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No. 216

**Transforming the Military:
The Energy Imperative**

Kelvin Wong Ka Weng

**S. Rajaratnam School of International Studies
Singapore**

7 December 2010

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Abstract

Contemporary war-fighting platforms on land, sea and air are continually evolving, becoming more agile and deadly. But despite their increasing performance, one factor remains unchanged, that of a near-total dependency on oil. Oil, processed into a range of refined liquid hydrocarbon fuels, is the primary source of mobility energy for almost every combat and utility platform in any modern military force. Extensive mechanisation of military forces since the First World War has resulted in a great thirst for fuel in contemporary battlefield operations, creating significant oil logistics burdens that degrade overall battlefield performance. This problem is compounded by the fact that the global oil market is inherently uncertain, as industrialised nations vie for a guaranteed supply of oil to satisfy their economic and military needs. As a result, oil stocks are often prone to price fluctuations, stressing defence budgets as well as affecting peacetime operations and readiness. Technological solutions—in the form of alternative energy and propulsion options—are emerging but a number of challenges will need to be addressed before such technologies can be fully exploited. These challenges range from the technical—such as the immaturity of emerging technologies and their unproven operational performance—to psychological barriers preventing military leadership from effecting change to established oil-based infrastructures.

Kelvin Wong is an Associate Research Fellow at the S. Rajaratnam School of international Studies (RSIS), Nanyang Technological University. He is attached to the Military Transformations Programme at the School's constituent unit, the Institute of Defence and Strategic Studies. He is a graduate of the Australian National University's Graduate Studies in Strategy & Defence (GSSD) Programme, where he obtained a Master's degree in Strategic Studies.

Transforming the Military: The Energy Imperative¹

Introduction

Contemporary war-fighting platforms on land, sea and air continually evolve with marked improvements in agility and lethality. Despite their increasing performance, however, one factor remains unchanged, that of near-total dependency on oil. Processed petroleum products such as liquid hydrocarbon fuels are primary sources of mobility energy for almost every combat and utility platform in any modern military force. The importance of oil as the military's lifeblood was observed when mechanical oil-powered combat platforms—such as tanks, ships and aircraft revolutionised warfare during the First World War. However, the subsequent intensification of oil dependence, brought about as military forces increasingly mechanised their forces, created its own set of issues.

As a consequence of this dependence, military organisations are frequently burdened by increased operational and training costs during peacetime, while the requirement for copious quantities of fuel to sustain military operations on the battlefield creates significant logistical issues which degrade performance. In the longer term, if the demand for oil grows beyond the ability of supply to sustain, the continued reliance of fossil fuels would cease to be a tenable exercise. However, recent literature argues that the confluence of new and evolving operational concepts, high fully-burdened fuel costs, fiscal constraints and emerging technologies will push the next energy transformation for military forces.

This paper will explore the possibility of an “energy transformation” for military forces. It aims to contribute to the existing literature by first providing the historical context of previous transition to new forms of war, examining the energy transformation from coal to oil in the early 1900s. Second, it will explore the intensification of oil dependence by

¹ The author would like to acknowledge the contributions of Dr. Stephan Fruehling, Lecturer at the Australian National University, for supervising the graduate thesis on which this paper is based upon. This paper has also benefited from the support of Professor Bernard Loo and Mr. Samuel Chan, respectively Coordinator and Associate Research Fellow of the Military Transformations Programme at RSIS, and from the valuable insights of Major Cameron Leckie of the Australian Defence Force.

military forces as a direct result of extensive mechanisation, and establish the fact that oil has been institutionalised to such a degree that combat performance is degraded. Third, it will provide a brief overview on a range of technological alternatives that are being developed to alleviate, and perhaps, entirely eliminate, military oil dependence in the future. Finally, it provides a study of the limitations and barriers that may impede the deployment of new technological solutions.

