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WASTE TO WATTS AND WATER: ENABLING SELF-CONTAINED FACILITIES USING MICROBIAL FUEL CELLS

by

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Preface

Throughout my career in the United States Air Force, I have had the opportunity to see engineering technologies from two different angles. I began my career as a Research and Development Mechanical Engineer at the Air Force Research Laboratory. I worked daily with technologies for the 30-year time horizon and that 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 they are about future capabilities. Our business forms us into loyal servants who find innovative ways to "git 'r done." Furthermore, our operational pace leaves little opportunity to pontificate on capabilities for the 30-year horizon. This pace 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 this year 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 to the Blue Horizons staff for providing a framework from which I could shape an argument. Colonel Rich Fryer, Major 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, my 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.

Abstract

Lack of investment in future agile combat support technologies will lead to a strategic surprise that diverts military attention and resources from critical air, space, and cyber operations. Looking to the national security 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 dispose of waste (sewage, food scraps, graywater, and so forth) and produce clean water (up to 70% of required volumes) and power (up to 600 watts/person). Using relevance tree methodology, the research concludes that a successful MFC strategy will be collaborative, addressing not only funding and technological barriers, but also key social, industrial, and political hurdles to enabling this capability. Fully developed, this technology will save up to $50M/day for a 150,000-person deployment. Beyond cost and mobility advantages, MFCs enable homeland security against the terrorist threat and provide power, water, and sanitary waste disposal after wars or natural disasters. They also add legitimacy to stressed governments, offer security against water and energy shortages, and function in isolated areas as well as urban centers. In addition to military uses, MFCs are a diplomatic and economic tool to pursue a better state of peace by building a foundation for democratic and economic development.

Glossary

AFCESA - Air Force Civil Engineer Support Agency.

Airpower - For brevity, “airpower” is occassionaly used alone in this text, but it refers to airpower, spacepower, and cyberpower.

AOC - Air and Space Operations Center. Also known as the AN/USQ-163 Falconer Air and Space Operations Center weapon system. The AOC plans, tasks, and coordinates execution of air and space operations and provides centralized control for friendly forces.

Blackwater - 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. Craftsmen maintain general skills at the home station, but must also attend specialized training to be qualified on expeditionary-specific assets. Similar expeditionary and home-station assets reduce this training.

DoD - Department of Defense.

DoE - Department of Energy.

DoS - Department of State.

EU - European Union.

FG07 - Future Capabilities Game 2007. This is a USAF far-term focused wargame.

Fouling - The term used to describe MFC membranes encrusted with deposits.

Graywater - Wastewater that does not contain urine or solid waste. Examples include water from showers, washing machines, and bathroom sinks.

IED - Improvised Explosive Device.

Infrastructure (or Infrastructure Network) - All components of utility systems that bring resources from one point to another. Examples 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.

Infrastructure Nodes - Key points in an infrastructure network that are essential to proper network function. Nodes are in the physical realm or cyber realm. Examples include a power plant or the software that operates the control system for any kind of infrastructure.

Inoculum - Microorganisms introduced into a suitable growing medium.

LOC - Line of communications. Used in a military sense to indicate a main supply route. It includes transportation by ships, trains, trucks, aircraft, or any other mode of travel.

MEC - Microbial Electrolysis Cells. This kind of Microbial Fuel Cell is more complex than the concept discussed in this research. It uses a voltage input to drive hydrogen production.

Mediator - A soluble molecule that actively gains and loses electrons.

MEP - Mobile Electric Power. This is an acronym used to describe generators typically used in USAF expeditionary engineering. They are 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.
NGO - Non-Governmental Organization.
NMS - National Military Strategy.
NSS - National Security Strategy of the United States.
Organic Wastes - Waste products that have high carbon contents. Examples include wastewater, food scraps, agricultural wastes, paper, wood, and plastics.
QDR - Quadrennial Defense Review.
R&D - Research and Development.
Relevance Tree - A research methodology that recursively breaks a 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 kind of clean energy.
ROWPU - Reverse Osmosis Water Purification Unit. ROWPUs are USAF expeditionary engineering assets that produce up to 600 gallons of potable water per hour from sea water or fresh water.
Self-Contained Facilities - Facilities that do not rely on outside infrastructure or lines of communication for utilities such as water, wastewater, and power.
SSTR - Stability, Security, Transition, and Reconstruction.
TRL - Technology Readiness Level.
USAF - United States Air Force.
Wastewater - Water that has been used. Examples include graywater, blackwater, and industrial waste streams.

Chapter 1: Introducing the Research Question and Methodology

The year is 2030. At a major US air base, the power grid has failed and limited fuel is available for purchase. Water reservoirs are nearly empty and 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 to save the day. After twenty 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 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 must invest in MFC research because this technology gives life to sustainable facilities decoupled from the infrastructure network, a key capability for national security in 2030. 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 the technological barriers along with the key social, industrial, and political hurdles that will bring about significant savings for the USAF.

The research methodology applied to capture 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 to resolve issues 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 *Megamistakes: Forecasting and the Myth of Rapid Technological Change*[2] and *Forecasting: An Appraisal for Policy-Makers and Planners*[3] make it clear that technological feasibility alone plays only a small part in adoption of new technologies; social, industrial, political, and economic factors often have the decisive role.

Need 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,"[4] but this "green" idea furthered global warming, deforestation, and food and water shortages.[5] If 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, MFC relevancy will be established for airpower, national security, the 2030 environment, and applications outside DoD interest. After relevancy is established, the concept of self-contained facilities decoupled from the infrastructure network will be explored. Since MFCs are a key capability for enabling self-contained facilities, the technology will be 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 will facilitate conclusions about the feasibility of a MFC strategic plan to enhance US national security by 2030.

Chapter 2: Who Cares?

The problem that MFCs address is defined by looking at the relevancy of MFCs. Air, space, and cyber power relevancy is described first. Next, the research will look at the broader relevancy to national security, the 2030 environment, and beyond the DoD.

Relevancy to Air, Space, and Cyber Power

Facilities[6] 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[7]), and will be critical to air, space, and cyber power as long as humans are involved with force projection. What demands will be placed on future facilities as we enter the cyber age and beyond? Since current facilities must last *at least* 67 years,[8] 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.

One capability the USAF will require in future facilities is the ability to operate cleanly and efficiently apart from the infrastructure network and line of communications (LOCs) both in an expeditionary setting and within the US. 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[9] and cyber[10] realms. 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.”[11] 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).[12] Additionally, fuel moving through ground LOCs creates exploitable vulnerabilities to equipment, supplies, and personnel that are mitigated when facilities require less or no fuel and water to operate. For facilities in a homeland defense posture (which all USAF facilities must anticipate[13]), decentralized utilities shift risks away from vulnerable physical and cyber infrastructure nodes, eliminating critical targets for the enemy. This risk shift is important because the first national military objective defined in the NMS is to protect the US[14] and the National Strategy for Combating Terrorism calls for “defense of potential targets of attack” to include critical infrastructure such as energy and water.[15] Furthermore, the synergy of using the same MFC technology at home and abroad will reduce craftsmen training requirements and increase their competence.

As a final note on MFC relevancy to the USAF, the author narrowed the scope of this research to facility applications, but MFC significance is not limited to facilities alone. MFCs apply to any application that requires clean energy, clean water, or organic waste disposal. Some obvious benefits beyond facilities include power for micro air vehicles; power for space assets; clean water, power, and waste treatment for aircraft latrines; power for ground vehicles; and clean, low heat signature generators[16] for flight line use.

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

The link between MFCs and air, space, and cyber power is clear, but 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. “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.”[17] 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.”[18] 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% a year (or 30% total) by 2015 and to reduce water consumption by 2% a year (or 20% total) by 2015.[19] The President launched goals that are even more aggressive in December 2007 by signing the Energy Independence and Security Act of 2007.[20] Considering that buildings in the United States consume 68% of electricity,[21] facilities are a logical target to reduce natural resource dependency. Former Secretary of the USAF 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.”[22] 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.[23] Most Americans, 63%, also agreed that energy is a national security issue by confirming that energy issues threaten the US more than terrorists so, according to a 2007 poll conducted for the Yale Center for Environmental Law and Policy.[24] 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.

Although the focus of this research is on US national security, technologies that reduce water and energy dependency may contribute to a reduction in armed conflicts throughout the world—conflicts that the US often attempts to resolve. Since water and energy resources spark conflicts,[25] alternative solutions to obtaining these natural resources will prevent conflicts. Three examples come to mind. First, in the Future Capabilities Game 2007 (FG07), the scenario's conflict centered on natural resources. If natural resources 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?[26] 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.[27] Would these conflicts be less likely to start, or be more likely candidates for peaceful resolution, if water resources were available? Natural resource availability is not a panacea for conflicts that have deeper cultural roots. The point of these examples, however, is simply to establish that water and energy resource availability, enabled by MFCs or other technologies, contributes 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.[28] For the future, however, MFCs provide capability that will be useful in all four quadrants of military challenges shown in the 2006 Quadrennial Defense Review (QDR)—irregular, catastrophic, disruptive, and traditional challenges.[29,30] Additionally, MFCs will provide capabilities that are essential to all six operational plan phases as described in Joint Publication 3-0.[31] The broad applicability of MFC capability allows this technology to fill a void outside the seize and dominate phases and traditional security challenges where USAF technological innovation attention is typically focused.

