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MASTER OF MILITARY STUDIES

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SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF MILITARY STUDIES

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Executive Summary

Title: Methods of Reducing Fuel Demand at the Small Maneuver Element Level

Author: Major Luke McLearen, United States Marine Corps

Thesis: One of the critical capabilities the Marine Corps will need to execute EABO is a considerably more energy efficient maneuver element that uses less fuel. **To accomplish this essential task, the Marine Corps must invest in technologies that reduce fuel demand at the small unit level.**

Discussion: Loud and inefficient JLTVs that tether small maneuver elements to slow and cumbersome fuel resupply convoys that create substantial signatures are not preparing the Marine Corps to “meet the demands of a future operating environment characterized by complex terrain, technology proliferation, information warfare, the need to shield and exploit signatures, and an increasing non-permissive maritime domain (Marine Corps Operating Concept).” Vehicles that rely on JP-8 are not the solution for equipping the future force. This thesis examines current and emerging technologies that generate power, store the energy, and more efficiently use the energy. It makes recommendations on which technologies to pursue to reduce fuel consumption at the small unit level.

Conclusion: Electrified vehicles serve as a materiel solution to all three critical enablers of the EABO effectiveness triad (lethality, signature management, and sustainability) and are therefore essential to the Marine Corps’ future concept of employment.

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THE OPINIONS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE INDIVIDUAL STUDENT AUTHOR AND DO NOT NECESSARILY REPRESENT THE VIEWS OF EITHER THE MARINE CORPS COMMAND AND STAFF COLLEGE OR ANY OTHER GOVERNMENTAL AGENCY. REFERENCES TO THIS STUDY SHOULD INCLUDE THE FOREGOING STATEMENT.

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Preface

My research is inspired by a 2018 Marine Corps Signature Management Wargame that was hosted by the Marine Corps Warfighting Laboratory and co-sponsored by the Deputy Commandant for Information and the Information Warfare Integration Division, Combat Development and Integration. The wargame introduced me to the triad of components consisting of lethality, signature management, and sustainability and how those components are intrinsically linked to the success of Expeditionary Advanced Based Operations (EABO). The wargame further highlighted how resupply missions drastically increase the signature of the supporting and supported unit. I recognized that extending a unit's operational reach by reducing its reliance on fuel mitigated the issues concerning two of the three components – signature management and sustainability. My research attempts to uncover and subsequently recommend specific technologies to reduce the fuel demand of small maneuver elements conducting EABO against a peer adversary.

I would like to thank Dr. Michael Baskin for his guidance and direction for this thesis. His knowledge of the subject matter and connections to the Energy Community contributed significantly to the breadth and depth of this research.

I would also like to thank Ms. Kari Drotleff and Mr. Kevin Centeck from the U.S. Army Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center. They were very responsive and provided vitally important information for my research. Additionally, the work their office is doing is encouraging as it is a key component to a more survivable and sustainable force of the future.

Introduction

According to the Marine Corps Operating Concept (MOC) published in September 2016, the Marine Corps is “currently not organized, trained, and equipped to meet the demands of a future operating environment characterized by complex terrain, technology proliferation, information warfare, the need to shield and exploit signatures, and an increasing non-permissive maritime domain.”¹ In response, the Marine Corps began developing new technology, restructuring the force, and creating new ways to employ the future force. One of the primary documents that is guiding the development of the future force is the draft Expeditionary Advanced Base Operations (EABO).² The EABO concept capitalizes on the Marine Corps’ ability to operate effectively in the maritime environment and its ability to conduct distributed operations. One of the critical capabilities the Marine Corps will need to execute EABO is a considerably more energy efficient maneuver element that uses less fuel. **To accomplish this essential task, the Marine Corps must invest in technologies that reduce fuel demand at the small unit level.** This thesis will examine current Marine Corps energy reduction related initiatives as well as emerging technologies to recommend specific technologies to create a more energy efficient and therefore a more logistically sustainable maneuver element for the future fight.

Considerations such as saving money and reducing the negative impact to the environment are extremely important, but that is not the focus.³ The sole factor considered in this thesis is

¹ Headquarters US Marine Corps, *The Marine Corps Operating Concept: How an Expeditionary Force Operates in the 21st Century*, (Washington, DC: Headquarters US Marine Corps, September 2016), 6.

² The Marine Corps Warfighting Laboratory is developing the EABO concept as a supporting concept to the MOC. As of 26 February 2019, the EABO concept is not yet officially signed, but according to a USNI article titled “Marines to Focus Investments on New Concepts, New Systems for the Future Fight” published on September 27, 2018, it is guiding future force development, specifically materiel solutions for identified gaps.

³ This thesis does not specifically consider cost savings; however, reducing fuel consumption reduces operating costs, especially when considering the fully burdened fuel cost (FBFC). The FBFC is the actual price of fuel once ancillary costs such as transportation from the source are factored in. A Wall Street Journal article by Nathan Hodge published on December 6, 2011 titled “U.S.’s Afghan Headache: \$400-a-Gallon Gasoline: Military Air Drops Fuel

centered around improving the effectiveness of EABO in a fight against a peer adversary. Specifically, the lens through which the technologies will be evaluated is that of a major contingency operation against a peer threat in a maritime environment within the adversary's targeting range.

During the development of the EABO concept through wargames, the Marine Corps Warfighting Laboratory (MCWL) identified three distinct critical enablers that are required to ensure the effectiveness of the operations. The three enablers are lethality, signature management, and sustainment (see Figure 1).⁴

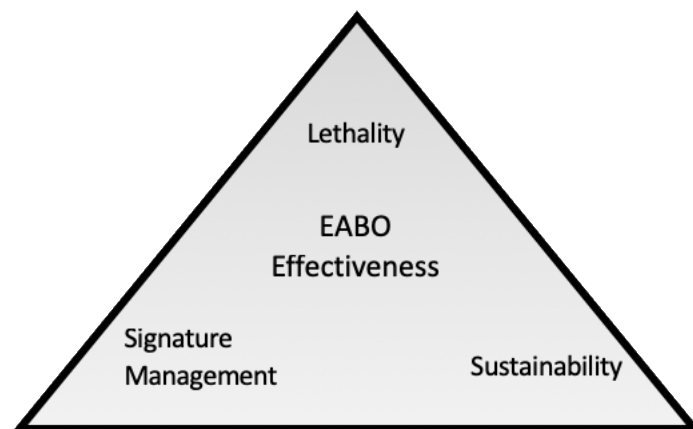


Fig 1: EABO Effectiveness Triad

As suggested by the diagram, the three enablers are dependent on each other. Successful EABO rely on significant future development of each enabler for the operations to succeed. The Marine Corps is pursuing technology that contributes to the development of the lethality component such as coastal defense cruise missiles, electronic attack platforms, and other lethal and non-lethal fires. The Marine Corps is also investing in capabilities to effectively conduct

Barrels to Avoid Dangerous Convoys” reported that the FBCF in Afghanistan reached costs of up to \$400 per gallon which is more than 100 times more expensive than the cost at the pump.

⁴ Personnel from MCWL developed the EABO Effectiveness Triad in figure 1. Although it is not officially codified, it is often referenced by those working in MCWL and Combat Development and Integration (CD&I).

signature management.⁵ Lastly, the Marine Corps is addressing sustainability by investing in methods to more effectively deliver supplies to small, distributed maneuver elements.⁶ Meeting the demand signal is only half of the sustainability issue; the other half is reducing the demand from the supported unit. The Marine Corps needs to also invest in technologies that reduce the energy demand of the supported units to make them more effective.

In June 2018, the Marine Corps conducted a signature management wargame that identified several vulnerabilities of units conducting EABO. One of the most significant vulnerabilities occurred when the maneuver elements were being resupplied. The maneuver element was able to remain relatively undetected during other operations, but quickly became detected during resupply. Due to the nature of the resupply operations, it was difficult to manage the physical, technical, and administrative signatures making both the combat and logistics units vulnerable to detection and targeting.⁷ Subsequent war games and live exercises will develop tactics, techniques, and procedures (TTP) to manage the signature of resupply operations, but one of the most logical methods is to decrease the frequency of the resupply missions. If a maneuver element is able to operate more efficiently with its available resources, it will be able to extend the amount of time between resupply missions and therefore increase its survivability as well as the survivability of logistics units. Reducing energy consumption, specifically petroleum, oil,

⁵ The author's previous billet was the Information Operations Brach Head at Combat Development Directorate (CDD), Combat Development and Integration (CD&I) and oversaw the Signature Management portfolio that was created in Fiscal Year 2018. Signature management refers to the holistic approach to managing a unit's physical, technical, and administrative signatures. The battle of signatures against a peer adversary is directly related to the survivability of the unit. In a fight against a peer adversary, the mismanagement of any or combination of the types of signature will lead to detection and subsequently targeting by the adversary. One of the main reasons the Marine Corps developed EABO is to reduce a unit's signature by operating in small, distributed, and austere formations that are in direct contrast to the large Forward Operating Bases (FOB) that the Marine Corps operated out of during Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF).

⁶ An Expeditionary Energy Office sponsored study, the MAGTF Bulk Fuel Study, dated July 5, 2018 highlights several Office of Naval Research (ONR) initiatives aimed at fuel distribution methods in a maritime environment.

⁷ The author led the development of the signature management wargame with the War Gaming Division of Marine Corps Warfighting Laboratory (MCWL). The final report from the war game is pending release by MCWL.

and lubricants (POL) (class III) increases a unit's operating time between resupply. Reducing demand for POLs does not completely negate the demand for food/water (class I) and ammunition (class V), but its reduction enables the unit to prioritize other classes of supply to extend its operational reach.⁸

This thesis directly ties to the 2018 Marine Corps Science and Technology Strategic Plan. It specifically addresses the logistics science and technology objective labeled "Enhanced Self-Sufficiency for Portable Electric Energy." According to the plan, the goal is to develop technologies that "reduce energy consumption and enhance power source compatibility supporting the expanded operational use of hand-held electronic devices."⁹ This thesis also supports one of the priorities titled "Operational Endurance" in the Naval Research & Development Framework. The Operational Endurance priority aims to "improve platform-level energy storage/efficiency for propulsion."¹⁰ Informing decision-makers on some of the emerging and applicable technologies will help prioritize investments to achieve the stated objective.

