2022 MajGen Harold W. Chase Prize Essay Contest: First Place

Powering EABO

Aluminum fuel for the future fight

by Capt Walker D. Mills, Maj Jacob Clayton & Erik R. Limpaecher

Logistics is the art of the possible. It defines the envelope within which military operations can happen. Logistics, specifically expeditionary logistics, will be critical in the success or failure of the Marine Corps' new operating concept Expeditionary Advanced Base Operations (EABO), and hydrogen can help overcome the logistics challenges inherent to EABO and future operations to power the Marine Corps.

EABO envisions groups of Marines and sailors operating from austere and distributed bases deep inside the enemy's weapons engagement zone, the area at which their conventional fires can effectively target U.S. forces. To persist forward, these forces will have to manage and reduce their observable signatures and win in the "hider-versus finder competition."[1] Equipped with the right sensors, fires, and command and control infrastructure, these Marines and sailors will operate as a stand-in force to create tactical and operational dilemmas for an adversary.

Wargaming has borne out that logistics will be the pacing function for EABO, and fuel will be the pacing commodity, meaning that EABO will only be as effective as the fuel logistics that support it. The Commandant's *Force Design 2030* report identified that "Logistics (sustainability) is both a critical requirement and critical vulnerability. Marine forces that cannot sustain themselves inside the WEZ (weapons engagement zone) are liabilities."[2] In the second iteration of the report, the CMC identified the systems necessary to "sustain Stand-In Forces in a contested environment" as a "Prioritized Investment."[3] The Marine Corps needs

>Capt Mills is a Marine infantry officer currently serving as an instructor at the Colombian Naval Academy in Cartagena, Colombia. He is also a non-resident WSD-Handa Fellow at Pacific Forum, the Military Fellow with Young Professionals in Foreign Policy, and a fellow at the Brute Krulak Center for Innovation and Future War.

>>Maj Clayton is the Head of Platform at Laconic Infrastructure Partners where he builds and delivers products across environmental monitoring, energy transformation, and regenerative eco-culture business lines. He served in the Marine Corps for fifteen years as an Infantry and LAR Officer.

>>>Mr. Limpaecher leads the Energy Systems Group at MIT Lincoln Laboratory, a Department of Defense federally funded research and development center in Massachusetts. He is a member of the Defense Science Board task force on DOD dependence on critical infrastructure and a nonresident fellow at the Krulak Center for Innovation and Future War at Marine Corps University. He holds a BSE in electrical engineering from Princeton University.

> ***"We must re-imagine our amphibious ship capabilities, prepositioning, and expeditionary logistics so they are more survivable, at less risk of catastrophic loss, and agile in their employment."***
>
> **—Gen David H. Berger,**
> **38th Commandant's Planning Guidance**

to hunt for ways to create a competitive advantage through innovative logistics and novel sources of operational energy. Marines and sailors have already been active in proposing novel platforms and concepts for making sure future Marines received the sustainment that they need.[4] However, too little attention has been paid to the promise of petroleum alternatives for powering EABO.

A recent breakthrough by researchers at the Massachusetts Institute of Technology (MIT) enables the activation of aluminum by heating it with small amounts of gallium and indium, (about 4 percent by weight), at normal oven temperatures (about 200 degrees Fahrenheit) for 1–2 hours.[5] The activated aluminum reacts with water to create hydrogen gas. Aluminum from nearly any source can be activated this way: foil, BB gun pellets, soda cans, or pots and pans. But once activated, they will react with distilled water, gray water, coffee, or even urine if necessary. Aluminum has long been known to create hydrogen when exposed to water, but this reaction is normally prevented by the oxidation of the outer layer of aluminum. Previous methods used to activate hydrogen have been costly, slow, and require larger quantities of additional metals to work. This innovative process could provide Marines with a potentially safe and efficient alternative to petroleum-based fuels to meet the operational energy needs of inside forces. Compared to hydrocarbon fuels, aluminum is far safer to transport, easier to source and distribute, and produces a much lower signature at the point of use. The Marine Corps needs to leverage this breakthrough to prepare itself for the future fight.

Today: King Petroleum

The U.S. military has long excelled at expeditionary and forward logistics to supply thousands of gallons of fuel to the tactical edge of the battlefield, from Operation PLUTO, which laid pipelines under the English Channel, to mastering the art of underway replenishment.[6] As often as not, the outcome of campaigns and battles has hung on fuel and the operational energy logisticians could provide.