MFC technology moves the USAF towards the 2005 DoD Directive that states, "Stability operations are a core US military mission…they shall be given priority comparable to combat operations."[32] Since stability is key to transferring power to civil authorities, and since facility and infrastructure construction are a large component of stability, MFC technology expedites this transition in areas with damaged or absent infrastructure. New USAF irregular warfare doctrine acknowledges this mission by a call to Civil Engineers to perform this mission.[33] 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.[34]

Whether the military likes to acknowledge this aspect of their mission or not, SSTR operations are a core mission. While assigned to Iraq, Army Captain John Prior captured the sentiment prevalent in today's writing on SSTR and counterinsurgency efforts. "The '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."[35] The infrastructure provided by US military teams paves the way for winning the hearts and minds of the indigenous population by meeting their basic needs, adding legitimacy to stressed governments after war or disaster. In short, MFC technology adds capability across all phases of war and across all kinds of challenges.

Using the military 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) "ignite a new era of global economic growth through free markets and free trade," including "secure, clean energy development"[36] and 2) "expand the circle of development by opening societies and building the infrastructure of democracy."[37] 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,[38] and integrates nations lacking infrastructure into the global economy. Non-Governmental Organizations (NGOs) could use MFCs similarly to further these NSS objectives, but the technology also serves as a baseline for establishing or supporting refugee camps or humanitarian relief efforts. MFC technology is a tool for the DoS and NGOs to accomplish essential strategic tasks specified in the NSS.

To recap, MFCs 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 paint the 2030 environment and each of these scenarios needs MFC technology to enable national security. If the US faces a ***conventional, major-theater*** enemy in 2030, MFCs will 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 eliminate key nodes of vulnerability in the homeland infrastructure, such as the power grid, the water, and the 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 provide critical infrastructure to "win hearts and minds" and add legitimacy to nascent governments. If ***energy and water shortages*** or environmental concerns are the biggest national security concern in 2030,[39] MFCs will provide green power and clean water. No matter which scenario strategic planners assume is most important for 2030, MFCs reduce the probability of strategic surprise.[40]

The argument that follows looks more closely at the fourth scenario, water and energy resource shortages. Steven Schnaars, a marketing professor who specializes in future technologies, observed that "forecasters are imprisoned by their times."[41] Humans tend to look at today's crisis and project it into the future. Conventional threats; terrorism; small wars, insurgencies, and humanitarian crises are today's discernable threats. Energy and water resource shortages are tomorrow's overlooked strategic threats that result in unnecessary risk. Therefore, this discussion will focus 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.[42] Today's energy crisis is well-recognized and built into future national security strategy.[43] Projects are underway 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 drop since 30% of most electric bills is for transmission costs and 10% of electricity is lost in transmission.[44] Self-contained facilities are more likely to survive physical or cyber terror attacks as well as natural disasters.[45] Brownout vulnerabilities that threaten productivity and the economy will also be reduced.[46] Self-contained facilities address the non-availability threat.

Water availability, on the other hand, will be a bigger natural resource crisis in 2030 than decision makers grasp today. Failure to plan 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.[47] A potential water shortage in 2030 is well documented and the USAF must prepare for it today. 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 2030. In their 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."[48] These futurists observed 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."[49] They also note, "80% of diseases in the developing world are water-related. Many are due to poor management of human excreta. About 2.6 billion people lack adequate sanitation."[50] MFCs address the water and sanitation challenges forecast by the United Nations Millennium Project.

Second, the Nobel Prize-winning Intergovernmental Panel on Climate Change predicted that by 2020 as many as 250 million Africans could experience water stress.[51] Third, Air Force planners looking at scenarios for 2025 also expect future water shortages. The King Khan scenario predicts that "clean drinking water [will be] scarce and competition over water rights [will] become a source of conflict in Africa and Southwest Asia."[52] Finally, FG07 also reflected this same natural resource shortage. Future water shortages consistently appear in strategic planning scenarios.

Individual futurists also agree about future water scarcity. Peter von Stackelberg highlighted the need for future water technology by predicting, "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."[53] *The Futurist* magazine's cover for May 2008 delcared, "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% of water consumption is for agriculture, water shortages will also lead to a food shortages.[54] Professional futurists expect to see a water crisis by 2030.

Even popular media, which is not future-focused, is reporting on the likelihood of water scarcity in 2030. Starting in 2009, demand for water will outstrip supply in La Paz-El Alto, Peru, the government estimates.[55] Even more surprising, the predicted water shortage in 2030 is not limited to places outside of the US. The main water source for Phoenix and Las Vegas, Lake Meade, "has a 50 percent chance of becoming unusable by 2021."[56] 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 US, in 2030. Sustainable technologies that minimize natural resource losses and produce beneficial by-products will be necessary to project air, space, and cyber space power, regardless of the most likely threat.

Relevancy beyond the Department of Defense

This research focuses on the applicability of MFCs to national security through the military IOP but MFCs also enable the diplomatic and economic IOPs. Understanding the larger impact of this technology allows the USAF to identify R&D partners. It also paints a picture of how important MFCs become for 2030. Figure A.1 shows application and benefit areas and a starting point for collaboration partners is detailed in Appendix A.

Chapter 3: Understanding Microbial Fuel Cell Technology

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

Self-Contained Facilities Concept

The genesis of this research was 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 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 are 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 quite broad, this research will focus on the one technology that offers the most capability toward self-contained facilities—MFCs. MFCs fold in several infrastructure and LOC dependencies—power, water, wastewater treatment, and waste disposal. For 2030's threats, self-contained facilities enabled by MFCs 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 provide and the best way to move forward. A brief study of Figure 3.1 is the best way to gain a basic understanding of MFC technology. Following the pictorial overview, this section will give a summary of how MFCs work and then address the salient technology components for a more in-depth understanding of MFCs.

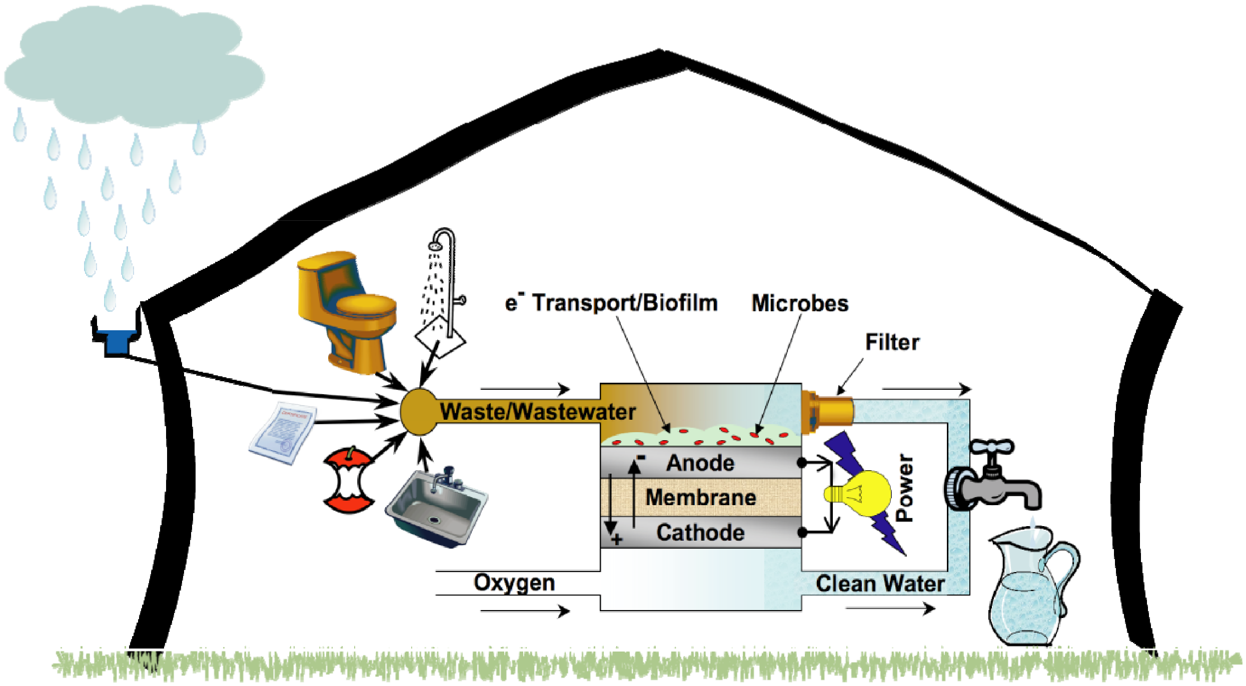

Figure 3.1: Microbial Fuel Cell Technology Overview

MFCs are one type of biological fuel cell.[57] They use living microbes as a catalyst for an electrochemical reaction to convert waste to power and water. 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."[58] Wastewater is cleaned,[59] as it is in wastewater treatment plants today, and the by-products of the reaction are clean water and power. With this understanding, the stage is set to discuss the primary components.

Components

Fuel. Fuel is the substrate in which the microbes act. Examples of fuels for MFCs include wastewater such as graywater, blackwater, and stormwater;[60] kitchen scraps; industrial waste streams;[61] agricultural waste streams;[62] sugars[63] such as glucose,[64] fructose, lactose, mamose, and so forth; algae;[65] or any other kind of carbon-rich waste product such as wood, paper, or plastic. The ideal mixture of the substrate is a key investigation area.[66]

Electrodes. MFCs 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 occurs.[67] Electrode surface area also governs how quickly waste is processed and the density of power output.[68]

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."[69] The catalyst governs the reaction speed at both electrodes[70] and therefore becomes a variable that dictates how quickly power and clean water is produced. A robust mixture of microbes, such as *Geobacter* and *Shewanella*,[71] in the anode chamber catalyze the reaction and allow for fuel flexibility. Several microbiologist are studying the genetic engineering involved with optimizing microbes for MFCs.[72,73]

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 occur at both electrodes.[74] Membranes are a current research topic and recent publications suggest replacing Nafion® membranes with a nanoporous filter[75] or "fast proton conducting ceramic membranes"[76] to optimize power output and reliability.