Current Demand Signal

The average Marine Corps infantry company of 2013 used more fuel than an entire infantry battalion circa 2001.¹¹ Based on future platforms and concepts of employments, the fuel demand will continue to increase through at least 2025 according to the MAGTF Bulk Fuel Study II published in 2018.¹² Approximately 70 percent of a Marine Expeditionary Brigade (MEB) fuel consumption is due to aviation while vehicles account for 21%. The remaining 9% of fuel is

⁸ According to Marine Corps Order 3900.19, fuel and water account for 70% of required logistics.

⁹ United States Marine Corps., "2018 U.S. Marine Corps S&T Strategic Plan.," 2018: 48.

¹⁰ Office of Naval Research Science and Technology, "Naval Research and Development: A Framework for Accelerating to the Navy & Marine Corps After Next," 2018: 7.

¹¹ Commandant of the Marine Corps, *Applying Energy Performance Metrics and Measures In Requirements Development and Acquisition Decision-Making*, MCO 3900.19, May 23, 2013, 1, https://www.hqmc.marines.mil/Portals/160/Docs/MCO%203900_19.pdf.

¹² Innovative Decisions Incorporated, "MAGTF Bulk Fuel Study II," Marine Corps Combat Development Command, July 5, 2018, 100.

consumed by generators.¹³ Despite using less than a quarter of the overall MEB's fuel, vehicles create a substantial demand signal.¹⁴ A single weapons company in an infantry battalion is estimated to use 4,524 gallons of fuel per day.¹⁵ The company's fuel demand is equivalent to the total capacity of a MK970 Mobile Refueler, the Marine Corps' largest mobile refueling platform.¹⁶ Furthermore, the research team that collected the above data based most of it on a static command post in the Marine Corps Air Ground Combat Center (MCAGCC) Twentynine Palms training area. Staying in one place produces an easy target for an adversary, therefore units must be more dynamic to reduce the likelihood of being targeted in the future operating environment, thus increasing fuel consumption.

Current Initiatives to Reduce Fuel Consumption

The Marine Corps has several initiatives designed to reduce fuel consumption. Perhaps one of the quickest and most cost-effective method is changing unit tactics, techniques, and procedures (TTPs). A research team from the Naval Surface Warfare Center Carderock Division and Oak Ridge National Laboratory studied the energy use of several Marine Corps units during training exercises. The team determined that the ground units could reduce their fuel consumption by 10% if they tweaked their TTPs. While most of the TTPs related to the use of generators and camp design, some of them were vehicle related. The main waste of fuel was

¹³ Eric B. Shields, Sean M. Sadler and Dr. Amy Wolfe, "Behavioral Energy Operations Demonstration Phase I," Naval Surface Warfare Center Carderock Division, August 2018, 12.

¹⁴ The author specifically chose to focus on vehicle vice aviation fuel consumption because the latter will be a joint logistics problem; whereas, the MEF and below will have to solve the tactical fuel distribution for the vehicles it operates. Furthermore, the author wanted to identify solutions to increasing the small vulnerable maneuver elements constantly operating well within the adversary's targeting range.

¹⁵ Innovative Decisions Incorporated, "MAGTF Bulk Fuel Study II," Marine Corps Combat Development Command. July 5, 2018, 89.

¹⁶ Innovative Decisions Incorporated, "MAGTF Bulk Fuel Study II," Marine Corps Combat Development Command. July 5, 2018, 35.

non-mission essential idling of vehicles.¹⁷ The Marine Corps can reduce fuel consumption by instituting changes in the way that it operates vehicles, but these efforts are not sufficient on their own to substantially lower a unit's consumption level and must be accompanied with specifically designed technologies that require less fuel.

SPACES/GREENS

In addition to TTPs, the Marine Corps is pursuing material solutions as well. One of them is a fielded Marine Corps program that uses solar power to provide electricity for fixed positions and small, mobile forces. It is a two-part system comprising of the Solar Portable Alternative Communications Energy System (SPACES) and the Ground Renewable Expeditionary Energy System (GREENS). SPACES consists of a portable lightweight battery charger and DC power distribution system with an output of 160W that primarily uses solar energy.¹⁸ GREENS consists of a modular, portable solar energy conversion and management system that distributes energy using an intelligent management system, and stores excess harvested energy to provide an average continuous output of 300W (see Figure 2).¹⁹



Fig 2: Infantry Battalion Uses GREENS to Power COC Communication Equipment (Source: <https://www.hqmc.marines.mil/e2o/Fleet/>)

¹⁷ Eric B. Shields, Sean M. Sadler and Dr. Amy Wolfe, "Behavioral Energy Operations Demonstration Phase I," Naval Surface Warfare Center Carderock Division, August 2018, 85-86.

¹⁸ Marine Corps Warfighting Laboratory, "Guide to Employing Renewable Energy and Energy Efficient Technologies, X-File 4-11.61xx," U.S. Marine Corps (September 10, 2012), 23.

¹⁹ Marine Corps Warfighting Laboratory, "Guide to Employing Renewable Energy and Energy Efficient Technologies, X-File 4-11.61xx," U.S. Marine Corps (September 10, 2012), 27.

This particular program is progress compared to relying on nothing but fuel-thirsty generators that are underutilized; however, GREENS and SPACES are of limited utility in the next fight. Solar power generation devices such as GREENS and SPACES require relatively unimpeded exposure to sunlight at an optimal angle to generate electricity. When a unit conducting EABO is not physically moving it will attempt to reduce its signatures (physical, technical, and administrative) using cover, concealment, and deception (CCD) TTPs such as terrain masking and multi-spectral camouflage netting. A unit maneuvering in the battlespace will most likely not have the luxury to lay out solar panels. The CCD TTPs will significantly degrade the amount of solar energy a unit will be able to harvest. The last thing a unit will do is raise its signature by laying out large, reflective solar panels. Furthermore, it is unreasonable to force a small unit leader to decide between power generation for the unit's electronic devices (i.e., use SPACES) and force protection (i.e., remain cover and concealed).

Despite its limited use in its current configuration, GREENS and SPACES technology can be leveraged to develop future technologies. For example, some of the engineering behind the power distribution and storage could be used in a system that harvests energy from sources other than solar. Additionally, the solar panels from GREENS and SPACES could be redesigned to integrate with a tactical vehicle's body panels such as the roof. Further research is needed, however, to determine if there is enough physical space on the roof of a tactical vehicle to generate electricity. The roof-mounted solar panels would also elevate the vehicle's visual signature, but it could be an option.

HEIT

The Marine Corps Warfighting Laboratory (MCWL) is currently sponsoring a project under development called the Hybrid Energy Internally Transportable Vehicle (ITV) Trailer (HEIT)

(see Figure 3). The HEIT is a Hybrid Electric power supply with a battery pack, providing a power source and the ability to scavenge power (ex. solar, fuel cell, shore power) integrated on a trailer light enough to be transported by an ITV.²⁰ During field testing, the HEIT was able to provide 3.5kW of continuous power without the generator running 60% of the time.²¹ Similar to GREENS and SPACES, the HEIT relies on solar power generation during its field testing. Despite its reliance of solar power, the HEIT is designed to work with other sources of power such as fuel cells. Additionally, the HEIT is an effective power management system that is able to intake energy from multiple different sources at the same time, store the energy, and automatically match the proper load to the demand, whereas a generator is constantly producing power even if there is no demand, wasting energy.



Fig 3: Field Testing the HEIT (source: MCWL)

Compared to GREENS and SPACES, the HEIT is considerably more practical in an EABO scenario because it does not solely rely on static solar power. Its original configuration was designed to supplement the ITV, but the technology should be integrated into the Joint Light Tactical Vehicle (JLTV) (i.e., utilize the JLTV's diesel engine to augment the alternator) to

²⁰ According to an email from Captain Kyle Brown from MCWL, S&T, to the author on April 22, 2019, MCWL is researching the possibility of incorporating fuel cell generators.

²¹ Brad Goldvarg, *Hybrid Energy Internally Transportable Vehicle (ITV) Trailer (HEIT) User Evaluation*, (Marine Corps Warfighting Laboratory Science and Technology, Quantico, VA, December 18, 2018), PowerPoint presentation.

create an onboard power management and distribution system to solve some of the issues of power generation at the small unit level. The on board JLTV power management system could allow the unit to power and recharge essential equipment (e.g., radios, fire control systems, etc.) without running the engine of the JLTV all of the time.

MTVR Fuel Efficiency Improvement

Military vehicles such as the JLTV are highly inefficient in terms of energy conservation. Commercial vehicles which are similar to tactical vehicles waste between 80-90 percent of energy to actions other than propelling the vehicle. Most of the energy is lost through friction and heat losses.²² The Marine Corps is attempting to gain more efficiency out of the vehicles it currently operates. One particular example is the Medium Tactical Vehicle Replacement (MTVR). In 2018, engineers from Marine Corps Systems Command (MCSC) worked with partners in industry, academia, and other government experts to develop ways to make the MTVR more fuel efficient given its usage profile. The team considered everything from software-based recalibrations to hardware modifications. In the end, the team settled on calibrations to the engine and transmission as well as reducing the engine's idle speed. These changes resulted in a 11-14 percent increase in fuel efficiency without any operational performance degradation.²³ Any measurable improvement in efficiency is worth the effort, but this does not directly contribute to the problem the small combat unit has because they do not always operate MTVRs. If the effort is extrapolated to other platforms such as the JLTV; however, it will help. Because the JLTV is a much newer vehicle than the MTVR and may already have some fuel efficiencies incorporated, it most likely will not have the same 11-14

²² Ruichen Wang, et al, "Modelling, Testing and Analysis of a Regenerative Hydraulic Shock Absorber System." *Energies* 9, no. 5 (2016): 386.

²³ Trung Huynh, et al., "The Fuel Efficient MTVR: Paving the Way to a More Fuel Efficient Fleet of Vehicles Through Technology." *Marine Corps Gazette*. 102, no. 8, (August 2018): 21-22.

percent increase in fuel efficiency. Despite that fact, every effort should be made to extract the most performance and efficiency out of every vehicle.