Mechanisation and oil dependence since the First World War

It was not until the early twentieth century, when the Industrial Revolution brought about the invention of the internal combustion engine, that oil became militarily important. Oil could fuel machines capable of enhancing the mobility and fighting capability of military forces on land, at sea, and with the advent of powered flight, in the air.² By the time of the First World War, the mechanisation of war had reached unprecedented heights, and so had the military's dependence on oil. On the battlefield, oil became an increasingly indispensable commodity, as critical as munitions, food and water. Although the size of mechanised forces were still modest compared to the long established horse-mounted cavalry and foot and rail-bound infantry, the conflict marked the first ever deployment of oil-powered aircraft and tanks, submarines, as well as massed motorised transport for troops and supplies.³

Oil subsequently became inextricably linked with war. Not only did industrialised nations need oil to wage war, countries increasingly went to war for oil itself. Access to oil and security of supply became important military considerations during the Second World War as military forces became almost entirely dependent on oil-fuelled machines.⁴ For example, at the end of World War I, the U.S. military had produced 799 tanks, but only 64 were actually delivered to the front prior to the Armistice. In contrast, during World War II, the United States would construct a total of 116,457 combat vehicles including

² Tom Cutler, *The Military Demand for Oil*, London: Petroleum Economist, 1989.

³ John W. Frey, "Petroleum Utilisation in Peacetime and in Wartime", *Annals of the Association of American Geographers*, Vol. 31, No. 2, 1941, p. 113–118.

⁴ Cutler 1989, p. 1.

86,333 tanks. Similarly, during World War I, the U.S. military only had 4,100 combat aircraft and 9,500 trainers. During World War II, almost 300,000 aircraft had been constructed.⁵

The importance of oil to military forces has only increased after the Second World War, with the emphasis on the two main physical characteristics of modern warfare: extensive mechanisation and high mobility. Mechanisation inevitably leads to an increased demand for energy in the production and use of oil-powered combat platforms, and high mobility involves the rapid deployment of units worldwide, thus increasing the demand for oil.⁶ As a consequence, energy demands for today's military forces are even greater and more complex than ever. The liberation of Kuwait during the Gulf War in 1991 is an example of this new military paradigm. The war was defined by a series of highly mobile land and airborne attacks across a great expanse of land, requiring a great number of combat vehicles and aircraft, as well as their attendant support vehicles and the requisite transports needed to send them to the operational theatre. Even without taking into account the oil consumption of the rest of the coalition forces, the U.S. forces in the Gulf War consumed an average of approximately 450,000 barrels of oil daily—more than four times as much as the entire two million strong Allied forces that liberated Europe during World War II.⁷

Fuel requirements have yet again increased in the second Persian Gulf War from 2003 onwards. During Operation Iraqi Freedom, it is estimated that the coalition forces used over 4 million gallons of fuel per day, with the lion's share used by the U.S. Army.⁸ It is also worth noting that a rough comparison of the 2004 fuel requirements for the 150,000 coalition soldiers in Iraq with one million Allied soldiers in Germany during the final

⁵ Milton R. Copulos, "America's Achilles Heel: The Hidden Cost of Oil", *The National Defence Council Foundation*, 2003, http://ndcf.dyndns.org/ndcf/energy/NDCF_Hidden_Costs_of_Imported_Oil.pdf (accessed 9 August 2008), p. 15.

⁶ Stockholm International Peace Research Institute, p. 57.

⁷ Copulos, p. 17.