During the Pacific campaigns in the Second World War, fuel was repeatedly a decisive factor. Early in the battle for Guadalcanal, Marine aviators were so short on fuel they were forced to pick through the remains of destroyed aircraft to "drain the last of their tanks."[7] RADM Aubrey Fitch, Commander of all landbased aircraft in the South Pacific, wrote to his superior that he could "USE NO MORE AIRCRAFT UNTIL THE AVGAS SITUATION IMPROVES."[8] It was not until they were adequately supplied with fuel that they would retake the skies and attack the infamous Tokyo Express. On the other side of Guadalcanal, Japanese forces were also critically low on fuel and were forced to expend as much as a ton and a half of fuel for every soldier or barrel of supplies that landed at Guadalcanal.[9] Electing to use destroyers to transport men and supplies, Japanese convoys bled the empire of precious fuel resources. The struggle for Guadalcanal was fought as much with gasoline and diesel as it was with rifles and bullets. On the other side of the world, during the Battle of the Bulge, German troops were so hamstrung for fuel that they went into battle with siphons, and their operational plans counted on using captured fuel from the Allied stocks.[10] Future operations in the Pacific will demand even more energy at the tactical level to power the weapons and platforms that Marine forces rely on.

The energy required by deployed U.S. forces even in austere environments has risen steadily since. In Afghanistan, U.S. troops required up to 22 gallons of fuel per person, per day to meet operational needs.[11] Not only was fuel a pacing function of operations, but it was also a vulnerability. Hundreds if not thousands of trucks supplying fuel for coalition forces in Afghanistan were attacked and destroyed. Fuel trucks were so vulnerable that troops jokingly called them "Taliban targets."[12] In Iraq, attacks on fuel convoys were a major source of casualties for coalition forces; between 2003 and 2007 over 3,000 U.S. soldiers or contractors were killed in fuel supply convoys.[13]

Today, the U.S. military's reliance on petroleum fuels again represents a critical risk to its ability to execute new concepts like EABO. Soldiers and Marines have grown dependent on easy access to nearly unlimited fuel. However, the 2016 *Operational Energy Strategy* warned that "these logistically intensive future concepts may not be supportable" without major changes in the way that the DOD uses and produces energy.[14] For several years, the military has taken steps to try and reduce energy use and experiment with alternative energy sources, but fossil fuel use has continued to rise. Instead of reducing its petroleum tether, the DOD has become the "world's largest institutional user of petroleum."[15]

The military's ability to provide historical levels of sustainment to forward-deployed forces is in doubt. Distributed operational concepts and a peer or near-peer adversary will frustrate U.S. efforts at sustainment. Logistics will be contested—Chinese military leaders have made clear that U.S. logistics vessels like tankers will be targeted in a conflict.[16] Enemy forces will target resupply platforms and storage depots. It is unlikely that a stand-in force will have easy access to the fuel necessary for sustained operations.

Distributed operational concepts and a peer or near-peer adversary will frustrate U.S. efforts at sustainment. Logistics will be contested …

Tomorrow: Queen Aluminum?

The new aluminum activation process, discovered at MIT through a lab accident, could make it possible to safely and quickly generate large amounts of hydrogen at the tactical edge of the battlefield.[17] Marines could do the activation process with gallium and indium on-site, using aluminum recycled or scavenged locally—a commercially available oven in just one to two hours. The discovery was significant enough that at MIT, normally reserved researchers were so excited by the potential of their discovery that referred to it as a potential component of the "Holy Grail of fuel delivery logistics."[18] Once it has been activated, aluminum has among the highest energy densities of any non-nuclear fuel, over twice the energy per volume of petroleum fuels. Once generated, hydrogen is a highly efficient fuel. According to the U.S. Department of Energy, hydrogen fuel cells paired with electric motors are two to three times more efficient than an internal combustion engine running on gasoline, further—hydrogen gas has nearly three times the energy density of gasoline.[19]

The technology to use hydrogen as a fuel is nothing new: General Motors modified a Handi-Van to run on hydrogen back in 1966. But hydrogen propulsion has been held back because until now, creating the fuel was costly, difficult, time-consuming, and often dangerous. Despite this, hydrogen still has a long history of military use—including both world wars—but the problem has always been generating and transporting this gas. Manufacturing the gas required large amounts of electricity, caustic substances, or heavy equipment and was done far from the tactical edge of the battlefield. In the First World War, it was generated in plants with a stew of caustic chemicals, many of which were located in the United States, and then shipped in metal cylinders across the Atlantic to the trenches. Now, hydrogen can be safely generated by Marines at the tactical edge of the battlefield using this newly discovered process.