Biofuels

While not specifically a Marine Corps initiative, the Department of Defense explored using biofuels as a substitute for pure petroleum-based fuels. Biofuel is an alternate fuel made from biomass.²⁴ The most common biofuel used by the military is biodiesel which is also called fatty acid methyl ester (FAME).²⁵ Biodiesel is produced from numerous sources such as animal fats, waste oil, edible vegetable oil, and non-edible vegetable oil. It can also be blended with normal petroleum-based diesel and used in diesel engines without modification; however, biodiesel has significant limitations to include the temperature at which it can reliably operate. Biodiesel begins to gel in colder weather and can cause issues with the fuel filter. It can also act as a solvent in some fuel storage tanks leading to clogged fuel tanks and filters.²⁶

Another notable biofuel is one that uses algae instead of oil as the source material. Compared to most biofuels, algae biofuel has a significantly higher yield. An additional advantage of using algae as the source material is that the byproducts can either be used as fertilizer or be used to make ethanol.²⁷ Additionally, unlike the production of ethanol, algae do not need vast amounts of agricultural land that could otherwise be used for food. Algae requires

²⁴ Biomass is organic matter used as a fuel.

²⁵ Alex Macdiarmid, "Biofuels in The DoD: Impact on System Reliability, Availability, and Maintainability," *Defense Systems Information Analysis Center Journal*, 2, no. 1 (Winter 2015): 6, <https://www.dsiac.org/resources/journals/dsiac/winter-2015-volume-2-number-1>.

²⁶ Alex Macdiarmid, "Biofuels in The DoD: Impact on System Reliability, Availability, and Maintainability," *Defense Systems Information Analysis Center Journal*, 2, no. 1 (Winter 2015): 7-8, <https://www.dsiac.org/resources/journals/dsiac/winter-2015-volume-2-number-1>.

²⁷ Fertilizer is not an immediate benefit to the military, but it could aid during stability operations. Ethanol could be used as an additional fuel, potentially for fuel cells.

limited sunlight, water, or carbon dioxide.²⁸ While biofuels will reduce the military's sole reliance on petroleum-based fuels, it does little to help extend the operational reach of the maneuver element. The only measurable advantage is that units could potentially collect locally-sourced used vegetable oil or other available biofuels to augment their petroleum-based fuels for the vehicles. Outside of that remote possibility, biofuels offer little to combat units conducting EABO and should not be considered.

Research Methodology

While squeezing more efficiency out of existing vehicles is helpful, it is shortsighted if it is not accompanied with efforts to look at completely new technologies that are more efficient and easier to sustain. The next section of the thesis will discuss current and emerging technologies that have the potential to reduce the energy demand of small maneuver elements. To scope the research, the author focused on small tactical units (i.e., infantry company size and below) conducting EABO against a peer adversary operating in austere conditions in a maritime environment. These conditions lead to five criteria that the author used to evaluate potential technologies against. The first criteria is that the technology must provide a noticeable reduction in fuel consumption. Trading one energy source for another that does not increase a unit's operational reach by decreasing dependency on fuel resupply does not provide a distinct advantage. This is the main reason that this thesis does not specifically mention plug-in hybrid electric vehicles because it necessitates that a unit tether itself to a robust electricity-producing infrastructure. The second criteria is that the technology must not elevate a unit's overall signature in the battlespace. Technologies that reduce a unit's fuel consumption, but raise its

²⁸ Alex Macdiarmid, "Biofuels in The DoD: Impact on System Reliability, Availability, and Maintainability," *Defense Systems Information Analysis Center Journal*, 2, no. 1 (Winter 2015): 9, <https://www.dsiac.org/resources/journals/dsiac/winter-2015-volume-2-number-1>.

signature are counterproductive to the goal of this research. For example, technologies that necessitate increasing the physical footprint of a unit such as those that rely on solar and wind are therefore not included. Next, the technologies must be highly mobile which is another reason static wind and solar based technologies are not considered. Additionally, the technologies must seamlessly integrate into existing platforms or otherwise not overly complicate and/or distract a unit from its mission. The author did not select technologies that require additional manpower and other resources to maintain. Finally, the author considered relatively mature (i.e., not hypothetical) technologies. The identified technologies are at various technology readiness levels (TRL), but have all been tested in a laboratory. While most have not been incorporated into a military application, only those with potential applicability are included.

Using the above scenario and the identified criteria to scope the research, the author began the research by first identifying what the various Department of Defense (DoD) science and technology (S&T) organizations such as MCWL, Office of Naval Research (ONR), the U.S. Army Combat Capabilities Development Command (CCDC), and Air Force Research Laboratory (AFRL) are developing. The author then examined U.S. government projects and initiatives with potential applicability, specifically those of the Department of Energy (DOE) and national laboratories. Next, the author leveraged the research of leading civilian organizations in the energy and resource efficiency field such as Rocky Mountain Institute to further guide research efforts. Additionally, the author assessed applicable research of leading universities. The author primarily focused on University-Affiliated Research Center laboratories (UARC) due to their pre-existing relationships with the DoD, but did not preclude relevant research from non-UARCs if it was in accordance with the identified criteria. Research included using passive measures such as reading published studies in databases and scholarly journals as well as active

measures such as email and phone correspondence with key members of the identified organizations.

Existing and Emerging Technologies

The next section of the thesis will discuss current and emerging technologies that have the potential to reduce the energy demand of small maneuver elements operating in austere conditions in a maritime environment. To effectively reduce fuel consumption, a unit must be able to generate power while also efficiently using the energy and storing it as appropriate. The first section will quickly summarize energy efficiency and energy storage technologies. The section following it will examine power generation technologies.

There are several ways to more efficiently use energy as previously noted in the Naval Surface Warfare Center Carderock Division study. Another notable way is to reduce the energy demand of the devices a unit uses. Researchers at University of California San Diego (UCSD) developed ultra-low power sensors in 2017 that sacrifice a little accuracy to achieve a 628-time reduction in power compared to the next most efficient power sensor.²⁹ When designing future electrical systems in a vehicle, the Marine Corps should attempt to reduce the power demand even if it means sacrificing an unnoticeable amount of accuracy.

Efficient energy storage for later use is also critical to reducing overall demand and there are several technologies that the Marine Corps should leverage. A research team led by a MIT professor developed a Li-ion battery with a solid-state electrolyte in 2015 that provides a 20-30 percent improvement in power density of a comparably sized liquid electrolyte battery.³⁰

²⁹Hui Wang and Patrick P. Mercier, "Near-Zero-Power Temperature Sensing via Tunneling Currents Through Complementary Metal-Oxide-Semiconductor Transistors," *Scientific Reports*, 7, (2017): <https://www.nature.com/articles/s41598-017-04705-6#author-information>.

³⁰ David L. Chandler, "Going Solid-State Could Make Batteries Safer and Longer-Lasting: New Research Paves the Way for Rechargeable Batteries With Almost Indefinite Lifetimes, Researchers Say," *MIT News*, August 2015, <http://news.mit.edu/2015/solid-state-rechargeable-batteries-safer-longer-lasting-0817>.

Another development is the use of graphene in batteries. Graphene is a thin layer of tightly bonded carbon atoms that is only thickness of one atom that has the potential to save weight and increase the energy density of batteries.³¹ A group of researchers from Zhejiang University in China successfully used graphene to improved its lifecycle, charge rate, and operating temperature range in 2017.³² Researchers from Georgia Tech University are using thin sheets of graphene in supercapacitors to make their energy density four times that of supercapacitors that use carbon particles.³³ The properties of graphene are especially relevant in a vehicle application because it could decrease the overall weight of the vehicle, increasing its fuel efficiency.

One research team from Penn State University developed a two-dimensional lightweight composite polymer in 2017 that can be mass produced and used to store energy.³⁴ This type of material could be used for components such as fenders, bumpers, and hoods while also replacing the traditional battery, saving weight.³⁵

While efficiently using and storing energy are critical components to reduce fuel consumption, the focus of this research is to examine methods of generating power that augment and/or replace traditional jet propellant-8 (JP-8) fuel. The Marine Corps is already pursuing alternative methods of generating power as evidence in the GREENS/SPACES technology discussed earlier, but there is significant potential for advancement in this area. The majority of

³¹ Alex Bernardo, "Graphene: A Miracle Material With Promising Military Applications," *Defense Systems Information Analysis Center Journal*, 5, no. 2 (Spring 2018): 39, 41, <https://www.dsiac.org/resources/journals/dsiac/spring-2018-volume-5-number-2/graphene-miracle-material-promising-military>.

³² Hao Chen, et al., "Ultrafast All-Climate Aluminum-Graphene Battery With Quarter-Million Cycle Life," *Science Advances*, 3, no. 12, (December 2017), doi: 10.1126/sciadv.aao7233.

³³ T.J. Becker, "Power Up: Energy Storage Innovations Will Make Renewables Less Expensive, More Reliable," *Georgia Tech Research Horizons*, Issue 1, 2015, <http://www.rh.gatech.edu/features/power>.

³⁴ Amin Azizi, et al., "High-Performance Polymers Sandwiched with Chemical Vapor Deposited Hexagonal Boron Nitrides as Scalable High-Temperature Dielectric Materials," *Advanced Materials*, 29, no. 35. (July 2017), doi:10.1002/adma.201701864.

³⁵ For example, the material could be molded into fenders, hoods, brackets and other elements to serve a dual purpose as energy storage.

the following technologies are only practical if combined with a platform that has a robust power supply and distribution system (i.e., they are not compatible with the JLTV in its current configuration). The next section examines five groups of technologies that were selected based on the five criteria discussed in the research methodology. The technologies are regenerative braking systems, regenerative hydraulic shock absorber systems, thermal energy to electricity technologies, electricity producing fibers, and hydrogen fuel cells. The five technologies are summarized in a table at the end and will be evaluated against the criteria outlined above.