Electron Transport. Mediators help move electrons in the anodic chamber to the electrode where they are captured to produce electricity. Many MFC publications report supplementing the solution around the anode with mediators that are toxic chemicals such as methylene blue.[77] Microbes, however, synthesize and excrete mediators as they "breathe."[78] This natural method of transporting electrons to the anode, typically 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.[79,80] Biofilms enable electron transport by orienting cell surfaces so that the electron-transporting proteins are a certain distance from the electrode, allowing electron hopping.[81] Biofilms coat the anode and grow on a carbon-based fiber.[82]

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 there are many competing and complementary alternative energy projects in the spotlight, it is important to understand what differentiates these technologies. Some technologies not to 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 be coupled with these complementary energy and water technologies to build self-contained facilities.

Microbial Electrolysis Cells (MECs), 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 (possibly 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.[83]

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)[84] as two,[85] meaning that the basic concept or idea has just been formed.[86] In Dr. Johnson's assessment, in 10 years, leaders will talk about MFCs with the same frequency that they discuss ethanol today.[87] Derek Lovley, an MFC researcher at 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."[88] MFC technology is still in its formative stages—the perfect time for the USAF to envision future uses for this emerging technology and to shape the research.

Chapter 4: Microbial Fuel Cell Relevance Tree—A Systems Analysis Framework

With an understanding of MFC relevancy and technology, analysis is now appropriate. MFCs make a significant contribution toward self-contained facilities, but how do they contribute and what must be addressed to achieve it? 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 analysis, 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 are identified and addressed. A graphical representation of this research is presented in Figure B.1 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 technological node has three main branches: basic science, engineering, and military suitability. This analysis will highlight the biggest challenges in each of these branches.

Basic science challenges exist for all the major MFC components: fuels, electrodes, catalysts, membranes, and electron transport. Fuel mixtures and sources must be determined.[89]

Electrode size, shape, and materials must be optimized.[90, 91] Catalytic microbes must be better understood to determine power outputs limits and optimal mixtures for fuel flexibility.[92] Nanotechnology breakthroughs[93] will enable high-integrity membranes that transport protons quickly without fouling. For electron transport, hairlike structures on the microbe surface that form nanowires must be investigated.[94] Finally, microbiologists must advance biofilms[95] to learn the mixtures,[96] inoculation methods,[97] and the best materials[98] to grow microbial catalysts.

Beyond these challenges, engineering challenges must be identified early and addressed in parallel with the basic science. Configuration issues such as modularity and stacking,[99] energy storage, and coupling with other power and water generation equipment must be considered now. 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.[100] Mass manufacturing nanomembranes will also chart new territory. Of course, manufacturing puzzles are solvable if the physics are possible, but they drive costs, size, or weight of the final product.

The final technological branch is military suitability. Like any biological system, microbes are fragile. On the positive side, they thrive in a broad range of environments and adapt to any niche over time.[101] They exist in permanently frozen lakes (though water flow stops in frozen conditions) and in high-temperature sea vents.[102] On the negative side, living organisms may not have a shelf life and may require lead-time to form productive populations.[103] 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 enroute 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 Figure B.1.

Key Social Nodes

With the key technological nodes complete, now the three key nodes on the "social" branch of the MFC relevance tree will be discussed. The three key nodes are operational transparency, resistance to change, and cost.

The first key social node on the relevance tree is operational transparency. In facilities, technologies that do not require occupants to change their lifestyle or business model will be most successful,[104] so MFCs designed to be compatible with today's facilities are more likely to see widespread adoption. For example, it is easier to design technologies that capture household organic waste than it is to train a whole society to feed sorted kitchen scraps into an MFC in the basement. Others will resist the change if they know toilet water returns to their kitchen sinks after cleaning and recycling. 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 closely related to the second key node—social willingness to change. In *The End of Oil*, Paul Roberts asserts that the success in hybrid vehicles sales[105] might indicate social readiness to accept revolutionary technologies that decrease dependence on traditional energy sources.[106] But social trends related to automobiles do not necessarily translate into a desire for change in American homes and businesses. Among other reasons, Americans change vehicles more frequently than they change homes.[107]

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' 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."[108]

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.[109] 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.[110] The same could be true for MFCs if policies on security, energy, or water change.

In summary, social inertia is daunting, but change is always possible. This change will be easier in the civilian sector than it will be 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 timeframe.

Key Industrial Nodes

Many industrial factors affect MFC adoption and widespread use. This analysis will consider two main industries: the construction industry and the utility industry. The construction industry, which accounts for 20% of the American economy,[111] does not embrace innovation. "The building industry is characterized by relatively slow rates of innovation due to its size, diversity, fragmentation, and low investments in research."[112] In *Megamistakes*, technological change expert Steven Schnaars suggests that a precedent for lack of innovation means "leaders are napping."[113] This innovation dearth reflects lack of government interest, investment,[114] incentive, and century-long facility lifespans. The utility industry will show similar resistance to adopting new sustainable technologies. Infrastructure such as high-voltage transmission lines, buried power lines, water lines, and sewage pipes are costly investments that utility companies will not abandon quickly; however, incentives allow innovative companies and municipalities to gracefully bridge a transition that could span 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 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 the 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 Chapter 5.

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

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

Operations costs will quickly pay for capital investments. According to this research's calculations, organic wastes have the potential to provide up to 25% of the power at an expeditionary base. It is still uncertain how much of this potential energy MFCs will capture (alone or in combination with other technologies), scientists are optimistic that the technology will be more efficient than combustion engines that peak at about 50% efficiency.[115] If MFCs and complementary technologies capture 90% of the potential energy available (energy efficiencies have already been recorded at 65%[116] and electron capture efficiencies at 96%[117]), they could replace one of the four Mobile Electric Power (MEP)-12 generators during a 1,100-person deployment. *This replacement 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, as much as $50M will be saved each day! The capital costs of an MFC (even if double the cost of today's generators) will be recouped quickly 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 blackwater and graywater, 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 will 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% 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 benefits from reduced costs and increased capabilities.

Maintenance decreases, too. MFCs do not have moving parts like gas-fired generators. Maintenance requirements will 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 will 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. Finally, efficiencies result from eliminating maintenance on underground utilities. Overall, maintenance requirements will be similar to or less than existing systems.

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

This analysis section sought to quantify MFC capability and to identify the major obstacles in brining MFC technology online. After building a relevance tree as an analysis framework, key technological, social, industrial, and political nodes emerged. Understanding these key nodes allowed for conclusions about capabilities and limitations. After quantifying potential capabilities and limitations, a basic cost analysis revealed that MFCs yield savings of up to $50M per day in operating costs for a major theater deployment.

Chapter 5: 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 must invest in MFC R&D but investment alone is insufficient. This section will explain this conclusion by discussing MFCs for self-contained facilities, strategy suggestions, 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% of that requirement. The fundamental capability that distinguishes MFCs from other sustainable facilities technologies is its 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.

Although MFCs will meet 100% of the waste disposal requirements, expecting MFCs to meet 100% of facility power and water requirements is unrealistic.[118] For power and water, MFCs must be coupled with demand reduction through both technology and conservation efforts. "In fact, 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. Efficiency remains our greatest hope."[119] Even with increased efficiencies, MFC power densities will not meet forecasted power demand alone. MFCs only meet 25% of full power requirements[120] so MFC technology must be coupled with other sustainable power sources such as hydrogen fuel cells, solar power, wind, and thermal technologies.[121] These are promising energy sources with capability gaps that MFCs 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 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% of water used that now moves into the sewage treatment process and evaporates (in an expeditionary setting).[122] The water cleansing and reaction by-product capabilities must be augmented by tapping industrial waste streams or through water collection technologies such as rainwater and dew harvesting.[123]

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% of power and water requirements, they augment production and dispose of all wastes and fill 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 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.”[124]

Next, the USAF must develop a roadmap for MFC technology to vector the R&D funds. The roadmap must include basic science milestones, but it must 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 will identify the toughest obstacles to be addressed in parallel with the basic science development to optimize research time and dollars. Figure B.1 is a starting point for science, systems integration, manufacturing, and military suitability challenges that must be addressed in the roadmap.

In addition to the roadmap, the technology investment strategy must be collaborative. Collaboration must first begin with USAF and DoD pursuit of academic partners, but it must become an interagency plan since this technology has the potential to contribute to areas of interest beyond the DoD (see Figure A.1). The DoD has initiated several notable energy projects, but no unified, concerted effort exists yet across the services.[125] 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) the USAF must invest R&D dollars in MFC technologies, 2) a roadmap needs to be developed to spend those investment dollars properly, and 3) the technology approach must be collaborative.

Social Considerations

The social barriers to widespread use of MFCs are the perhaps the most vexing challenges from the perspective of a USAF engineer.[126] 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."[127] 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; with a deliberate plan, however, these obstacles are surmountable. Incentives are powerful change agents and specific recommendations should be the focus of future research. A starting point for this research is lessons learned from ethanol infrastructure.[128]

Political Considerations

First, policy makers must deliberately decide if a free market can shape the future energy and water economy or if government intervention is necessary to protect the economy and national security. In *The End of Oil*, Paul 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.[129] "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 to ensure that such change actually happens."[130] 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 is 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 decisions. Wing commanders, for example, see new technologies as risks without rewards since operational savings are snatched at higher levels. Furthermore, incentives such as tax credits or renewable energy credits penalize the government since no benefits are gained. "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."[131] The USAF must 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 must investigate policies that jeopardize or enhance bringing MFCs to fruition. Specific areas to be addressed are investment policies and levels, incentives, regulations, standards, taxes, and subsidies. This future research must specifically consider how decisions in these areas directly and indirectly affect the social, industrial, technological, and governmental realms.