⁸ Kip P. Nygren, Darrell D. Massie and Paul J. Kern, *Army Energy Strategy for the End of Cheap Oil*, p. 4, New York: West Point, United States Military Academy, 2006.

phase of World War II suggests that contemporary soldiers require about 16 times the fuel used per soldier in 1944.⁹

The dragon's tail: Logistical issues on the battlefield

Problems associated with oil dependence starkly manifest themselves in the form of logistical burdens during military operations. Deployed forces are particularly vulnerable to fuel supply disruptions because of the uncertainties and dangers inherent on the battlefield, and ensuring a steady supply of fuel to enable combat units to execute their objectives can pose significant problems, particularly when dealing with a capable adversary who exploits this vulnerable centre of gravity. It must be noted that the logistics challenge is not a new phenomenon. Military organisations have grappled with supply issues since the dawn of mass, organised warfare. Even if the military did not need fuel for its operations, supply lines will still be required to deliver other necessities such as ammunition, food and water. The crux of the issue is that contemporary military forces require vast quantities of fuel in order to operate their fleets of combat platforms.¹⁰

Ongoing operations in Afghanistan demonstrate the challenges of supplying fuel to the forward-deployed fighting units and bases. The unavailability of petroleum products in-country meant that fuel supplies had to be transported by long truck convoys from foreign soil while frequently being exposed to insurgent and IED attacks, as well as bad weather and treacherous terrain. In June 2008, a combination of these factors resulted in the loss of 44 fuel tankers and 220,000 gallons of fuel [source]. North Atlantic Treaty Organisation (NATO) supply operations to its 152,000 strong forces in Afghanistan are now under pressure as insurgents conduct what seems to be a consistent effort to disrupt logistics operations to Afghanistan. In October 2010, insurgents destroyed a combined total of over 30 oil tankers loaded with NATO fuel in south-east Afghanistan and north-

⁹ Ibid. p. 4.

¹⁰ Centre for Naval Analyses Military Analysis Board, *Powering America's Defence: Energy and the Risks to National Security*, May 2009.

west Pakistan, following earlier attacks on fuel transports in Islamabad, Baluchistan and southern Pakistan.¹¹

As a further consequence, battlefield fuel deliveries can incur price penalties of tens, and sometimes, hundreds of times the cost of fuel itself. For example, the JASON Defence Advisory Group notes that the cost of delivering fuel to land forces in contemporary operations could range from US\$100-US\$600 per gallon, depending on the distance that the fuel needs to be transported as well as the terrain and the size of the security forces escorting the fuel delivery vehicles.¹² The reason for this issue is as simple as it is surprising—the ubiquitous fuel and supply trucks, the workhorses in any logistics infrastructure, are the top battlefield fuel users because these logistics vehicles require tremendous amounts of fuel in order to deliver fuel and supplies to the combat units in battle.

Oil price fluctuations and its effects on military operations

Uncertainties surrounding the global oil demand and supply and price instabilities in the past few years have caused great stress to defence budgets around the world. This is unsurprising, since military forces are often the single largest operator of aircraft, ships and vehicles in many nations. In theory, military forces are assured of priority access to the petroleum needed for its missions. As defence analyst Michael O’Hanlon notes, the military is the user that is at the least risk of “having its fuel supply cut off or having economics really crimp its ability to fill up the gas tank” because it is the ultimate guarantor of the nation’s sovereignty in wartime.¹³

¹¹ See Reuters, “NATO Tankers Torched in New Attack”, *New York Times*, 8 October 2010, <http://www.nytimes.com/2010/10/09/world/asia/09quetta.html> (accessed 10 October 2010) and Associated Press, “Afghanistan: Taliban Attack NATO Fuel Convoy, Killing 3”, *New York Times*, 22 October 2010, <http://www.nytimes.com/2010/10/23/world/asia/23briefs-ATTACK.html> (accessed 24 October 2010).

¹² JASON Defence Advisory Group, *Reducing DoD Fossil-Fuel Dependence*, Mclean VA: The MITRE Corporation, 2006, pp. 30–31.

¹³ Jeff Brady, “Military’s Oil Needs Not Deterred by Price Spike”, *National Public Radio*, 2007, Morning Edition, <http://www.npr.org/templates/story/story.php?storyId=16281892> (accessed 10 August 2008).