Regenerative Braking System

One of the most common power generation techniques utilized by hybrid car manufacturers is regenerative braking. In 2018, students at Naval Postgraduate School (NPS) researched the feasibility of incorporating regenerative braking systems into military vehicles through the lens of a cost-benefit analysis. While found not cost effective using FBCF calculations, regenerative braking systems did produce a noticeable gain in efficiency when combined with battery storage devices on several Marine Corps vehicle platforms.³⁶ These calculations, however, did not consider the additional benefits of increased survivability and operational reach that increased fuel economy provide to a small maneuver element. In a future operating environment against a peer adversary, signature management should be included as one of the criteria of a cost-benefit analysis of new equipment, especially vehicles.

Regenerative Hydraulic Shock Absorber System

Another method of vehicle power regeneration is through the use of a hydraulic shock absorber system. Traditional shock absorbers transfer kinetic energy into thermal energy that is

³⁶ Tyrone Barrion and Dianna Zempel, “Integration of Regenerative Braking Systems Into DOD Tactical Vehicles, and Their Potential to Provide a Short-Term Power Source,” master’s thesis, Naval Postgraduate School, 2018), 85, Calhoun Institutional Archive of the Naval Postgraduate School, <http://hdl.handle.net/10945/61309>.

absorbed into the atmosphere thus wasting the potential energy. Fuel efficiency increased by one to four percent in most applications using the regenerative hydraulic shock absorber system. In some tests, electric and hybrid vehicle efficiency increased by eight percent.³⁷ The regenerative shock absorbers can also transform the mechanical energy into electrical energy to power on-board devices.³⁸ In his research at University of Huddersfield in 2016, Dr. Ruichen Wang determined that heavier vehicles produced substantially more regenerative power from shock absorbers and could produce an average of approximately 260 watts of power.³⁹ This figure is low; however, when compared to the system Audi developed in 2016 that is capable of producing 613 watts of power on bumpy roads that would typify the surfaces that the Marine Corps would operate on during expeditionary operations.⁴⁰ The electrical power could be integrated into an on-board power management system to store and export power when needed. A JLTV with a hybrid electric drivetrain could use the regenerated power to increase its range and operating time in between fuel resupply missions while allowing it to power onboard devices in a relatively silent operating mode.

Thermal Energy to Electricity

The previous technologies are designed to capture lost mechanical energy. The next technology is designed to capture wasted energy in the form of heat. There are efforts to convert that wasted thermal energy into a useable form such as electricity. Thermoelectric devices have the ability to convert distinct temperature gradients into electricity. The application for this

³⁷ Zhongjie Li, Zachary Brindak and Lei Zuo, "Modeling of an Electromagnetic Vibration Energy Harvester With Motion Magnification," *ASME International Mechanical Engineering Congress and Exposition 7*: (November 7-11, 2011): 291. doi:10.1115/IMECE2011-65613.

³⁸ Xuechun Zheng and Fan Yu, "Study on the Potential Benefits of an Energy-Regenerative Active Suspension for Vehicles." *SAE Transactions* 114 (2005): 244. <http://www.jstor.org/stable/44658108>.

³⁹ Ruichen Wang, et al, "Modelling, Testing and Analysis of a Regenerative Hydraulic Shock Absorber System." *Energies* 9, no. 5 (2016): 386.

⁴⁰ Stephen Edelstein, "Audi regenerative shock absorbers recaptures energy," *Green Car Reports*, August 15, 2016, https://www.greencarreports.com/news/1105548_audi-regenerative-shock-absorber-recaptures-energy.

technology is widespread and can take advantage of the thermal gradients of engines like those on JLTVs. Unfortunately, the thermoelectric devices are not normally very efficient; however, in 2018, Massachusetts Institute of Technology (MIT) researchers identified specific topological materials that triple the efficiency of ordinary thermoelectric devices that use materials such as silicone.⁴¹ Other advances in thermoelectric devices include innovative materials such as thermoelectrical paints. Engineers from the Republic of Korea designed thermoelectrical paints for curved surfaces that are applied using techniques similar to additive manufacturing.⁴² These thermoelectrical paints have the potential to convert thermal energy on numerous surfaces of the JLTV such as the roof, engine bay and the exhaust system to capture some of the 80-90% of lost energy in the vehicle.

In 2018, another group of researchers at MIT developed materials to create electricity from thermal energy without the need for a simultaneous temperature gradient. Instead, the material takes advantages of the temperature change throughout the day and night to create its own temperature gradient on a surface. The key advantage of this technology is that it is passive and it creates energy from the ambient temperature meaning it does not depend on the sun like solar energy.⁴³ This means the technology can be used in the shade of solar panels or camouflage netting and still create electricity as part of an integrated system when combined with other power regeneration technologies such as those that convert wasted mechanical energy. A unit

⁴¹ Jennifer, Chu, "Turning Heat into Electricity: Study Finds Topological Materials Could Boost the Efficiency of Thermoelectric Devices," *MIT News*, January 2018, <http://news.mit.edu/2018/topological-materials-turning-heat-electricity-0117>.

⁴² Park, S. H. *et al.* High-performance shape-engineerable thermoelectric painting. *Nature Communications*. 7, 13403 (2016): doi: 10.1038/ncomms13403.

⁴³ David L Chandler, "System Draws Power From Daily Temperature Swings: Technology Developed at MIT Can Harness Temperature Fluctuations of Many Kinds to Produce Electricity," *MIT News*, February 2018. <http://news.mit.edu/2018/system-draws-power-daily-temperature-swings-0215>.

conducting EABO can employ CCD tactics (e.g., camouflage netting) and still produce electricity with this technology.

Electricity Producing Fibers

Vehicles are not the only systems in the battlespace that need energy or can assist in the generation of energy. Over the last decade, researchers have developed several techniques to harness electricity from a human being's normal motion throughout the day. One of the more intriguing and efficient technologies is a yarn-like substance that produces electricity when stretched. Researchers from the University of Texas (UT), Virginia Tech (VT), and Hanyang University in South Korea partially funded by the Air Force Office of Scientific Research, NASA, and the Office of Naval Research developed a carbon nanotube 10,000 times smaller than a strand of hair that when twisted, coiled, dipped into an electrolyte, and then stretched produces an electric current. These particular fibers produced over 100 times higher electrical power per weight than other reported fibers. In their research published in 2017, the researchers showed that even the miniscule amount of stretching caused by normal breathing created an electric current.⁴⁴ This technology has the potential to help power the myriad electronic devices a Marine carries if sewn into the uniform. If a Marine is sweating, the fibers would be exposed to an electrolyte or they could be splashed in salt water to have the same effect.

The electric current producing carbon nanotubes are not limited to uniform textiles. The idea can be extrapolated to military vehicles as well. The current seats of the JLTV can

⁴⁴ The University of Texas at Dallas, "No Batteries Required: Energy-Harvesting Yarns Generate Electricity," UTD News Center, August 2017, https://www.utdallas.edu/news/2017/8/25-32663_No-Batteries-Required-Energy-Harvesting-Yarns-Gen_story-wide.html.

incorporate the carbon nanotubes to capture the movement of a Marine sitting. The electric current produced by the seats can be routed to the on-board power management system as a system of systems approach combined with other power generation technologies that are seamlessly integrated and invisible to the operator.

Hydrogen Fuel Cells

This section will examine hydrogen fuel cells and their applicability to the Marine Corps. Hydrogen fuel cells are one of the most promising technologies to serve as a replacement for the fuel-thirsty vehicles currently in the U.S. military inventory. In a model developed in 2017 by the Joint Operational Energy Initiative, fuel cell powered vehicles used significantly less JP-8 than internal combustion variants. The model calculated that it would take 15,000 gallons of JP-8 reformed into hydrogen to power a fuel cell vehicle fleet for a 30-day period. For a traditional diesel engine vehicle fleet, it would take 130,000 gallons of JP-8 in the same 30-day period.⁴⁵ Due to its vast potential, the thesis will examine hydrogen fuel cells more comprehensively than the other technologies. The following section will include military and civilian examples of hydrogen fuel cell vehicles as well as several emerging methods of producing, storing, and distributing hydrogen.

Hydrogen fuel cell vehicles provide numerous benefits over both internal combustion engines (ICE) and battery-powered electric vehicles. One advantage that both battery-powered and fuel cell-powered electric vehicles have over traditional engines is their near silent operation. Some fuel cell vehicles (e.g., Chevrolet Colorado ZH2, discussed later), have a 75-90% acoustic

⁴⁵ Scott Schramm, "Hydrogen Generation & Infrastructure Workshop Technical Report," U.S. Army Tank Automotive Research, Development and Engineering Center, April 6, 2017, 11.

signature reduction compared to a high mobility multi-wheeled vehicle (HMMWV).⁴⁶

Furthermore, fuel cell powered vehicles do not produce near as much heat as ICEs. These advantages are significant when it comes to the battle of signatures in a future fight against a peer adversary. Acoustic and thermal signatures are easily detected and can lead to targeting. Engineers at the U.S. Army CDCC Ground Vehicle Systems Center estimate that hydrogen fuel cell vehicles may enable a unit to operate within 100 meters of the adversary without detection under certain conditions.⁴⁷ Compared to most battery-powered electric vehicles, the fuel cells can meet the power demands of heavy military vehicles. The current power densities of batteries cannot match the performance output of fuel cells making them less desirable compared to fuel cells.⁴⁸

In addition to the practical advantages that hydrogen fuel cell vehicles provide, they also have a high technology readiness level compared to some of the previously mentioned technologies. In 2017, General Motors (GM) released a vehicle called the Colorado ZH2 that they built in collaboration with the U.S. Army CDCC Ground Vehicle Systems Center (see Figure 4).



⁴⁶ Kari Drotleff, *Hydrogen Fuel Cell Technology and Its Military Applications* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, February 22, 2019), PowerPoint presentation.

⁴⁷ Kevin Centeck, *Ground Vehicle Systems Center Fuel Cell Update* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, April 2, 2019), PowerPoint presentation.

⁴⁸ Kami Bucholz, "TARDEC Pursues Advanced Power Generation," last modified February 2, 2018, <https://www.sae.org/news/2018/02/tardec-pursues-advanced-power-generation>.