Business Case

No investment strategy or policy decision is complete without a business case. This research included a cursory cost analysis focusing on a 1,100-person expeditionary base. The analysis showed cost advantages of MFCs for remote and expeditionary facilities. Future research must further explore the business case, especially for permanent facilities that require more investments to update building systems to accommodate MFCs. Plus, the facilities have less organic waste (as a percentage of power required) from which to generate power.

Summary

National security planners cannot know the exact threats for 2030, but the environment will 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 must 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 2030. The USAF must develop facility energy, water, and wastewater capabilities to ensure future combat effectiveness of air, space, and cyberspace warriors whose battle stations are inside facilities. Leaders cannot assume that these enablers will be available in the future; they must plan for them. However, an MFC investment strategy must include more than R&D funds alone. The USAF must pursue a collaborative approach that will address not only the technological barriers at the scientific and systems integration level, but also the key social, industrial, and political hurdles as well. US national security depends on it!

End Notes

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[1] This research methodology is described in detail in: The Futures Group International, "Chapter 12. Relevance Tree and Morphological Analysis," in *Futures Research Methodology--V2.0* (Washington, DC: American Council for the United Nations University).

[2] Steven P. Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change* (New York London: Free Press; Collier Macmillan, 1988).

[3] William Ascher, *Forecasting: An Appraisal for Policy-Makers and Planners* (Baltimore: The Johns Hopkins University Press, 1978).

[4] "Biofuels May Threaten Environment, U.N. Warns," *CNN* (23 January 2008), http://www.cnn.com/2008/TECH/science/01/23/biofuels.fears.ap/index.html. & Roger Harrabin, "EU Rethinks Biofuels Guidelines," *BBC News* (14 January 2008), http://news.bbc.co.uk/2/hi/europe/7186380.stm.

[5] David Biello, "Biofuels Are Bad for Feeding People and Combating Climate Change," *Scientific American* (7 February 2008), http://www.sciam.com/article.cfm?id=biofuels-bad-for-people-and-climate. & Elizabeth Rosenthal, "Biofuels Deemed a Greenhouse Threat," *The New York Times* (8 February 2008), http://www.nytimes.com/2008/02/08/science/earth/08wbiofuels.html.

[6] Facility is defined as "a real property entity consisting of one or more of the following: a building, a structure, a utility system, pavement, and underlying land" according to JP 1-02. 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. Joint Publication 1-02, *Department of Defense Dictionary of Military and Associated Terms* (Department of Defense, 2001), 25-27.

[7] "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 JFACC/CFACC 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, *The Air Force Handbook 2007* (Washington, DC: Department of the Air Force, 2007), 64-65.

[8] Raymond F. DuBois, *Defense Installations Strategic Plan* (Washington, DC: 2004), 8.

[9] "Increased security of energy supply and distribution systems have 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." Whole Building Design Guide Sustainable Committee, "Optimize Energy Use," http://www.wbdg.org/design/minimize_consumption.php.

[10] The vulnerability of infrastructure to attack in the cyber realm was confirmed by the Department of Homeland Defense and is reported in this article: Jeanne Meserve, "Sources: Staged Cyber Attack Reveals Vulnerability in Power Grid," *CNN* (26 September 2007), http://www.cnn.com/2007/US/09/26/power.at.risk/index.html.

[11] "Research & Development Projects: Logistics Fuel Reformer/Processor for Mobile Electric Power (MEP) Fuel Cells Power Generation," http://www.dodfuelcell.com.

[12] "Agility is the ability to rapidly deploy, employ, sustain and redeploy capabilities in geographically separated and environmentally diverse regions." General Richard B. Myers, *The National Military Strategy of the United States of America* (Washington, DC: 2004), 6.

[13] 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.

[14] Myers, *The National Military Strategy of the United States of America*, 8.

[15] George W. Bush, *National Strategy for Combating Terrorism* (Washington, DC: 2006), 13.

[16] The Army has already developed fuel cells (but not MFCs) for silent, low-heat signature generators. Franklin H. Holcomb et al., "Energy Savings for Silent Camp™ Hybrid Technologies," *Journal of Fuel Cell Science and Technology* 4 (2007). Other examples of the low-heat signature capability of fuel cells abounds in the literature, including this article: Christy Lambert, "Fuel Cells Help Make Noisy, Hot Generators a Thing of the Past," *EurekAlert!* (11 December 2007), http://www.eurekalert.org/pub_releases/2007-12/dnnl-fch121107.php#.

[17] Whole Building Design Guide Sustainable Committee, "Optimize Energy Use." (electronic article)

[18] Lieutenant Colonel John M. Amidon, "A "Manhattan Project" for Energy," *Joint Forces Quarterly*, no. 39: 76.

[19] George W. Bush, "Executive Order 13423--Strengthening Federal Environmental, Energy, and Transportation Management," (24 January 2007).

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[20] "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 and Confronting Climate Change through Investment in Renewable Technologies," (5 March 2008), http://www.whitehouse.gov/news/releases/2008/03/20080305-2.html.

[21] Whole Building Design Guide Sustainable Committee, "Optimize Energy Use." (electronic article)

[22] United States Air Force, "U.S. Air Force Renewable Energy Program Brochure," (Tyndall Air Force Base, FL: Air Force Civil Engineer Support Agency, 2006), 3.

[23] The Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting through Reduced Fuel Burden* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, January 2001), 10.

[24] American Council for the United Nations University, "Worldwide Emerging Environmental Issues Affecting the U.S. Military," (March 2007), 7.

[25] These four references provide evidence that resources are a source of conflict:
"Global Policy Forum," http://www.globalpolicy.org/security/docs/minindx.htm.
Chris Abbott, Paul Rogers, and John Sloboda, *Beyond Terror: The Truth About the Real Threats to Our World* (Berkshire, United Kingdom: Random House Group, 2007), Chapter 3.
Michael T. Klare, *Resource Wars: The New Landscape of Global Conflict* (New York: Metropolitan Books, 2001).
Michael Renner, *Worldwatch Paper #162: The Anatomy of Resource Wars*, ed. Thomas Prugh, State of the World Library 2002 (Danvers, MA: Worldwatch Institute, 2002).

[26] Terri Morrison and Wayne A. Conway, *Kiss, Bow or Shake Hands*, 2nd ed. (Avon, MA: Adams Media, 1995), 121.

[27] Shira B. Yoffe, "Basins at Risk: Conflict and Cooperation over International Freshwater Resources" (Ph.D. Dissertation, Oregon State University, 2001).

[28] Carl Builder asserts that the altar of worship for the USAF is technology and the enchantment with technological marvels, especially flying machines, characterizes USAF culture. Carl H. Builder, *The Masks of War: American Military Styles in Strategy and Analysis* (Baltimore: The Johns Hopkins University Press, 1989), 19.

[29] Donald H. Rumsfeld, *Quadrennial Defense Review Report* (2006).

[30] ———, *The National Defense Strategy of the United States of America* (March 2005), 2-3. This array of four challenges—traditional, irregular, catastrophic, and disruptive—originally appeared this document.

[31] The six plan phases are: shape, deter, seize the initiative, dominate, stabilize, and enable civil authority. Joint Publication 3-0, "Joint Operations," (17 September 2006): IV-26.

[32] Department of Defense Directive 3000.05, *Military Support for Stability, Security, Transition, and Reconstruction (SSTR) Operations* (28 November 2005), 19.

[33] Air Force Doctrine Document 2-3, *Irregular Warfare* (1 August 2007), 42-43.

[34] Bruce A. Elleman, "28. Waves of Hope: The U.S. Navy's Response to the Tsunami in Northern Indonesia," in *The Newport Papers* (Naval War College Press, February 2007), v.

[35] George Packer, "Letter from Baghdad: War after the War: What Washington Doesn't See in Iraq," *The New Yorker* 79 (24 November 2003), http://www.newyorker.com/archive/2003/11/24/031124fa_fact1. See also Meserve, "Sources: Staged Cyber Attack Reveals Vulnerability in Power Grid." (electronic article)

[36] George W. Bush, *The National Security Strategy of the United States of America* (Washington, DC: 2006), 25-27.

[37] Ibid., 31-34.

[38] "Modern wastewater treatments have accomplished more to protect human health and our environment than perhaps any single technology." B. E. Logan, "Energy Diversity Brings Stability," *Environmental Science & Technology* 40, no. 17 (2006): 5161.

[39] For a thorough analysis of environmental threats to national security and a sustainable security strategy, see John T. Ackerman, "Climate Change, National Security, and the Quadrennial Defense Review: Avoiding the Perfect Storm," *Strategic Studies Quarterly* 2, no. 1 (Spring 2008).

[40] In his recent White Paper, General Michael Moseley emphasized that future fights will not be the same as today's fights and the USAF must look ahead make proper assumptions about the future to avoid unnecessary risk. General T. Michael Moseley, *The Nation's Guardians: America's 21st Century Air Force (CSAF White Paper)* (Washington, DC: United States Air Force, 29 December 2007), 9.

[41] Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change*, 63.

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[42] Energy Information Administration, *International Energy Outlook 2007* (Washington, DC: United States Department of Energy, Office of Integrated Analysis and Forecasting, May 2007), 61.

[43] See, for instance, George W. Bush, *National Energy Policy* (May 2001).

[44] Col Elwood Amidon, "Needed Now: A National Energy Security Manhattan Project," (briefing, AF/A8PE, modified by Dr. John Ackerman, 6 March 2006): Slide 44.

[45] Ibid.

[46] Many power systems "have become overburdened in recent years, illustrated by the California energy brownouts in 2001." United States Green Building Council, "Building Momentum: National Trends and Prospects for High-Performance Green Buildings," (Washington, DC: 2003), 10.

[47] Joseph P. Martin, "Technological Forecasting: An Introduction," *The Futurist* (1993): 14.

[48] Jerome C. Glenn and Theodore J. Gordon, *2007 State of the Future* (Washington, DC: The Millennium Project, World Federation of United Nations Associations, 2007), 10.

