standard cost of fuel tripled from 2001 to 2008, $17.50 x 3 = $52.50 is the 2008 delivered cost estimate. Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting*, ES-3, 20. For additional validation of this estimate, see Col Elwood Amidon, briefing, subject: Needed Now, slide 22.
5. In 2001, the cost of delivered fuel was "hundreds of dollars per gallon for Army forces deep into the battlespace." Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting*, ES-3. Other sources suggest this number could be as high as $600 per gallon. See Dimotakis, Grober, and Lewis, *Reducing DoD Fossil-Fuel Dependence*, 20.
6. Air Force Pamphlet 10-219, vol. 5, *Bare Base Conceptual Planning Guide*, 87.
7. Ibid., 86.
8. Ibid., 115.
9. Biever, "Plugging into the Power of Sewage."

Appendix F

Quad Chart

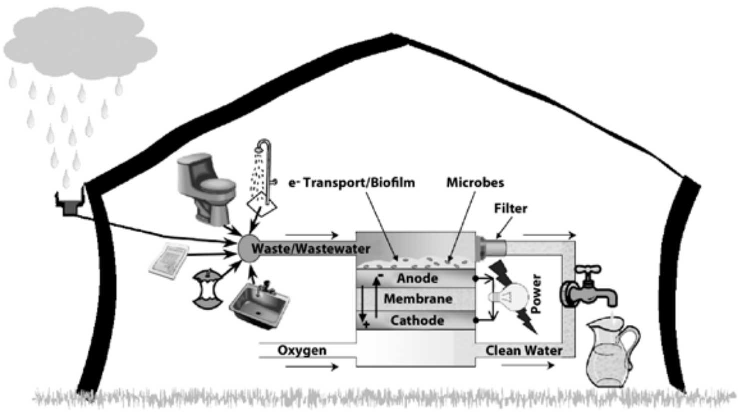
Microbial Fuel Cells



Appendix G

Tech Sheet

Microbial Fuel Cells



System Description: Microbial fuel cells (MFC) convert wastewater and organic material to clean water and electricity.

MFCs are fed by sewage, gray water (shower and laundry water), stormwater, industrial waste, kitchen scraps, paper, wood, or any other type of organic matter. Through anaerobic metabolism at the anode, microbes restore wastewater to a recyclable quality and produce electrons that can be captured for power. The by-product of the reaction is potentially potable-quality water.

MFCs operate on similar principles to hydrogen fuel cells, but neither hydrogen nor a sealed cathode in an oxygen-pure environment is required. Power is not the only benefit; MFCs also sanitarily dispose of organic waste and produce clean water.

Possible Concept of Operations: MFCs should be coupled with other technologies to meet 100 percent of the power, water, wastewater, and solid waste disposal requirements autonomously and covertly—without sustainment support from lines of communications (LOC) or an infrastructure network.

- Phases 0–V (Shape, Deter, Seize Initiative, Dominate, Stabilize, Enable Civil Authority)
    - Establish maneuverable bases that are light, transportable, and modular requiring no heavy equipment to build, no utilities infrastructure to support, and no fuels to sustain
    - Generate power without a heat signature or noise (flight-line operations or facility power)
- Phases 0–I (Shape, Deter)
    - Prevent conflicts sparked by water and energy resource demand
    - *National Security Strategy* (*NSS*): "Expand the circle of development by opening societies and building the infrastructure of democracy"[1]
    - *NSS*: "Ignite a new era of global economic growth through free markets and free trade" which includes "secure, clean energy development"[2]
- Phases IV–V (Stabilize, Enable Civil Authority)
    - Provide water, sanitation, and power post-conflict or post–natural disaster
    - Provide essential services (remote or urban) without major construction or resources
    - Quickly gives nascent government legitimacy by providing for the people's needs
- Homeland Defense: Reduce/eliminate risk associated with critical nodes of vulnerability in both the physical and cyber realms by distributing the infrastructure network (power grid, water, and sewage); threat could be from enemy, natural disaster, or resource shortage

Capabilities:

- Within 48 hours enables basic ground services (water, electricity, and waste disposal) apart from the vulnerable infrastructure network in a clean and efficient manner