Fig 4: Colorado ZH2 (source: General Motors)

The vehicle is based on an extended mid-size truck platform propelled by an electric motor that gets its energy from hydrogen fuel cells. The fuel cells provide enough excess capacity to provide anywhere from 25kW to 50kW of external power via the truck's Exportable Power Take-Off (EPTO) (see Figure 5). The EPTO aboard the ZH2 provides high and low voltage power to accessories like communication equipment and tools. If properly configured, the Colorado ZH2 (and other fuel cell powered vehicles) can export all of the power from the fuel cell stacks when operated in a stationary mode.⁴⁹ In contrast, the JLTV is projected to provide only 10kW of power to on-board systems.⁵⁰ The 2.5 – 5 time increase in external power output over the JLTV is a marked improvement that will provide a small unit with the ability to operate its communication, navigation, and other ancillary equipment for a significantly longer period of time without additional batteries. In addition to the greatly increased exportable power compared to the JLTV, the Colorado ZH2 is able to provide extended exported power at a minimal amount of fuel consumption. The ZH2 provided 2.5kW of power for 24 hours and used only 4 kilograms of H₂ which is the equivalent of approximately 4 gallons of JP-8.⁵¹ This is a significant benefit to a unit conducting EABO within an adversary's targeting range. The unit can passively monitor its communication devices without operating their noisy JLTV and will consume minimal fuel while doing so.

⁴⁹ Kari Drotleff, telephone conversation with the author, April 4, 2019.

⁵⁰ Project Manager Joint Light Tactical Vehicles, "Test & Evaluation Master Plan Milestone C: Joint Light Tactical Vehicle (JLTV)," Survivability/Vulnerability Information Analysis Center, January 20, 2016, 10.

⁵¹ Kevin Centeck, *Ground Vehicle Systems Center Fuel Cell Update* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, April 2, 2019), PowerPoint presentation.



Fig 5: EPTO – On-board Power Supply (source: General Motors)

Beginning in April 2017, GM and the U.S. Army CDCC Ground Vehicle Systems Center tested the vehicle over the course of a year during several field exercises.⁵² The U.S. Army used several communities such as Airborne, Cavalry, Rangers, Infantry, and Special Forces Groups to test the vehicles in various training environments.⁵³ While the U.S. Army does not have a formal transition agreement to a future military program, Kevin Centeck and Kari Drotleff from U.S. Army CDCC Ground Vehicle Systems Center informed the author that these user evaluations will advise U.S. Army requirements managers regarding relevant technology for future capabilities.⁵⁴ It is possible that data from these tests will spur requirement changes to the JLTV or persuade decision makers to design a new joint ground vehicle based on the ZH2.⁵⁵ Therefore, in order to leverage the U.S. Army's existing investment, it is imperative that Marine Corps requirements managers as well as MCWL coordinate with the U.S. Army CDCC Ground Vehicle Systems Center to monitor and influence future testing and development of the ZH2.

⁵² Kami Bucholz, "TARDEC Pursues Advanced Power Generation," last modified February 2, 2018, <https://www.sae.org/news/2018/02/tardec-pursues-advanced-power-generation>.

⁵³ Kari Drotleff, *Hydrogen Fuel Cell Technology and Its Military Applications* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, February 22, 2019), PowerPoint presentation.

⁵⁴ Kevin Centeck and Kari Drotleff, telephone conversation with the author, April 4, 2019.

⁵⁵ In a telephone conversation with the author on April 4, 2019, Kari Drotleff stated that the Special Operations Force community is interested in leveraging the technology. Additionally, Space and Naval Warfare Systems (SPAWAR) expressed interest in the joint GM/U.S. Army CCDC Ground Vehicle Systems Center hydrogen fuel cell vehicle project.

GM and the U.S. Army CDCC Ground Vehicle Systems Center expanded their scope and developed a multi-functional and reconfigurable base platform using the same design methodology as the Colorado ZH2. The platform called the Silent Utility Rover Universal Superstructure (SURUS) incorporates both hydrogen fuel cells and autonomous driving capabilities. The vehicle has a range of 400 miles, greater than most battery powered electric vehicles.⁵⁶ The vehicle can also serve as a large power plant for external applications, producing up to 100kW of power, ten times the capacity of the JLTV (see Figure 5 for example GM power supply).⁵⁷

The testing data coupled with the interest in the Colorado ZH2 and SURUS prompted the U.S. Army CDCC Ground Vehicle Systems Center and GM to develop a third hydrogen fuel cell vehicle in 2018. The third vehicle is based on their medium/heavy duty truck, the Chevrolet Silverado. The hydrogen fuel cell Silverado features a more advanced propulsion system compared to the Colorado ZH2, features rapid recharging in less than 3 minutes and provides 2 gallons of water per hour in addition to its unique capabilities of being odorless, smokeless, and quiet with a low heat signature.⁵⁸ Those last few capabilities are critical in an EABO scenario where signature management is the main factor contributing to unit survivability. Compared to the currently configured JLTV, the hydrogen fuel cell vehicle's overall signature is substantially lower. While early in its development, the third vehicle is promising because of its increased cargo and passenger capacity compared to the field-tested Colorado ZH2.

⁵⁶ Kami Bucholz, "TARDEC Pursues Advanced Power Generation," last modified February 2, 2018, <https://www.sae.org/news/2018/02/tardec-pursues-advanced-power-generation>.

⁵⁷ Douglas Halleaux, "TARDEC, GM Bring SURUS to Smithsonian and SOFIC," last modified May 21, 2018, <https://www.dvidshub.net/news/277762/tardec-gm-bring-surus-smithsonian-and-sofic>.

⁵⁸ General Motors, "GM Defense – The Ultimate Ally," accessed 20 March 2019, <https://www.gmdefensellc.com/>.

There are not many hydrogen fuel cell vehicles in the market right now, but recent advances in the commercial industry have made it easier for the military to adopt similar technologies. The U.S. government is currently investing in these efforts which creates a precedent for using the vehicles in future government endeavors. Alameda Contra-Costa Transit District (AC Transit) in California operates a fleet of 13 hydrogen power advanced-design fuel cell buses and two hydrogen fueling stations. The majority of their buses have operated more than 18,000 total hours.⁵⁹ This is an isolated use case that relies on its own controlled hydrogen fuel infrastructure, but is a successful use case that shows the potential of hydrogen fuel cell vehicles in the transportation sector. Furthermore, it shows the utility of large vehicles powered by hydrogen fuel cells vice smaller energy efficient vehicles that do not share commonality with heavy tactical vehicles.

In addition to the above examples of existing hydrogen fuel cell vehicles, there are numerous efforts to effectively and efficiently produce, store, and distribute hydrogen for the fuel cells. Despite successful case studies in the commercial industry, the Department of Defense is resistant to acquiring vast quantities of hydrogen fuel cell for use in vehicles or other platforms. One of the arguments against widespread adoption of hydrogen fuel cells is that it would complicate the supply chain by adding yet another type of fuel in the inventory. Further complicating the supply system is a factor when considering new acquisition programs; however, it should pale in comparison to fielding a capability that drastically improves a unit's survivability by decreasing its signature. Nonetheless, the Army's Communications-Electronics Research, Development and Engineering Center (CERDEC) is developing methods of powering

⁵⁹ National Renewable Energy Laboratory, "Hydrogen Fuel Cell Electric Bus Evaluation Project Reveals Success for Transit Partner," last modified June 15, 2018, <https://www.nrel.gov/news/program/2018/hydrogen-fuel-cell-electric-bus-evaluation-project-reveals-success-for-transit-partner.html>.

the fuel cells with materials already in the supply system. In 2018, CERDEC made methanol by stripping away the cleaner agents from windshield wiper fluid. The transformed methanol would power the fuel cell without the need to distribute methanol in its raw form. CERDEC is also experimenting with an existing fuel cell called the XX55 that is developed by the Livermore, CA based company (Ultracell LLC) to show the utility of fuel cells. CERDEC used the fuel cell to power an experimental expeditionary joint battle command platform that is designed to provide satellite connectivity to dismounted troops. CERDEC swapped two standard batteries for the fuel cell coupled with a one-liter bottle of methanol to power the system for 24 hours. The swap reduced the weight of the system by over 50 percent.⁶⁰ The Air Force Research Laboratory (AFRL) worked with Ultracell LLC and Universal Technologies Corporation (UTC) to solve materials and scale-up challenges and to make manufacturing of the fuel cells more cost-effective. Currently, the XX55 fuel cell provides a continuous power output of 50 watts. The fuel cells are powered by methanol containers ranging in size from a small container that provides eight hours of charge all the way to a five-gallon container of methanol that ensures the XX55 can provide almost two weeks of charging capability.⁶¹

Using methanol is not the only method to power a fuel cell. The primary way is to use hydrogen.⁶² Early processes used electricity to separate the hydrogen from the oxygen in purified water, but this practice is not efficient because of the electricity required and the need for purified water. Researchers from the University of Central Florida (UCF) developed a

⁶⁰ Stew Magnuson, "Windshield Wiper Fluid a Potential Battlefield Fuel," *National Defense*, August 2018, <http://www.nationaldefensemagazine.org/articles/2018/8/30/windshield-wiper-fluid-a-potential-battlefield-fuel>.

⁶¹ Burnett, Heyward, "New Fuel Cell System Reduces Weight for Warfighters," last modified January 9, 2012, <https://www.wpafb.af.mil/News/Article-Display/Article/399658/new-fuel-cell-system-reduces-weight-for-warfighters/>.

⁶² National Renewable Energy Laboratory, "Hydrogen Fuel Cell Electric Bus Evaluation Project Reveals Success for Transit Partner," last modified June 15, 2018, <https://www.nrel.gov/news/program/2018/hydrogen-fuel-cell-electric-bus-evaluation-project-reveals-success-for-transit-partner.html>.

technique to harness solar energy to extract hydrogen from seawater in 2017. The research team used a specially designed photocatalyst composed of a hybrid material that is twice as effective as conventional methods.⁶³ The major appeal to this technique is the ease to which Marines will have access to the raw material of seawater. Due to the Marine Corps' amphibious nature, seawater is likely to be readily available. A maneuver element could simply collect the seawater themselves without relying on a resupply convoy or the system could be set up at various locations along the coastline producing hydrogen and storing it in easily collectable containers. The UCF team is further researching the possibility of harvesting hydrogen from waste water using solar energy.⁶⁴ This method is also valuable to a small unit conducting EABO for many of the reasons listed above.