[49] Ibid., 14.

[50] Ibid.

[51] Intergovernmental Panel on Climate Change, ed., *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland: 2008), 11.

[52] Col Joseph A. Engelbrecht, Jr. et al., "Alternate Futures for 2025: Security Planning to Avoid Surprise," (United States Air Force, 1996), 76.

[53] Water technology is one of 12 technologies highlighted by von Stackelberg as essential to the future. Peter von Stackelberg, "The Future of Universal Water," *Nanotechnology Now* (25 February 2008), http://www.nanotech-now.com/news.cgi?story_id=28193.

[54] Lester R. Brown, "Draining Our Future: The Growing Shortage of Freshwater," *The Futurist* 42, no. 3 (May-June 2008).

[55] "Loss of Andes Glaciers Threatens Water Supply," *CNN* (26 November 2007), http://www.cnn.com/2007/TECH/science/11/26/andes.water.ap/index.html.

[56] Tim P. Barnett and David W. Pierce, "When Will Lake Mead Go Dry?," *Water Resources Research* 44, no. W03201, doi:10.1029/2007WR006704 (2008).

Also reported in the print media by Felicity Barringer, "Lake Mead Could Be within a Few Years of Going Dry, Study Finds," *The New York Times* (13 February 2008), http://www.nytimes.com/2008/02/13/us/13mead.html?_r=1&scp=1sq=Lake+Mead+Could+Be+Within+a+Few+Years+of+Going+Dry%2C+Study+Finds&st=nyt&oref=slogin.

[57] The other type of biological fuel cell is an enzyme or protein fuel cell. These are explained in Appendix C.

[58] Celeste Biever, "Plugging into the Power of Sewage," *New Scientist* (10 March 2004), http://www.newscientist.com/article/dn4761-plugging-into-the-power-of-sewage.html.

[59] 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. Bruce E. Logan et al., "Microbial Fuel Cells: Methodology and Technology," *Environmental Science & Technology* 40, no. 17 (2006): 5189.

[60] M. A. Rodrigo et al., "Production of Electricity from the Treatment of Urban Waste Water Using a Microbial Fuel Cell," *Journal of Power Sources* 169, no. 1 (2007).

[61] "Project to Turn Beer Wastewater into Power," *Fuel Cells Bulletin* 2007, no. 7 (2007).

[62] Hiroshi Yokoyama et al., "Treatment of Cow-Waste Slurry by a Microbial Fuel Cell and the Properties of the Treated Slurry as a Liquid Manure," *Animal Science Journal* 77, no. 6 (2006).

[63] Tunc Catal et al., "Electricity Production from Twelve Monosaccharides Using Microbial Fuel Cells," *Journal of Power Sources* 175 (2008): 196.

[64] Korneel Rabaey et al., "A Microbial Fuel Cell Capable of Converting Glucose to Electricity at High Rate and Efficiency," *Biotechnology Letters* 25, no. 18 (2003).

[65] Patrick G. Hatcher, "New Sources of Biomass Feed Stocks: Algae and More," (Lecture. Sierra Club, Old Dominion University, Virginia: 2 April 2008).

[66] The maximum power density from MFC fuel found to date is 1 kW of power per cubic meter of waste. Yanzhen Fan, Hongqiang Hu, and Hong Liu, "Enhanced Coulombic Efficiency and Power Density of Air-Cathode Microbial Fuel Cells with an Improved Cell Configuration," *Journal of Power Sources* 171, no. 2 (2007): 348.

[67] Bruce Logan et al., "Graphite Fiber Brush Anodes for Increased Power Production in Air-Cathode Microbial Fuel Cells," *Environmental Science & Technology* 41, no. 9 (2007): 3341.

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[68] Top power output based on electrode surface area is 5.8 watts per square meter. Miriam Rosenbaum et al., "Interfacing Electrocatalysis and Biocatalysis with Tungsten Carbide: A High-Performance, Noble-Metal-Free Microbial Fuel Cell," *Angewandte Chemie* 118, no. 40 (2006).

[69] Lars Angenent, "Microbial Fuel Cells Turn on the Juice," *EurekAlert!* (4 December 2007), http://www.eurekalert.org/pub_releases/2007-12/wuis-mfc120407.php.

[70] Microbes are typically not used at the cathode, but the cathodic catalyst is still and important variable in power and water output. See Shaoan Cheng, Hong Liu, and Bruce E. Logan, "Increased Performance of Single-Chamber Microbial Fuel Cells Using an Improved Cathode Structure," *Electrochemistry Communications* 8, no. 3 (2006). Also see Shijie You et al., "A Microbial Fuel Cell Using Permanganate as the Cathodic Electron Acceptor," *Journal of Power Sources* 162, no. 2 (2006).

[71] Derek R. Lovley, "Bug Juice: Harvesting Electricity with Microorganisms," *Nature Reviews Microbiology* 4, no. 10 (2006): 501-02.

[72] Justin C. Biffinger et al., "A Biofilm Enhanced Miniature Microbial Fuel Cell Using *Shewanella Oneidensis DSP10* and Oxygen Reduction Cathodes," *Biosensors & Bioelectronics* 22, no. 8 (2007).

[73] Bruce E. Logan and John M. Regan, "Electricity-Producing Bacterial Communities in Microbial Fuel Cells," *Trends in Microbiology* 14, no. 12 (2006): 517.

[74] Proton exchange is governed by the surface area of the anode and the membrane. Sang-Eun Oh and Bruce E. Logan, "Proton Exchange Membrane and Electrode Surface Areas as Factors That Affect Power Generation in Microbial Fuel Cells," *Applied Microbiology & Biotechnology* 70 (2006): 162.

[75] Justin C. Biffinger et al., "Diversifying Biological Fuel Cell Designs by Use of Nanoporous Filters," *Environmental Science & Technology* 41, no. 4 (2007).

[76] Eliza M. Tsui and Mark R. Wiesner, "Fast Proton Conducting Ceramic Membranes Derived from Ferroxane Nanoparticle-Precursors as Fuel Cell Electrolytes," *Journal of Membrane Science* Manuscript Accepted (2008).

[77] Charles W. Walker, Jr., and Alyssa L. Walker, "Biological Fuel Cell Functional as an Active or Reserve Power Source," (United States Army Research Laboratory, 2006).

[78] Many microbes synthesize and excrete soluble redox-active molecules to enable anaerobic respiration. Alfons J. M Stams et al., "Exocellular Electron Transfer in Anaerobic Microbial Communities," *Environmental Microbiology* 8, no. 3 (2006): 371.

[79] Yuri A. Gorby et al., "Electrically Conductive Bacterial Nanowires Produced by *Shewanella Oneidensis* Strain MR-1 and Other Microorganisms," *Proceedings of the National Academy of Sciences of the United States of America* 103, no. 30 (2006).

[80] Gemma Reguera et al., "Extracellular Electron Transfer Via Microbial Nanowires," *Nature* 435, no. 7045 (2005).

[81] Biffinger et al., "A Biofilm Enhanced Miniature Microbial Fuel Cell Using *Shewanella Oneidensis DSP10* and Oxygen Reduction Cathodes."

[82] Angenent, "Microbial Fuel Cells Turn on the Juice." (electronic article)

[83] For an non-technical explanation of this concept, see Bruce E. Logan, "Microbial Electrolysis Cell Research," (19 December 2007), http://www.engr.psu.edu/ce/ENVE/BEAMR/BEAMR.htm. For a recent scientific publication on this configuration see Shaoan Cheng and Bruce E. Logan, "Sustainable and Efficient Biohydrogen Production Via Electrohydrogenesis," *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 47 (2007).

[84] Technology Readiness Level is a measure of the maturity of an emerging or desired technology. For more information, please see Deputy Under Secretary of Defense for Science and Technology, "Technology Readiness Assessment (TRA) Deskbook," (May 2005).

[85] Glenn R. Johnson, "ML Bio Program White Paper: Microbial Fuel Cell for Remote Power Generation and Waste Stream Treatment," (2007), 5.

[86] Additional information concerning 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.” Deputy Under Secretary of Defense for Science and Technology, "Technology Readiness Assessment (TRA) Deskbook."

[87] Glenn R. Johnson and Robert Diltz, Discussion with the author during visit to Air Force Research Laboratory, Tyndall AFB, FL, 6 February 2008.

[88] Biever, "Plugging into the Power of Sewage." (electronic article)

[89] Table 3 in the following article provides a summary of different fuel sources matched with different microbes. Byung Hong Kim, In Seop Chang, and Geoffrey M. Gadd, "Challenges in Microbial Fuel Cell Development and Operation," *Applied Microbiology & Biotechnology* 76, no. 3 (2007): 487.

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[90] The “high surface-area-to-chamber volume ratio utilized in the mini-MFC enhanced power density when compared to output from similar macroscopic MFCs.” Bradley R. Ringeisen et al., "High Power Density from a Miniature Microbial Fuel Cell Using Shewanella Oneidensis DSP 10," *Environmental Science & Technology* 40, no. 8 (2006): 2629. Cross section and area matter; see Bradley R. Ringeisen, Ricky Ray, and Brenda Little, "A Miniature Microbial Fuel Cell Operating with an Aerobic Anode Chamber," *Journal of Power Sources* 165, no. 2 (2007): 591.

[91] 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 from Wastewater," *Membrane Technology* 2006, no. 12 (2006).

[92] Many microbes may still be awaiting discovery. Lovley, "Bug Juice: Harvesting Electricity with Microorganisms," 506.

[93] Biotechnology and nanotechnology are closely linked for MFC research. Once example: A. Morozan et al., "The Biocompatibility Microorganisms-Carbon Nanostructures for Applications in Microbial Fuel Cells," *physica status solidi* 204, no. 6 (2007).