- Eliminates need for fuel and water to flow through LOCs (reduces risks/vulnerabilities/costs)
- Sanitarily disposes of 100% of sewage and other carbon-rich waste
- Reduces water requirement by at least 70%
- Generates 600+ watts of power per person—25% of an expeditionary base power requirement
- For a 150,000-person deployment
    - Saves 2 million (2M) gallons/day of water
    - Saves 180,000 gallons/day of fuel
    - Saves $50M/day in fuel operating costs (fuel price plus transport cost)

Notes

1. Bush, *National Security Strategy*, 31.
2. Ibid., 30.

Glossary

Air and Space Operations Center	Also known as the AN/USQ-163 Falconer Air and Space Operations Center (AOC) weapon system. The AOC plans, tasks, and coordinates execution of air and space operations and provides centralized control for friendly forces.
airpower	For brevity, *airpower* is occasionally used alone in this text, but it refers to air, space, and cyber power.
black water	Wastewater that contains biological or solid wastes. Examples include water flowing from toilet and kitchen drains.
clean energy	Energy that does not consume limited natural resources or produce harmful by-products. Renewable energy is a subset of clean energy.
craftsmen	Air Force civil engineers, assigned to the 3EXXX Air Force specialty codes, who construct, maintain, repair, and operate facilities and infrastructure at home stations and in deployed environments. Currently, craftsmen maintain general skills at the home station but must also attend annual Silver Flag training to be qualified on expeditionary-specific assets. Similar expeditionary and home-station assets would eliminate much of this training.
fouling	Term used to describe microbial fuel cell membranes encrusted with deposits.

Future Capabilities Game 2007	A USAF far-term focused war game.
gray water	Wastewater that does not contain urine or solid waste. Examples include water from showers, washing machines, and bathroom sinks.
infrastructure nodes	Key points in an infrastructure network that are essential to proper network function. Nodes can be in the physical or cyber realm. Examples include a power plant or the software that operates the control system for any type of infrastructure.
infrastructure (or infrastructure network)	All components of utility systems that bring resources from one point to another. Examples might include oil pipelines, power plants, electrical transmission lines, water towers, water mains, sewage mains, and sewage treatment plants. Institutions and facilities, such as schools, prisons, and post offices, are not included in this definition.
inoculum	Microorganisms introduced into a suitable growing medium.
line of communications	Used in a military sense to indicate a main supply route. It may include transportation by ships, trains, trucks, aircraft, or any other mode of travel.
mediator	A soluble molecule that actively gains and loses electrons.
microbial electrolysis cell	A type of microbial fuel cell that is more complex than the concept discussed in this research. It uses a voltage input to drive hydrogen production.

mobile electric power (MEP) cell	Describes generators typically used in USAF expeditionary engineering. Designed to work alone or with expeditionary power plants. For example, a MEP-12A generator provides 750 kW of 3-phase power.
modular	Consisting of small units or sections that allow flexible, scaleable configurations and standardized construction.
Nafion®	A chemically stable polymer developed by DuPont.
organic wastes	Waste products that have high carbon contents. Examples include wastewater, food scraps, agricultural wastes, paper, wood, and plastics.
relevance tree	Research methodology that recursively breaks problem into smaller components until enough detail is reached to understand the fundamental issues surrounding a problem. This term also refers to the graphical diagram that represents this process.
renewable energy	Energy that comes from sources that are naturally replenished. Examples include energy captured from the sun, wind, or geothermal sources. Renewable energy is a type of clean energy.
reverse osmosis water purification unit	USAF expeditionary engineering assets that produce up to 600 gallons of potable water per hour from seawater or freshwater.

self-contained facilities	Facilities that do not rely on outside infrastructure or lines of communications for utilities such as water, wastewater, and power.
wastewater	Water that has been used. Examples include gray water, black water, and industrial waste streams.

Abbreviations

ACSC	Air Command and Staff College
AOC-WS	Air and Space Operations Center–Weapon System
DOD	Department of Defense
DOE	Department of Energy
DOS	Department of State
EU	European Union
FG07	Future Capabilities Game 2007
IOP	instrument of power
JP	joint publication
LOC	line of communications
MEC	microbial electrolysis cell
MEP	mobile electric power
MFC	microbial fuel cell
NGO	nongovernmental organization
NMS	*National Military Strategy*
NSS	*National Security Strategy*
QDR	*Quadrennial Defense Review*
R&D	research and development
SSTR	stability, security, transition, and reconstruction
TRL	technology readiness level
USGBC	United States Green Building Council

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