Researchers at the Royal Melbourne Institute of Technology (RMIT) developed an additional method of harvesting hydrogen for fuel cells in 2017. Unlike the previous technique that uses solar energy to separate hydrogen from seawater, this technique collects water vapor from the air and then isolates the hydrogen. The researchers developed an ink-like substance from a silica-based compound that is able to extract water vapor from humid air and collect it on the surface painted with the ink.⁶⁵ The ink's chemical composition also doubles as a way of inducing electrocatalyst of the collected water vapor via sunlight which harvests hydrogen to be used later for fuel cells.⁶⁶ The main advantage of this technology is that the ink can be applied to almost

⁶³ University of Central Florida, "New nanomaterial can extract hydrogen fuel from seawater: Hybrid material converts more sunlight and can weather seawater's harsh conditions," ScienceDaily, www.sciencedaily.com/releases/2017/10/171004162013.htm.

⁶⁴ University of Central Florida, "New nanomaterial can extract hydrogen fuel from seawater: Hybrid material converts more sunlight and can weather seawater's harsh conditions," ScienceDaily, www.sciencedaily.com/releases/2017/10/171004162013.htm.

⁶⁵ Daeneke, Torben et al. "Surface Water Dependent Properties of Sulfur-Rich Molybdenum Sulfides: Electrolyteless Gas Phase Water Splitting." ACS Nano, 11, 7 (2017): 6784.

⁶⁶ Daeneke, Torben et al. "Surface Water Dependent Properties of Sulfur-Rich Molybdenum Sulfides: Electrolyteless Gas Phase Water Splitting." ACS Nano, 11, 7 (2017): 6788.

any surface making the surface a passive hydrogen producing device. Unlike the previous technique, Marines would not have to collect water as the ink applied on the surface of a JLTV, for example, would extract water vapor from the air to produce the hydrogen.

U.S. Army researchers developed a less energy-intensive method of extracting hydrogen from water. In 2017, the team discovered that when water came into contact with a specially designed compound of nano-galvanic aluminum-based powder it quickly made a bubbling reaction that split water into hydrogen and oxygen. The unique quality of this type of electrolysis is that the reaction does not require elevated temperatures or the addition of a chemical catalyst required by most techniques. Furthermore, the process is extremely quick. The team determined that one kilogram of the aluminum powder can produce 220kW of power in three minutes when exposed to water. The powder can be printed using additive manufacturing techniques to scale up and it will work with any liquid that contains water, not just purified water.⁶⁷ This technique may not be useful as the sole means of providing hydrogen for a fuel cell, but it could serve as a backup or emergency supply. A maneuver element could replace the five-gallon jugs of JP-8 they carry for a few blocks of the aluminum powder to provide a considerable amount of reserve power if needed.

There is no shortage of attempts to isolate hydrogen from oxygen in water. Many processes use expensive raw materials like platinum to act as the catalyst. The high cost contributes to the slow adoption of hydrogen powered fuel cells. In 2017, a chemist at University of New South Wales developed a catalyst using cheap and abundant materials like nickel, iron, and copper using nontechnology methods. The technique increases the conductivity of the cheap materials

⁶⁷ David McNally, "Army Discovery May Offer New Energy Source," Last modified July 24, 2017, <https://www.arl.army.mil/www/default.cfm?article=3036>.

to be on par with the expensive materials.⁶⁸ This breakthrough will not directly affect the military, but if the technique is adopted it could lead to further development of a hydrogen infrastructure, making hydrogen fuel cell vehicles more feasible.

The current infrastructure necessary to produce sufficient hydrogen for military application is lacking. The infrastructure that supports JP-8, however, is robust. Therefore, the Army is exploring methods to transform JP-8 into hydrogen. The technology is not ready for fielding to a combat unit; however, the U.S. Army CDCC Ground Vehicle Systems Center used a prototype version of the fuel reforming system for the Chevrolet Colorado ZH2 during field testing in 2017.⁶⁹ The main issue with JP-8 is that it contains high levels of sulfur that contaminate the fuel cells. Sources of JP-8 in the United States are fairly clean, but in a deployed environment, the military relies on locally sourced JP-8 that often contains significantly higher concentrations of sulfur, exacerbating the potential problem of contaminated fuel cells.⁷⁰ The U.S. Army CDCC Ground Vehicle Systems Center is working with technical specialists from the U.S. DOE, the automotive industry, U.S. Army laboratories, and universities to develop alternative methods of extracting hydrogen from JP-8. The U.S. Army CDCC Ground Vehicle Systems Center is also collaborating with the technical specialists to help develop the most efficient concept of employment for the process.⁷¹ While intriguing, this process does not provide an immediate benefit to a small maneuver element because logistics units will still have to distribute the converted hydrogen during resupply missions. The benefit that it does provide is that it could

⁶⁸ Sue Min Liu and Deborah Smith, “New Ultrathin Material for Splitting Water Could Make Hydrogen Production Cheaper,” last modified June 7, 2017, <https://newsroom.unsw.edu.au/news/science-tech/new-ultrathin-material-splitting-water-could-make-hydrogen-production-cheaper>.

⁶⁹ Kami Bucholz, “TARDEC Pursues Advanced Power Generation,” last modified February 2, 2018, <https://www.sae.org/news/2018/02/tardec-pursues-advanced-power-generation>.

⁷⁰ Stew Magnuson, “Fuel Cells Fail to Make Inroads With the Military (UPDATED),” *National Defense*, May 2017, <http://www.nationaldefensemagazine.org/articles/2017/5/26/fuel-cells-fail-to-make-inroads-with-the-military>.

⁷¹ Kami Bucholz, “TARDEC Pursues Advanced Power Generation,” last modified February 2, 2018, <https://www.sae.org/news/2018/02/tardec-pursues-advanced-power-generation>.

enable the Marine Corps to adopt fuel cells in applications where they provide a longer operating time than solely on JP-8. More importantly, the process could facilitate the Marine Corps adopting fuel cell vehicles in the near-term vice waiting until the infrastructure is built. This would ensure the Marine Corps is able to take advantage of the signature management capabilities inherent in hydrogen fuel cell vehicles such as its low heat signature and near silent operation.

The need to store hydrogen in highly pressurized containers is one of the limiting factors preventing its widespread adoption and lack of supporting infrastructure. Scientists from Lawrence Livermore National Laboratory (LLNL) developed a method of storing hydrogen in a solid-state in 2017. This has two distinct advantages. First, it increases safety by negating the need to store hydrogen in highly pressurized containers. Increased safety increases the likelihood of future hydrogen infrastructure development and makes it more feasible for the military to adopt the technology. The second advantage that solid-state hydrogen provides is that it enables hydrogen to be stored in a more compact form.⁷² This translates to more energy production per volume which increases the operating time. The advantages also simplify distribution methods making the transition to hydrogen fuel cell vehicles more palatable.

To solve the issue of having both a battery backup device and a fuel cell, researchers at Georgia Tech University (GT) and University of California-Los Angeles (UCLA) began developing a fuel cell with specially designed electrodes in 2015. The electrodes would store chemical fuels like hydrogen and methane and would perform like a battery during any lapses of energy while using the fuel cell.⁷³ This configuration would save weight and space on the host

⁷² Anne M Stark, “A Solid Pathway Toward Hydrogen Storage,” last modified September 25, 2017, <https://www.llnl.gov/news/solid-pathway-toward-hydrogen-storage>

⁷³T.J. Becker, “Power Up: Energy Storage Innovations Will Make Renewables Less Expensive, More Reliable,” *Georgia Tech Research Horizons*, Issue 1, 2015, <http://www.rh.gatech.edu/features/power>.

platform, making it more efficient and appealing as an alternative to traditional JP-8 fueled vehicles.

The existence of the field-tested GM/ U.S. Army CDCC Ground Vehicle Systems Center collaborative vehicles combined with the numerous hydrogen generation methods is solid evidence that the Marine Corps should invest in hydrogen fuel vehicles. The U.S. Army invested approximately \$25M over the last 5-7 years into fuel cell research and development for military purposes which reduces the capital costs for the Marine Corps to adopt the technology.⁷⁴ Additionally, the U.S. Army has a six-year funded program starting in fiscal year 2020 to further develop their past efforts.⁷⁵ The future program will leverage all previous hydrogen fuel cell projects and will focus heavily on developing the production, storage, and distribution of hydrogen in the battlespace.⁷⁶ Most of the future research is related to three technical challenges/gaps spread across six specific projects scheduled for completion in fiscal year 2025.⁷⁷ The Department of Energy also recognizes the need to improve the hydrogen infrastructure and is taking steps toward that end. On March 4, 2019 it announced \$31M in funding to enable large-scale hydrogen generation, transport, storage, and utilization.⁷⁸

⁷⁴ The Fuel Cell Technologies Team from the U.S. Army CDCC Ground Vehicle Systems Center has a stated mission to “explore and evaluate fuel cell power generation technologies and their support equipment that enable tactical advantages for ground vehicle systems.” Their recent and ongoing projects include solid oxide fuel cell (SOFC)/JP-8 reformation auxiliary power unit, fuel cell all terrain transport (FCATT), tactical hydrogen operational refueler (THOR), GM Hydrogen Ecosystem, in addition to the Colorado ZH2 and SURUS. Future demonstrations include a hydrogen transportation and distribution trailer and another fuel cell vehicle with increased payload capacity that is capable of a 300-mile off-road range using its on-board storage of approximately 10 kilograms of hydrogen (Kari Drotleff, *Hydrogen Fuel Cell Technology and Its Military Applications* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, February 22, 2019), PowerPoint presentation).

⁷⁵ Funding for the six-year fuel cell/hydrogen program is funded through a future years Program Objective Memorandum (POM), therefore specific funding budget is not available.

⁷⁶ Kari Drotleff, email message to author, April 10, 2019.

⁷⁷ Kevin Centeck, *Industry Days* (U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, April 2, 2019), PowerPoint presentation.

⁷⁸ U.S. Department of Energy, “Department of Energy Announces \$31 Million in Funding To Advance H2@Scale,” accessed March 22, 2019, <https://www.energy.gov/articles/departments-energy-announces-31-million-funding-advance-h2scale>.