[94] For a visual depiction of biological nanowires from pili, see Figure 4 in Gorby et al., "Electrically Conductive Bacterial Nanowires Produced by *Shewanella Oneidensis* Strain MR-1 and Other Microorganisms," 11361.

[95] "Power Boosted 10-Fold in Microbial Fuel Cells," *Fuel Cells Bulletin* 2006, no. 7 (2006): 7.

[96] “Multiple populations within microbial communities can co-operate to achieve energy generation.” K. Rabaey et al., "Microbial Ecology Meets Electrochemistry: Electricity Driven and Driving Communities," *The ISME Journal: Multidisciplinary Journal of Microbial Ecology* 1, no. 1 (2007): 9.

[97] M.M. Ghangrekar and V.B. Shinde, "Microbial Fuel Cell: A New Approach of Wastewater Treatment with Power Generation" (paper presented at the International Workshop on R&D Frontiers in Water and Wastewater Management, Nagpur, India, January 20-21 2006), 8.

[98] Logan et al., "Microbial Fuel Cells: Methodology and Technology," 5184.

[99] Peter Aelterman et al., "Continuous Electricity Generation at High Voltages and Currents Using Stacked Microbial Fuel Cells," *Environmental Science & Technology* 40, no. 10 (2006).

[100] MFCs show promise in the lab, but substantial additional optimization will be required for large-scale electricity production. Derek R. Lovley, "Microbial Fuel Cells: Novel Microbial Physiologies and Engineering Approaches," *Current Opinion in Biotechnology* 17, no. 3 (2006): 327.

[101] “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.” Bruce E. Rittmann et al., "A Vista for Microbial Ecology and Environmental Biotechnology," *Environmental Science & Technology* 40, no. 4 (2006): 1102.

[102] Johnson and Diltz. (personal communication)

[103] “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 Figure 2 in Rodrigo et al., "Production of Electricity from the Treatment of Urban Waste Water Using a Microbial Fuel Cell," 200.

[104] Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change*, 117.

[105] An Internal Revenue Service report indicates that Toyota alone has sold more than 60,000 hybrid vehicles in the US, ending a federal tax credit incentive program for purchasing that company’s hybrid vehicles. "2008 Hybrids Certified as Tax Credit for Toyota and Lexus Comes to an End," (8 November 2007), http://www.irs.gov/newsroom/article/0,,id=175518,00.html.

[106] Paul Roberts, *The End of Oil* (New York: Houghton Mifflin Company, 2005), 338-39.

[107] The average American driver purchases a new vehicle every three to five years. Susanne Jones, "What Is a Hybrid Vehicle?," http://www.helium.com/items/793791-prices-consumers-looking-driving.

[108] Roberts, *The End of Oil*, 338-39.

[109] Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change*, 118.

[110] Ibid., 121.

[111] United States Green Building Council, "Building Momentum: National Trends and Prospects for High-Performance Green Buildings," 4.

[112] Ibid., 17.

[113] Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change*, 153.

[114] 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: The Truth About the Real Threats to Our World*, 59.

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[115] Michael R. Lindeburg, *Mechanical Engineering Reference Manual for the PE Exam*, 11th ed. (Belmont, CA: Professional Publications, Inc., 2001), 29-11.

[116] Energy efficiency measures how much of the energy input can be converted to output. Rabaey et al., "A Microbial Fuel Cell Capable of Converting Glucose to Electricity at High Rate and Efficiency," 1533.

[117] This is a Coulombic efficiency measurement. It indicates how many of the electrons produced in the anodic chamber can be captured by the electrodes. Korneel Rabaey et al., "Tubular Microbial Fuel Cells for Efficient Electricity Generation," *Environmental Science & Technology* 39, no. 20 (2005): 8077.

[118] "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.

[119] Roberts, *The End of Oil*, 338.

[120] See estimates calculated in Appendix E.

[121] See potential synergistic technologies in Appendix C.

[122] See estimates calculated in Appendix E.

[123] Tom Simonite, "Dew-Harvesting 'Web' Conjures Water out of Thin Air," (15 November 2007), http://technology.newscientist.com/channel/tech/dn12923-dewharvesting-web-conjures-water-out-of-thin-air.html.

[124] United States Green Building Council, "Building Momentum: National Trends and Prospects for High-Performance Green Buildings," 2.

[125] Harold K. James, "Sierra Bravo: New Base Design Concept for the Air Force," (Lecture. AF/A8X, Washington, DC: 26 July 2007).

[126] Even experienced forecasters find social trends the most aspect difficult aspect of future technologies to predict. Schnaars, *Megamistakes: Forecasting and the Myth of Rapid Technological Change*, 100.

[127] Scott C. Buchanan, "Energy and Force Transformation," *JFQ: Joint Force Quarterly*, no. 42 (2006): 54.

[128] Johnson and Diltz. (personal communication)

[129] Roberts, *The End of Oil*, 340.

[130] Ibid., 339.

[131] Buchanan, "Energy and Force Transformation," 53-54.

Appendix A: Applications and Collaboration Partners

MFCs have many potential applications within the Department of Defense and beyond. Figure A.1 lists some applications and the agencies that are potential collaboration partners.

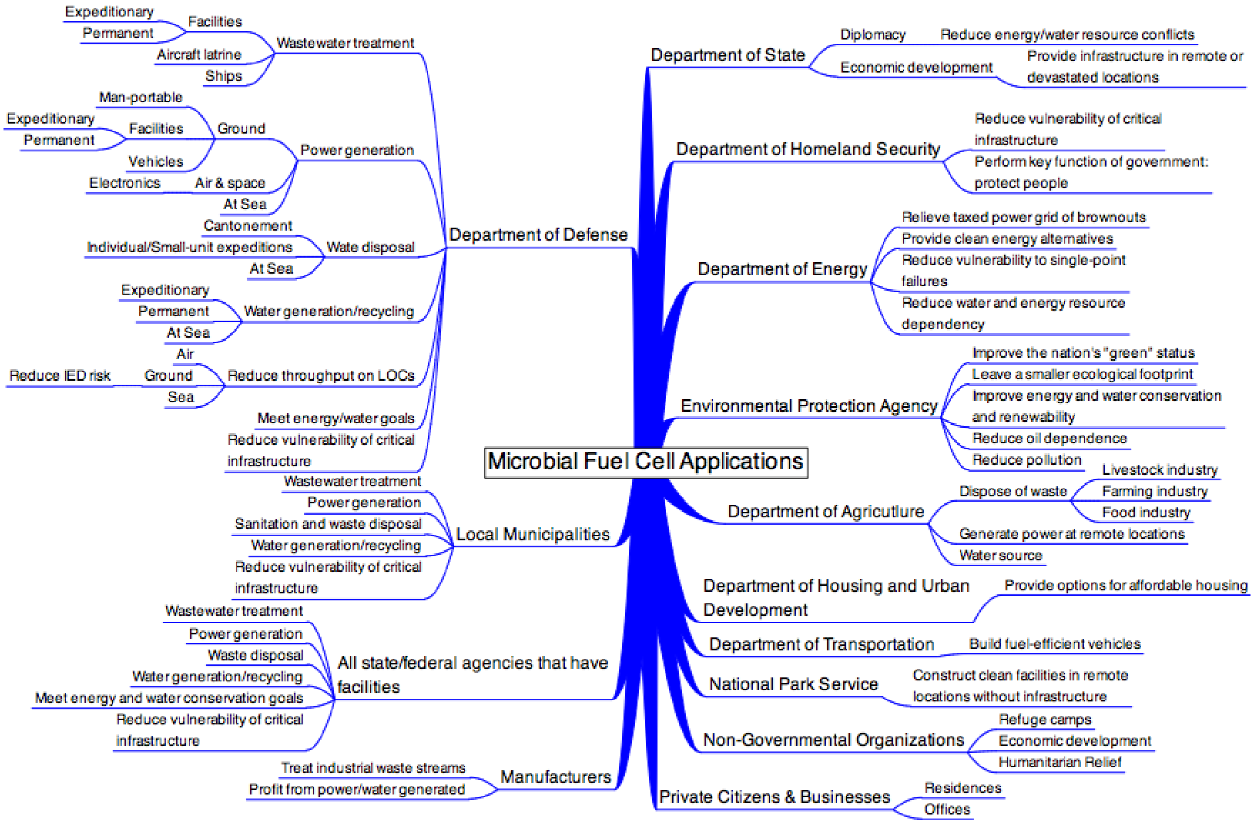

Figure A.1: Application Relevance Tree

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

Organization	Contact	Research Interest
AF APTO	Mike Mead 478-222-1827 (DSN 472) Mike.Mead@robins.af.mil	Identify, assess, transition, and integrate advanced power and alternative-energy & fuel technologies into the USAF's inventory of ground vehicles, support equipment, Basic Expeditionary Airfield Resources (BEAR), and fuel-cell equipment/applications
AFCESA/CC	Colonel Richard Fryer 850-283-6101 (DSN 523) Richard.Fryer@tyndall.af.mil	Commander, Air Force Civil Engineer Support Agency
AFCESA/CEN	Major 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
AFOSR	Major Jennifer Gresham 703-696-7787 (DSN 426) jennifer.gresham@afosr.af.mil	Enzyme/Protein/MFCs for air and space vehicle applications
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 & enzyme) fuel cells
DARPA	Ms. Sharon Beermann-Curtin 571-218-4935 sharon.beermann-curtin@darpa.mil	Mobile Integrated Sustainable Energy Recovery, Integrated High Energy Dense Capacitors, Micro Power Sources, Nano-Composite Optical Ceramic, Robust Portable Power