To power EABO and other emerging concepts, the Marine Corps should invest in aluminum reactors and hydrogen fuel cells. Using aluminum to generate hydrogen on the battlefield could allow forces to take advantage of the inherent advantages of hydrogen fuel cell technology, of which there are several when compared to internal combustion engines. First, they run nearly silent.[20] With no necessary moving parts, fuel cells are much better suited for use by inside forces and reconnaissance units. They also generate less heat, meaning a smaller thermal signature for the vehicle or generator as a whole. Fuel cells can power high-torque electric motors, making them ideal candidates for platforms like vertical takeoff and landing unmanned aerial systems. They are also much better at generating high-peak output, which is critical for the employment-directed energy weapons, which are currently limited in employment by their power requirements.[21]

Since the reaction requires mostly water and aluminum, it can help change the logistics paradigm. Aluminum is one of the most abundant metals in the Earth's crust and is widely available on the civilian market. It can be bought, scavenged, or recycled almost anywhere. Gallium and indium, which are only needed in very small amounts, are used around the work in electronics and they are not considered rare-earth elements.[22] Gallium is roughly as common as lead and is usually extracted from bauxite ore during the aluminum refining process making it widely available. It is not currently refined in the United States, though it has been in the past, and the U.S. Geological Service estimates that domestics ores could be a "significant resource."[23] Indium is less common, roughly as prevalent as mercury or silver. It is a key component in liquid-crystal displays; while none is currently refined in the United States, over a third of global production is done by U.S. allies like Canada and South Korea.[24]

This new reaction could enable innovative distributed logistics. Scrap aluminum with small amounts of gallium and indium could be procured from recyclers throughout the Indo-Pacific, negating the need to transport large amounts of bulk liquid fuel through a contested theater or operational area over a static distribution network. Aluminum could even be used to package other supplies and then converted to fuel at the point of use. Aluminum also carries less political baggage than petroleum and can be hidden in plain sight. Aluminum storage facilities do not require intensive maintenance like fuel farms and there is no risk of an environmental disaster like a spill or large fire. For these reasons, U.S. partners and allies will be much more amenable to hosting forward stocks of aluminum in comparison to petroleum.

Hydrogen is also safer to use on the battlefield than petroleum. Aluminum isn't combustible, and hydrogen is only combustible under certain circumstances. Hydrogen gas will only combust at temperatures over *double* that of gasoline fumes and higher than propane or natural gas.[25] Testing has shown that hydrogen tanks can be designed to remain intact when punctured, and because hydrogen is a lighter-than-air gas, it vents vertically instead of pooling and spreading fire along the ground. In the First World War, U.S. pilots flying hydrogen-filled aerostat balloons had only a single combat fatality related to hydrogen—an artillery observer whose parachute burned up as he bailed out of his balloon—despite their relatively crude equipment and thousands of hours of combat flight time.[26]

Today, numerous companies are pursuing hydrogen fuel cells to power everything from cars to boats and airplanes. The airplane manufacturer Airbus recently announced that it is building a hydrogen-powered passenger aircraft.[27] Chevrolet has already demonstrated their hydrogen-powered truck designed for the Army.[28] Toyota and Yanmar are jointly developing a hydrogen-powered marine motor.[29] Multiple companies offer hydrogen-fueled electric-power generators on the commercial market. The Army and the Air Force have also invested in developing hydrogen-fueled platforms on a small scale, drones for the Army, and aviation-support equipment for the Air Force.[30] Hydrogen fuel cells have inherent advantages over internal combustion engines. They are more efficient and capable of powering electric drive trains, but they also have lower signatures which is critical for EABO and any type of clandestine operation.

Solving EABO's Sustainment Challenge

The technology to use hydrogen on the battlefield already exists; all that was missing from the equation was a cheap and safe way to generate that hydrogen on the battlefield. The MIT process could be that "Holy Grail." Hydrogen produced through an aluminum-water reaction is not a panacea, but it could give commanders an alternative path to meeting their operational energy needs, one that is optimized for sustaining units in contested areas. We do not propose that hydrogen completely replace existing systems that rely on fossil fuels but that hydrogen-capable platforms be introduced where we need improved stealth and performance. In the near-term, hydrogen technology is best suited for light tactical vehicles, small unmanned aerial vehicles, atmospheric balloons, and electricity generation—importantly all capabilities that have already been developed and prototyped commercially or with federal funds.

There is also interest in hydrogen fuel for the Marine Corps in Congress.

During a recent hearing on the Navy and Marine Corps budget by the House Appropriations Committee, Representative Marcy Kaptur (D-Ohio) noted, "The Marine Corps has led in terms of energy innovation within the entire Department of the Defense" and asked the Commandant of the Marine Corps "what you might be able to bring to the table to propel to use [hydrogen] technology more quickly? ... What about hydrogen?"[31] Left without time to answer, the committee asked Berger to get back to them in writing.

EABO will require greater flexibility and innovation from Marines to support and sustain logistically than is possible using legacy fuel. Marines can use aluminum reactors on the battlefield to generate hydrogen to meet their operational energy needs and overcome the challenges of distributed and expeditionary logistics. For numerous reasons both tactical and operational, using aluminum as a fuel can provide a competitive advantage and could become exactly the kind of safe, cost-effective, and low-signature technology needed to operationalize EABO and prepare the Marine Corps for the future fight while keeping them concealed and operating free of a petroleum tether.