Furthermore, the ONR is conducting research and development on fuel cell applicability to the military. ONR has several divisions developing different fuel cell related projects. ONR, Code 332 is incorporating fuel cells into unmanned vehicle applications (e.g., unmanned aerial vehicles and unmanned underwater vehicles).⁷⁹ ONR, Code 331 is developing fuel cell generators in the 3-10 kW range of power. Similar to the U.S. Army's Colorado ZH2, the fuel cell generators utilize a JP-8 reformer to produce the hydrogen. These projects are components of future naval capabilities (FNC) that will transition into actual programs.⁸⁰ The U.S. Army and ONR efforts will reduce initial investment costs and risks for the Marine Corps if it chooses to invest in hydrogen fuel cell vehicles.

Capital costs aside, the purpose of this research is to focus on improving the effectiveness of EABO by decreasing fuel demand which ultimately reduces the number of required resupply missions. In that vein, hydrogen fuel cell vehicles drastically extend a unit's operational reach. Additionally, a hydrogen fuel cell vehicle provides a near-silent and potentially self-sustaining alternative to the loud and fuel-thirsty JLTVs in their current configuration, drastically improving a unit's ability to manage its signature.⁸¹ The various hydrogen producing methods (or hydrogen alternatives) provide an opportunity to leverage the technology prior to the establishment of a global hydrogen fuel infrastructure. When combined with other electricity producing technologies, a hydrogen fuel cell equipped unit can be partially self-sufficient if it has access to water and a method of using electrolysis to create hydrogen. Furthermore, substantial military fuel cell vehicle investments may spur commercial development much in the same manner as government funding assisted the AC Transit in California. This is merely one of

⁷⁹ Dr. Michele Anderson, email to the author, April 1, 2019.

⁸⁰ Donald Hoffman, emails to the author, April 1, 2019 and April 3, 2019.

⁸¹ According to the MAGTF Bulk Fuel Study II, the JLTV uses 6.2 gallons of JP-8 per hour.

numerous indicators that adopting hydrogen fuel cell vehicles offers a high benefit with a relatively low risk.

Summary of Technologies

This thesis examined five different power generation technologies that have the ability to reduce a small unit's fuel consumption. Each of them is applicable during EABO against a peer adversary in a maritime environment. Furthermore, each technology satisfies the five evaluation criteria set forth in the beginning of the thesis (reduce fuel consumption, maintain or lower unit's signature, mobile, seamless integration, and mature technology). The below table (see Table 1) compares the selected technologies against the evaluation criteria using a High, Medium, or Low scale. A grade of High denotes a substantial advantage while a grade of Low indicates a lesser advantage.

	Fuel Reduction	Signature Management	Mobility	Integration	Maturation
Regenerative Braking	Med: significantly extends range of hybrid or all electric vehicle	Med: extends amount of time vehicle can operate on battery power	High: no impact on mobility	High: no impact to operator	High: numerous examples in industry
Regenerative Shock Absorbers	Med: significantly extends range of hybrid or all electric vehicle	Med: extends amount of time vehicle can operate on battery power	High: no impact on mobility	High: no impact to operator	Med: a few industry examples
Thermal Energy to Electricity	Low: produces electricity to extend operational time	Med: extends amount of time vehicle can operate on battery power	High: no impact on mobility	High: no impact to operator	Low: lab-demonstrated
Electricity Producing Fibers	Low: produces electricity to extend operational time	Med: extends amount of time vehicle can operate on battery power	High: no impact on mobility	High: no impact to operator	Low: lab-demonstrated
Hydrogen Fuel Cells	High: significant reduction (8x reduction)	High: significantly decreases thermal & acoustic signature compared to ICE	Med: still requires refueling, but does not directly impact mobility	Med: operator will notice difference compared to ICE	Med: a few industry examples, but lacks infrastructure

Table 1: Summary of Technologies

As indicated in the table, each of the technologies provide advantages to a small unit conducting EABO. The summarization of the technologies suggests that Hydrogen Fuel Cell

vehicles produce the most significant advantages across the selected criteria. Nevertheless, it is important to note that selection of one technology does not prevent future or simultaneous selection of another technology. In fact, the largest advantage comes from incorporating as many of the technologies as possible to work together as an integrated system.

Recommendations

Imagine replacing a platoon's section of JLTVs with hydrogen fuel cell powered vehicles such as the SURUS that incorporate an advanced battery that also serves as the hood and fenders of the vehicle, reducing overall weight. The vehicle is painted with a silica-like paint that autonomously absorbs water vapor from the air and uses the sun to extract hydrogen to refuel the fuel cell. As a backup measure, the vehicle has tanks that can be filled with seawater that is converted into hydrogen using a similar electrolysis method as the primary means of refueling the fuel cell. To capture potential energy losses through friction and heat, the vehicle will incorporate energy harvesting shock absorbers and regenerative braking to provide energy back to the smart power management system aboard the truck. Additionally, the fabric in the seats are woven with carbon nanotubes that when stretched provide electricity back to the same power management system. Excess water from the fuel cells is captured and used as potable drinking water to further reduce reliance on external logistics sources. In an effort to further mitigate dependence on external logistics and to reduce its signature, some of the weapon systems are replaced with directed energy weapons made possible because of the massive on-board energy storage, mitigating class V resupply missions.⁸² Not only do the hydrogen fuel cell vehicles lower their signature by reducing the frequency of resupply missions, hydrogen fuel cell vehicles

⁸² Andrew Feichert, *U.S. Army Weapons-Related Directed Energy (DE) Programs: Background and Potential Issues for Congress*, CRS Report for Congress R45098 (Washington, DC: Congressional Research Service, February 12, 2018), 9-12, <https://fas.org/sgp/crs/weapons/R45098.pdf>.

have a much lower thermal and acoustic signature compared to the current JLTV. This enables the small unit the ability to operate within a peer adversary's targeting range without being detected.

While the above scenario is the dream of both an operator and a logistician it is most likely only feasible in the distant future; however, there are existing and emerging technologies that the Marine Corps should pursue now to have an immediate effect and to prepare for a future fight against a peer adversary. There is no one technology that is going to magically reduce a unit's energy consumption. The solution must be a system of systems approach that is implemented across three phases.⁸³

Phase One

The JLTV is still in its initial fielding stage and will be a part of the inventory for many years to come.⁸⁴ It may not be possible to completely switch out its diesel engine for an electric motor powered by hydrogen fuel cells in the near term, but every effort should be made to integrate an onboard smart power intake and management system similar to the HEIT (MCWL). The power management system could be used to charge various electronics as well as power communication and other systems when the JLTV engine is not running. A more robust energy storage system will give operators the confidence to turn off their vehicles and know their vehicle-powered systems will still work. If the Marine Corps is unable to change the culture of idling vehicles, it could upgrade the JLTVs with stop/start technology similar to the systems installed in passenger cars (CDD/MCSC). An integrated smart power intake and management system on the JLTV

⁸³ The recommended office of primary responsibility (OPR) will follow the recommendation in parentheses.

⁸⁴ In an email message to the author on April 8, 2019, Douglas Edwards, the JLTV Capabilities Integration Officer (CIO) at Capabilities Development Directorate (CDD), Combat Development and Integration (CD&I) stated that the Marine Corps began fielding the JLTV in February 2019 and that it will replace all HMMWVs by fiscal year 2030. The JLTV has an economic useful life of 20 years and the Marine Corps plans to operate the vehicle for over 40 years. The U.S. Army plans to continue buying the JLTV through fiscal year 2044.

would significantly reduce the reliance on batteries and would decrease the fuel consumption of the JLTV.

Another method of reducing fuel consumption that can be implemented immediately is a program for the JLTV like the MCSC-led program for the MTRV (CDD/MCSC). Changes to the intake, exhaust, boost, and other engine programming attributes may increase fuel efficiency. The diesel engine in the JLTV was most likely programmed for maximum power output at a given engine speed and not fuel efficiency. In a battle of signatures against a peer adversary, fuel efficiency contributes more to a unit's survivability than vehicle speed and should therefore be prioritized accordingly.

Phase Two

While Phase One is still in its implementation, the Marine Corps should develop the requirements for a hybrid JLTV (CDD). The requirements should drive research and development towards technologies that can augment the existing JLTV powerplant. There are companies such as XL Hybrids that transform heavy duty non-hybrid vehicles into fully functional hybrid electric vehicles. XL Hybrids retrofits commercial trucks up to class 6 with electric motors that use regenerative braking to provide anywhere from a 20-25 percent increase in fuel efficiency.⁸⁵ The conversions on the commercial vehicles cost around \$10k, install in one day, are minimally invasive to the host platform, and are even compatible with existing manufacturer warranties.⁸⁶ Hybrids often capture lost energy through regenerative braking systems, but a hybrid could potentially leverage other technologies such as regenerative shock

⁸⁵ According to its website, XL Hybrids achieved up to 25% increases in fuel efficiency with its standard hybrid applications with regenerative brake systems and up to 50% increases in fuel efficiency with its plug-in hybrid system for a Ford F150.

⁸⁶ <https://www.xlfleet.com/>.

absorbers or thermal electric paint to further improve fuel efficiency. The majority of the technologies mentioned in this thesis rely on the ability to store and subsequently use the generated power; therefore, a hybrid or all electric drivetrain is foundational. The company mentioned above provides a use case that the DoD can model or even collaborate with to develop a hybrid JLTV. A hybrid JLTV will increase operational reach and reduce reliance on logistics resupply while noticeably improving the unit's ability to manage its signature, all valuable attributes in a fight against a peer adversary. Any tactical vehicle that does not incorporate a hybrid electric drivetrain (at a minimum) is all but obsolete on the modern battlefield.

Phase Three

Ultimately, the Marine Corps should abandon internal combustion engines in its vehicles, especially those employed by small maneuver elements attempting to remain under the enemy's detection threshold. The traditional ICE needs to be replaced by an all-electric vehicle that operates with a minimal signature (CDD/MCSC). Based on existing technology and future trends, hydrogen fuel cell vehicles offer the most potential. The Marine Corps and ONR should collaborate with the U.S. Army CDCC Ground Vehicle Systems Center regarding the hydrogen fuel cell vehicles already under development (Colorado ZH2, SURUS, and Silverado ZH2). The fuel cell technology should replace the diesel powertrain of the JLTV. If this is not feasible, it should provide the starting point for a completely new vehicle platform designed for small, maneuver elements conducting EABO. The platform must be flexible and designed to seamlessly integrate future improvements such as regenerative shock absorbers, thermoelectric paints, carbon nanotube fiber seats, and other relevant technologies to generate and store energy.