Organization	Contact	Research Interest
US Army CoE CERDEC	Pavel Fomin 703-704-1027 (DSN 654) armypower@conus.army.mil	Soldier and man-portable fuel cells
US Army CoE CERL/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 Navy NRL	Brad Ringeisen Justin Biffinger 202-767-0719 bradley.ringeisen@nrl.navy.mil justin.biffinger@nrl.navy.mil	Biofilms, nanoporous-membranes, microbe adaptation
Arizona State University	Dr. Bruce Rittmann 480-727-0434 Rittmann@asu.edu	Microbiology, biofilms renewable resources
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	Applied Research Center Jerry Miller (Col, Ret) 305-348-6623 jerry.miller@arc.fiu.edu	Self-contained facilities, Western Hemisphere Information Exchange (WHIX) Program—includes FIU, 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

Organization	Contact	Research Interest
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 in St. Louis	Dr. Lars Angenent 314-935-5663 angenent@seas.wustl.edu	MFCs to dispose of waste in the food and agriculture industries

Table A.1: Potential Collaboration Partners

Appendix B: Microbial Fuel Cell Relevance Tree

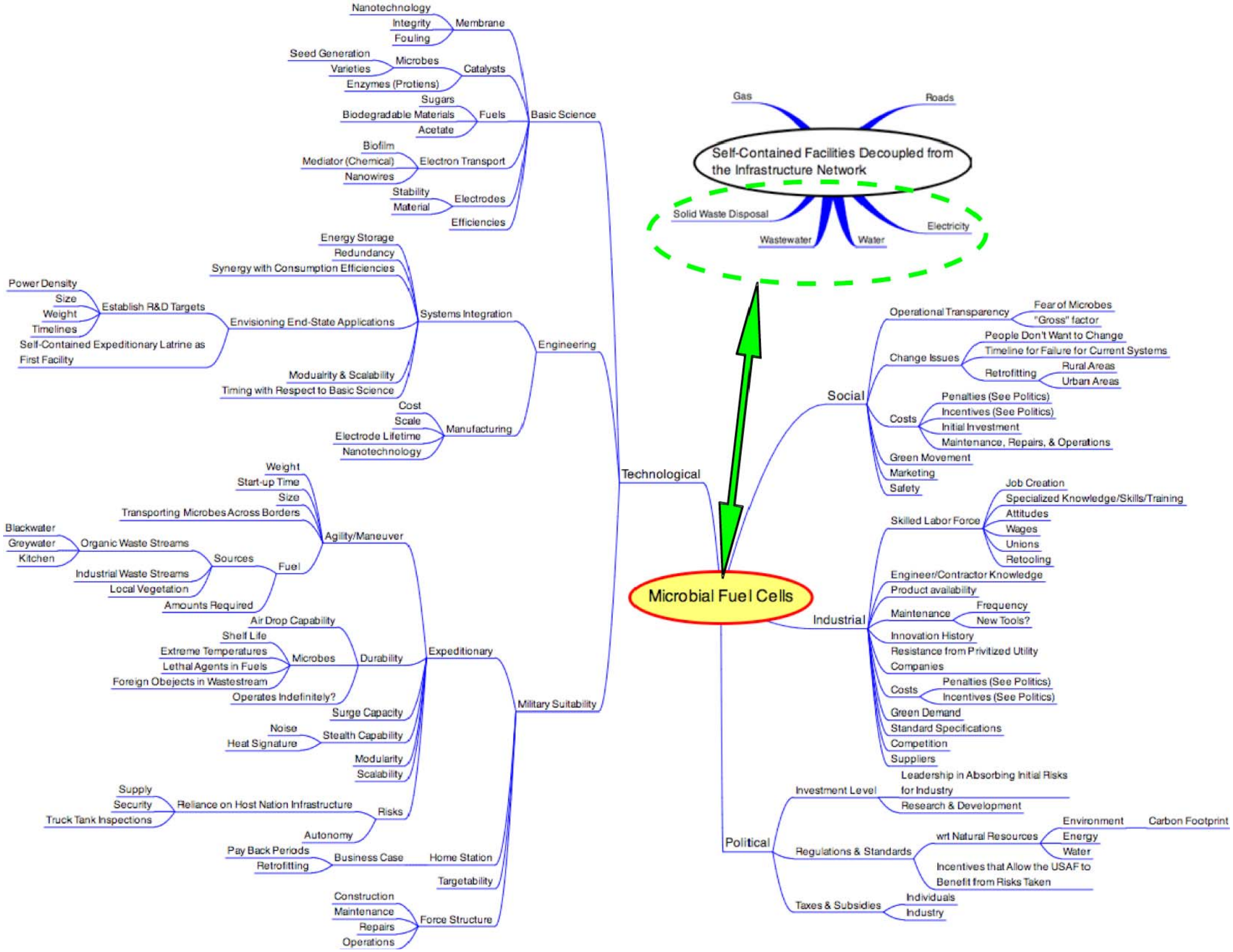

Figure B.1: Microbial Fuel Cell Relevance Tree

Appendix C: Competing and Complementary Microbial Fuel Cell Technologies

Biofuels and Biomass

MFCs are not fed by biofuels or biomass. MFCs 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. Although tailored MFCs could digest harvested biomass, they are meant to dispose of organic waste, rather than to 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 are 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 outputs. 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 theoretically sustain themselves forever as they regenerate. Different organisms also combine to allow fuel flexibility that is valued for ground applications. Unlike microbes, enzymes theoretically allow more complete electron harvesting since living microbes consume some of the chemical energy to survive and reproduce. Enzyme fuel cells, therefore, have potential to 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 uses in expeditionary settings. MFCs can operate in salt water to produce energy (often called sediment batteries),[3] but they will not convert saltwater to potable water because the microbes metabolize carbon-based compounds, not salt.

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[1] These ideas concerning differences and potential applications of the different types of biological fuels cells came from Major Jennifer Gresham, Air Force Office of Scientific Research (AFOSR). Phone interview with the author, 16 November 2007.

[2] Miriam Keith, "BEAR Base Solar Power System," (United States Air Force, Air Force Research Laboratory, Airbase Technologies Division, 2005).

[3] C. E. Reimers et al., "Microbial Fuel Cell Energy from an Ocean Cold Seep," *Geobiology* 4 (2006).

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, cleanly and efficiently - 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+ W of power per person—25% of an expeditionary base power requirement - For a 150,000-person deployment -- Saves 2M gallons/day of water -- Saves 180,000 gallons/day of fuel -- Saves $50M/day in fuel operating costs (fuel price plus transport cost) - Prevents natural resource conflicts - Generates power with no heat/noise	Sufficient waste volumes Microbe vulnerability Social acceptance Reluctance to invest in facility technologies Resistance from utility & construction industry Timeline to convert homeland infrastructure Must be coupled with demand-reducing technologies (energy & H2O)

Table D.1: Key Microbial Fuel Cell Capabilities and Limitations

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 MFC systems.

Electrical Power

Potential Power Source	MMBTU/day[1]	~ kW
Black/Graywater	2+	30
Food Waste	4+	50
Paper/Cardboard	40	480
Wood	10	120
Total	56	680

Table E.1: Organic Power Sources at 1,100-Person Expeditionary Base

Mobile Expeditionary Power (MEP)-12A Generator[2]
Rated capacity: 750 kW
Actual output capacity: 625 kW
Fuel consumption rate: 1,320 gallons per day (568 W/gal/day)
Cost: $165,000
Weight: 25,000 pounds

Expeditionary Base Power Planning Factor: 2.7 kW per person[3] (Four MEP-12s/1,100 people)

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

Fuel Costs (per gallon):
Standard cost: $3.04[4]
Delivered cost via USAF tanker: $52.50[5]
Delivered cost (conservative) to remote operating location: $300[6]

Amount saved daily by substituting an MFC for one MEP-12A
Standard cost: $3.04/gal x 1,320 gal/day = $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: $400K/day x 150,000 / 1,100 = $50M/day

Amount saved daily by substituting gray/blackwater 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

Water use planning factor (expeditionary): 20 gal/person/day[7]
Water use planning factor (permanent): 50 gal/person/day[8]
Wastewater planning factor: 14 gal/person/day[9]

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

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

Logan: “This system would produce 51 kilowatts on the waste from 100,000 people.”[10] Logan’s estimate only includes graywater and blackwater. Predicts 0.5 W/person.

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[1] Waste characterizations for “1100-Staff, 50-Hospital Bed Bare Bases” were provided in a table labeled “Battelle Report” and “ACC/WMO Report” by Johnson and Diltz. (personal conversation)

[2] Air Force Handbook 10-222 Volume 10, *Guide to Harvest Falcon Electrical System Installation* (1 MAY 2000), 8. & 49th Material Maintenance Squadron, *The Definitive Guide to Bare Base Assets* (Holloman AFB, NM: February 2000), 34.

[3] Air Force Handbook 10-222 Volume 2, *Guide to Bare Base Assets* (1 April 2006), 75.

[4] Greg Grant, "Surging Oil Prices Send Military Costs Skyrocketing," (3 January 2008), http://www.govexec.com/dailyfed/0108/010308g1.htm.

[5] 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. The Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting through Reduced Fuel Burden*, ES-3, 20. For additional validation of this estimate, see also Amidon, "Needed Now: A National Energy Security Manhattan Project," Slide 22.

[6] In 2001, the cost of delivered fuel was “hundreds of dollars per gallon for Army forces deep into the battlespace.” The Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting through Reduced Fuel Burden*, ES-3. Other sources suggest this number could be as high as $600 per gallon. See Paul Dimotakis, Nathan Lewis, and Robert Grober, *Reducing DoD Fossil-Fuel Dependence* (McLean, VA: JASON, The MITRE Corporation, September 2006), 20.