Notes

1. Gen David H. Berger, *Force Design 2030*, (Washington, DC: March 2020).

2. Ibid.

3. Gen David H. Berger, *Force Design 2030 Annual Update*, (Washington, DC: April 2021).

4. For examples see Walker Mills, Dylan Phillips-Levine, and Collin Fox, "Cocaine Logistics for the Marine Corps," *War on the Rocks*, (July 2020), available at https://warontherocks.com; and Michael Sweeney, "Sleeper Cell Logistics," *Marine Corps Gazette*, (January 2021), available at https://mca-marines.org.

5. Jonathan Slocum, "Characterization and Science of An Aluminum Fuel Treatment Process," (thesis, Massachusetts Institute of Technology, 2018).

6. John Lukacs, "Century of Replenishment at Sea," *Naval History Magazine*, (June 2018), available at https://www.usni.org.

7. James D. Hornfischer, *Neptune's Inferno: The U.S. Navy at Guadalcanal*, (New York, NY: Bantam, 2012).

8. Ibid.

9. Staff, "Oil and Japanese Strategy in the Solomons: A Postulate," *Combined Fleet*, (n.d.), available at http://www.combinedfleet.com.

10. Paul E. Mawn, "Oil and War," Defense.info, (October 2018), available at https://defense.info; and Hugh M. Cole, *The Ardennes: Battle of the Bulge*, (Washington, DC: Center for Military History, 1993).

11. Noah Sachtman, "Afghanistan's Oil Binge: 22 Gallons of Fuel Per Soldier Per Day," *Wired*, (November 2009), available at https://www.wired.com.

12. Steven M. Anderson, "Save Energy, Save Our Troops," *The New York Times*, (January 2021), available at https://www.nytimes.com.

13. Steve Hargreaves, "Ambushed Prompt Military to Cut Energy Use," *CNN Money*, (August 2011), available at https://money.cnn.com.

14. Department of Defense, *2016 Operational Energy Strategy*, (Washington, DC: 2016).

15. Neta C. Crawford, "Pentagon Fuel, Use, Climate Change and the Cost of War," (Providence, RI: Watson Institute, November 2019).

16. Peter Sicui, "The Really Boring Way China Would Try to Win a War Against America," *The National Interest*, (June 2020), available at https://nationalinterest.org.

17. "Characterization and Science of An Aluminum Fuel Treatment Process."

18. Erik R. Morgan, "Fuel Production Systems for Remote Areas Via an Aluminum Energy Vector," *Energy Fuels*, (July 2018), available at https://www.ll.mit.edu.

19. Staff, "Hydrogen Basics," U.S. Department of Energy (n.d.), available at https://afdc.energy.gov.

20. Patrick Tucker, "GM Has Built a Stealth Truck for the Army," *Defense One*, (October 2016), available at https://www.defenseone.com.

21. Erik Niiler, "The Pentagon is Pouring $328 Million Into High-Tech Laser Weapons," *Seeker*, (January 2017), available at https://www.seeker.com.

22. U.S. Department of Energy, *Report on Rare Earth Elements from Coal and Coal Byproducts*, (Washington, DC: January 2017).

23. Staff, "Gallium," U.S. Geological Survey, (January 2021), available at https://pubs.usgs.gov.

24. Staff, "Iridium," U.S. Geological Survey, (January 2021), available at https://pubs.usgs.gov.

25. Staff, "Hydrogen Compared to Other Fuels," Hydrogen Tools, Pacific Northwest National Laboratory, (n.d.), available at https://h2tools.org.

26. Samuel Taylor Moore, "When Sausages Blazed in the Sky," *Air Force Magazine*, (May 1963), available at https://www.airforcemag.com.

27. Staff, "Airbus Reveals New Zero-Emission Concept Aircraft," *Airbus*, (September 2020), available at https://www.airbus.com.

28. Jack Stewart, "Chevy's Making a Hydrogen-Powered Pickup for the US Army," *Wired*, (October 2016), available at https://www.wired.com.

29. Staff, "Yanmar Develops Hydrogen Fuel Cell System for Maritime Applications," Yanmar, (June 2020), available at https://www.yanmar.com.

30. Siddharth Vodnala, "U.S. Army Grant Supports Development of Hydrogen-powered Unmanned Aerial Vehicle," *WSU Insider*, (July 2019), available at https://news.wsu.edu; and Orlando Corpuz, "Clean Energy Partnership Demonstrates 'Alternative' Way to Move Aircraft," State of Hawai'i Department of Defense, (September 2019), available at http://dod.hawaii.gov.

31. Staff, "Fiscal Year 2022 United States Navy and Marine Corps Budget," House Committee on Appropriations, (April 2021), available at https://appropriations.house.gov.