Furthermore, the vehicle should leverage technologies to produce hydrogen on-board to make it completely self-sustaining (e.g., water vapor to hydrogen or seawater to hydrogen technology). When designing this vehicle, the above characteristics must be Key Performance Parameters (KPP) and not relegated to Key System Attributes (KSA) or Additional Performance Attributes (APA). These characteristics are the ones that will keep a unit alive on the future battlefield against a peer adversary.

Oftentimes, the conversation to reduce energy consumption is based around costs savings. This is the wrong metric. The desire to make a small maneuver element more effective is the correct metric. It is obvious that reducing the unit's energy consumption is critical to enhancing the unit's effectiveness as it maneuvers within a peer adversary's targeting range. Reduced energy consumption extends the unit's operational availability and lowers its signature, increasing its survivability rate. Another significant advantage of electrifying vehicles is that it provides a robust on-board power supply that can charge a unit's batteries. On average, a standard Marine Corps squad carries 117 pounds of batteries for a 72-hour mission.⁸⁷ Combat operations in OEF and OIF highlighted a steep rise in battery demand that is not predicted to wane. Some sources estimate that demand for batteries will increase over 30 percent in the next five years.⁸⁸ Modern battlefield equipment such as unmanned aerial and ground systems, electronic warfare systems, directed energy weapon systems, and exoskeletons will significantly drive power consumption past levels currently on the battlefield. Having a robust on-board power supply (i.e. those provided by hydrogen fuel cell vehicles like the SURUS which produces 100kW) will mitigate the need for multiple spare batteries because the unit can use rechargeable

⁸⁷ Marine Corps Warfighting Laboratory Science and Technology brief labeled Hybrid Energy Internally Transportable Vehicle (ITV) Trailer (HEIT) User Evaluation.

⁸⁸ "Demand for military batteries worldwide to grow by 31 percent over the next five years," <https://www.militaryaerospace.com/articles/2018/07/military-batteries.html>.

batteries. Moreover, hydrogen fuel cell vehicles provide a distinct advantage over ICE vehicles when considering signature management. They operate at much lower temperatures and are considerably quieter.

Because of the lengthy requirements and acquisition process, requirements managers should codify and register the above requirements immediately in the form of KPPs for the JLTV or other suitable ground vehicle. The DOE and U.S. Army are making substantial investments in the hydrogen infrastructure today that will be available for a future hydrogen fuel cell vehicle to leverage. KPPs should reflect required capabilities of the future force, not just the currently existing technology. Furthermore, it is not necessary to wait until the next Capabilities Based Assessment (CBA) to register a gap as an applicable gap already exists. The requirements for a hydrogen fuel cell (or other electrically powered) tactical vehicle can be directly tied to the highly ranked, Tier 1 Signature Management gap.⁸⁹

Further Research

Further research is required regarding Phase Three of the recommendations. The research should examine the feasibility of completely replacing the current JLTV engine and transmission with the SURUS, Colorado ZH2, and/or Silverado ZH2 powertrain. The feasibility should include both the engineering and acquisition aspects of this endeavor. It must not only be technologically feasible, but also legally possible under the current contract with Oshkosh Defense. Results from this research may influence the phasing approach of the recommendations.

⁸⁹ The Signature Management gap was introduced for POM-19 and is historically ranked as a high Tier 1 gap in the CBA process. Therefore, it is a fully funded initiative throughout the Future Years Defense Program (FYDP).

While this thesis examined the technologies required to create a more sustainable maneuver element while reducing its signature, it did not evaluate the cost effectiveness of the recommendations. Therefore, future research efforts should develop the business case model for implementing the proposed changes. The model, however, must include more than just FBCF and lifecycle management. It must also factor in the variables of signature management and thus, force protection of Marines operating within the adversary's targeting range. Electrified vehicles decrease the reliance on resupply missions, lower detectable heat signatures, and reduce the acoustic signature all combining to substantially lower a unit's physical, technical, and administrative signature. Additionally, the model must account for secondary benefits such as a large external electrical supply that can power the myriad devices that a technologically advanced Marine Corp unit carries.

Conclusion

Loud and inefficient JLTVs that tether small maneuver elements to slow and cumbersome fuel resupply convoys that generate substantial signatures are not preparing the Marine Corps to “meet the demands of a future operating environment characterized by complex terrain, technology proliferation, information warfare, the need to shield and exploit signatures, and an increasing non-permissive maritime domain.”⁹⁰ The enhanced performance and survivability characteristics of the JLTV are negated by its relatively high signature. It is not a foregone conclusion that fuel demand will continue to escalate as suggested by the 2018 MAGTF Bulk Fuel Study II; however, the Marine Corps must invest in the recommended technologies in the

⁹⁰ Headquarters US Marine Corps, *The Marine Corps Operating Concept: How an Expeditionary Force Operates in the 21st Century*, (Washington, DC: Headquarters US Marine Corps, September 2016), 6.

next Program Objective Memorandum (POM) cycle if it wants to increase EABO success by 2025.

This thesis examined current Marine Corps energy reduction related initiatives as well as emerging technologies to recommend specific technologies to create a more energy efficient and therefore a more logistically sustainable maneuver element for the future fight against a peer adversary. The thesis recognized that a single technology is not sufficient by itself to substantially reduce a unit's energy consumption. It will take a system of systems approach implemented across three phases. Phase One focuses on minor adjustments to on-going initiatives. For example, the Marine Corps can modify the SPACES/GREENS program to provide expeditionary power to a unit constantly moving. In the same vein, the Marine Corps can further develop the HEIT's power management system from its current form into one that is integrated into tactical vehicles such as the JLTV to provide a robust onboard power supply for various components. Other current initiatives such as the MCSC-led effort to retroactively improve the efficiency of the MTVR should be extrapolated to additional platforms such as the JLTV. Furthermore, the Marine Corps should prioritize capabilities that increase survivability (i.e., fuel efficiency) over speed and towing capacity in existing as well as future platforms.

The thesis also identified several emerging technologies that the Marine Corps should remain cognizant of and plan to incorporate. Vehicles that rely on JP-8 are not the solution for equipping the future force. The Marine Corps must immediately prepare to transition to electrified vehicles if it desires to conduct successful EABO against a peer competitor. This is the crux of Phase Two of the recommendations. The majority of the identified technologies are dependent on a robust energy storage system and require a hybrid electric drivetrain that can ingest and store generated power. Regenerative shock absorbers and brakes along with paints

and fibers that generate electricity have the potential to vastly extend the operating range of a tactical vehicle while decreasing the unit's signature. Phase Three of the recommendations highlighted the need to progress past the high-signature JP-8 fueled vehicle to an all-electric vehicle. Additionally, hydrogen fuel cell vehicles are an attractive alternative to traditional battery-powered electric vehicles due to their extended range, exportable power, potential to produce potable water, and technology maturation level. The Marine Corps should partner with the U.S. Army to leverage the existing work on the GM-produced hydrogen fuel cell vehicles, the Colorado ZH2, SURUS, and Silverado ZH2. There are existing methods and processes of producing hydrogen for fuel cells such as JP-8 reformation that enable the Marine Corps to adopt the technology before the creation of a global hydrogen infrastructure. This allows the Marine Corps to reap the many benefits of hydrogen fuel cell and other electric vehicles. The benefits of electric vehicles over traditional vehicles include reduced acoustic and thermal signatures, substantial exportable power (100kW+), potential to produce water, and extended operating range. All of these characteristics are essential to a fight against a peer adversary. Electrified vehicles, specifically hydrogen fuel cell-powered vehicles, serve as a materiel solution to all three critical enablers of the EABO effectiveness triad (lethality, signature management, and sustainability) and are therefore essential to the Marine Corps' future concept of employment.

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Acronyms

AC Transit: Alameda Contra-Costa Transit District

AFRL: Air Force Research Laboratory

APA: Additional Performance Attribute

C2: command and control

CCD: cover, concealment, and deception

CCDC: Combat Capabilities Development Command (U.S. Army)

CERDEC: Communications-Electronics Research, Development and Engineering Center

DC: direct current

DEW: directed energy weapon

EABO: Expeditionary Advanced Base Operations

EPTO: Exportable Power Take-Off

FAME: fatty acid methyl ester

FARP: forward arming and refueling point

FBCF: fully burdened cost of fuel

FOB: forward operating base

GM: General Motors

GT: Georgia Tech University

HEIT: Hybrid Electric Internally Transportable Vehicle Trailer

ICE: internal combustion engines

ISR: intelligence, surveillance, and reconnaissance

JLTV: Joint Light Tactical Vehicle

JP-8: jet propellant 8

kW: kilowatt

KPP: Key Performance Parameter

KSA: Key System Attribute

Li-on: Lithium-ion

LLNL: Lawrence Livermore National Laboratory

MCAGCC: Marine Corps Air Ground Combat Center

MCSC: Marine Corps Systems Command

MCWL: Marine Corps Warfighting Laboratory

MEB: Marine Expeditionary Brigade

MIT: Massachusetts Institute of Technology

MOC: Marine Corps Operating Concept

MTVR: Medium Tactical Vehicle Replacement

NRL: Naval Research Laboratory

NPS: Naval Postgraduate School

OEF: Operation ENDURING FREEDOM

OIF: Operation IRAQI FREEDOM

PV: photovoltaics

POL: petroleum, oil, and lubricant

POM: Program Objective Memorandum

RMIT: Royal Melbourne Institute of Technology

SURUS: Silent Utility Rover Universal Superstructure

TARDEC: Tank Automotive Research, Development and Engineering Center

TTP: tactics, techniques, and procedures

TRL: technology readiness level

UARC: University-Affiliated Research Center

UCLA: University of California Los Angeles

UCSD: University of California San Diego

UTC: Universal Technologies Corporation

W: watt