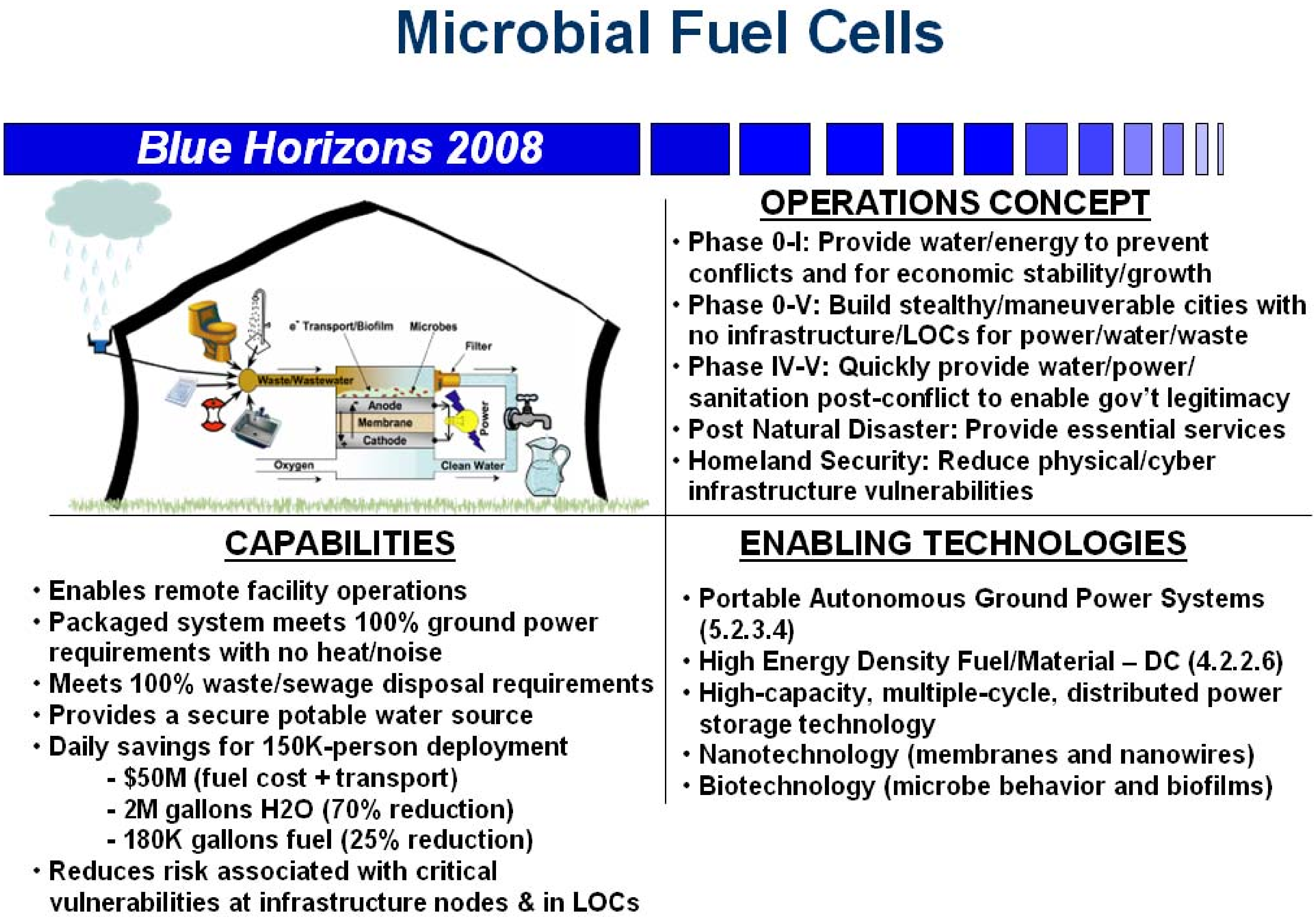
[7] Air Force Pamphlet 10-219 Volume 5, *Bare Base Conceptual Planning Guide* (1 June 1996), 87.

[8] Ibid., 86.

[9] Ibid., 115.

[10] Biever, "Plugging into the Power of Sewage." (electronic article)

Appendix F: Quad Chart



Microbial Fuel Cells

Blue Horizons 2008

OPERATIONS CONCEPT

- Phase 0-I: Provide water/energy to prevent conflicts and for economic stability/growth
- Phase 0-V: Build stealthy/maneuverable cities with no infrastructure/LOCs for power/water/waste
- Phase IV-V: Quickly provide water/power/ sanitation post-conflict to enable gov't legitimacy
- Post Natural Disaster: Provide essential services
- Homeland Security: Reduce physical/cyber infrastructure vulnerabilities

CAPABILITIES

- Enables remote facility operations
- Packaged system meets 100% ground power requirements with no heat/noise
- Meets 100% waste/sewage disposal requirements
- Provides a secure potable water source
- Daily savings for 150K-person deployment
    - \$50M (fuel cost + transport)
    - 2M gallons H2O (70% reduction)
    - 180K gallons fuel (25% reduction)
- Reduces risk associated with critical vulnerabilities at infrastructure nodes & in LOCs

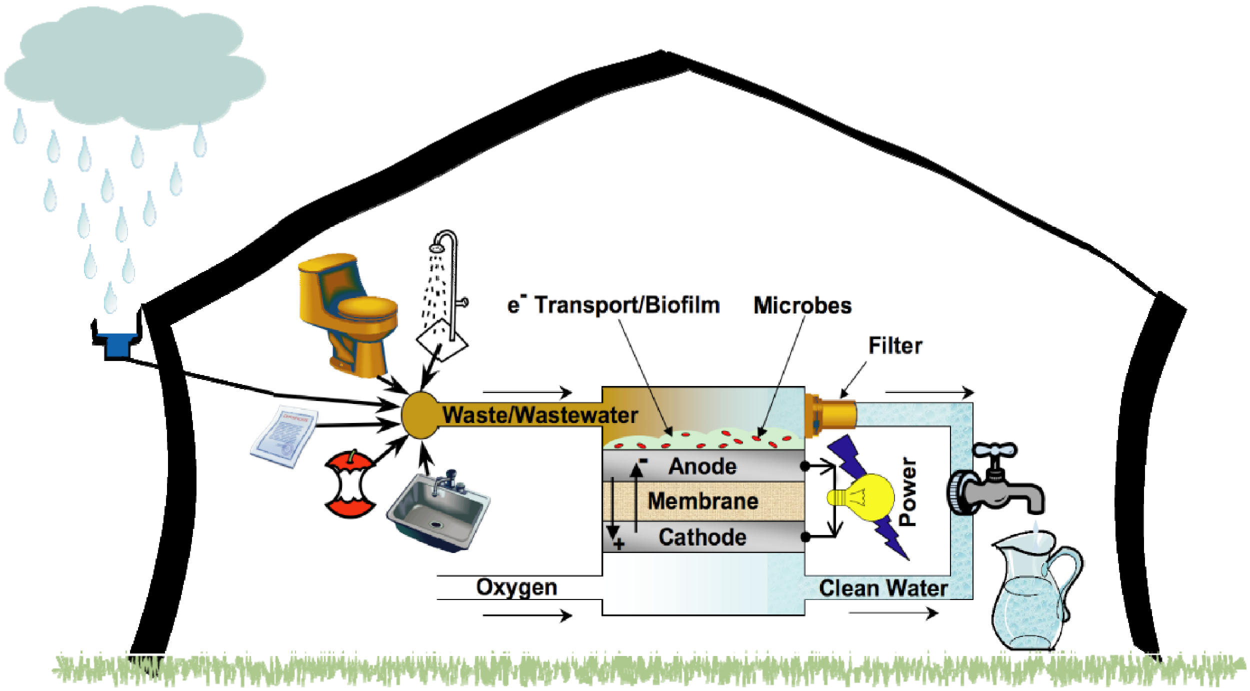
ENABLING TECHNOLOGIES

- Portable Autonomous Ground Power Systems (5.2.3.4)
- High Energy Density Fuel/Material – DC (4.2.2.6)
- High-capacity, multiple-cycle, distributed power storage technology
- Nanotechnology (membranes and nanowires)
- Biotechnology (microbe behavior and biofilms)

Figure F.1: Quad Chart

Appendix G: Tech Sheet

Microbial Fuel Cells



System Description: Microbial Fuel Cells (MFCs) convert wastewater and organic material to clean water and electricity.

MFCs are fed by sewage, graywater (shower and laundry water), stormwater, industrial waste, kitchen scraps, paper, wood, or any other kind of organic matter. Through anaerobic metabolism at the anode, microbes restore wastewater to a recyclable quality and produce electrons that are 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 CONOPS: MFCs must be coupled with other technologies to meet 100% of the power, water, wastewater, and solid waste disposal requirements autonomously and covertly—without sustainment support from LOCs or an infrastructure network.

- Phase 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)

- Phase 0-1 (Shape, Deter)
  - -- Prevent conflicts sparked by water and energy resource demand
  - -- NSS: “Expand the circle of development by opening societies and building the infrastructure of democracy”
  - -- NSS: “Ignite a new era of global economic growth through free markets and free trade” includig “secure, clean energy development”
- Phase 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 cleanly and efficiently
- 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+ W of power per person—25% of an expeditionary base power requirement
- For a 150,000-person deployment
  - -- Saves 2M gallons/day of water
  - -- Saves 180,000 gallons/day of fuel
  - -- Saves $50M/day in fuel operating costs (fuel price plus transport cost)

Key Enabling Technologies:

Enabling Technology	**TRL**	**Maturity**
Portable Autonomous Ground Power Systems (5.2.3.4)	3	2015
High Energy Density Fuel/Material – DC (4.2.2.6)	5	2012
High-capacity, multiple-cycle, distributed power storage technology	3	2015
Nanotechnology (membranes and nanowires)	2	2018
Biotechnology (microbe behavior and biofilms)	2	2018
Microbial fuel cells	**2**	**2020**

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