In peacetime, however, uncertainties about the length of interruptions and political reluctance to transfer scarce petroleum supplies from the civilian sector are likely to result in problems of reduced fuel availability with potentially serious impact on military operations.¹⁴ For example, non-critical and training missions may be particularly vulnerable to intermittent fuel shortages and higher prices as a result of severe market disruptions. Indeed, record oil prices in 2007 and 2008 demonstrated the aforementioned consequences of oil dependence in peacetime for some military forces.

In the Asia Pacific region, the Australian Department of Defence (DoD) reviewed its peacetime operations and implemented a number of energy-saving initiatives to reduce an oil expenditure that reached A\$420 million during Fiscal Year (FY) 2006–2007. The impact of each 10 per cent increase in the cost of oil results in an additional cost of about A\$42 million, implying that the 90 per cent rise in the price of oil since the end of FY 2006–2007 would have cost the DoD an additional A\$378 million in excess of regular spending.¹⁵

The South Korean military attempted to reduce fuel expenditures by more than US\$50 million in 2008 by cutting training and non-essential operations, raising concerns about its readiness.¹⁶ It was not the first time these measures were required—concerns had already been raised earlier in 2005, when cost-cutting measures due to unexpected fuel price hikes then had threatened to reduce naval border patrols, as well as forced a decline in naval, army and air force training.¹⁷

¹⁴ Desmond P. Wilson and Thomas C. O'Neill, *Long-Range Military Implications of Petroleum Availability for Navy Planning Study*, Centre for Naval Analyses, 1981.

¹⁵ See Jon Grevatt, "Australian Forces Must Consider Alternative Fuel Sources, Minister Warns", *Jane's Defence Industry*, 25 July 2008 and Jon Grevatt, "Oil Costs Fuel Australian Energy-Saving Initiative", *Jane's Defence Weekly*, 20 November 2009.

¹⁶ Lee Jiyeon, "Jon Herskovitz and Angela Moon, "S. Korea Military "Trains" Against Oil Price Surge", 24 March 2008, *Reuters*, <http://www.reuters.com/article/idUSSEO29100720080324> (accessed 27 August 2008).

¹⁷ See Chosun Ilbo, "Military Steps Up Energy-Saving Measures", *The Chosun Ilbo*, English News Section, 5 October 2005 and Associated Press, "South Korea to Scale Back Military Drills to Save Energy", *China Post*, 8 July 2008, <http://www.chinapost.com.tw/asia/korea/2008/07/08/164505/South-Korea.htm> (accessed 29 August 2008).

Similarly, rising oil prices threatened the Japanese Self Defence Force's (JSDF) readiness during this period. The JSDF was forced to reduce naval and air force training exercises and ordered its personnel to operate vehicles at slower speeds to conserve fuel. Despite these measures, its FY 2008 fuel allowance is expected to run dry well ahead of next year's budget. As a result, the defence ministry will seek a 2.2 per cent increase in its budget to US\$44.4 billion for FY 2009, more than half of which is attributed to cover increased fuel costs.¹⁸

However, these examples pale in comparison to the issues faced by the world's largest and most technologically preponderant military, the U.S. armed forces. The tremendous U.S. logistical capabilities allow its armed forces to be deployed around the world for both peacekeeping and combat operations. However, this capability comes at a high price—a great demand for energy¹⁹ and the resultant financial costs. The U.S. Government Accountability Office (GAO) noted that despite the U.S. military consuming less fuel in FY 2006 than FY 2005—4.6 billion gallons as opposed to 5.17 billion gallons—fuel expenditures increased nevertheless. In FY 2005, the DoD spent US\$7.95 billion for fuel, while in FY 2006 it spent US\$10.06 billion, a 26.5 per cent increase in fuel spending in spite of the fuel savings. The DoD estimates that for every US\$10 increase in the price per barrel of oil, its operating cost increase by approximately US\$1.3 billion.²⁰

Land warfare overview and technological options

Land combat platforms are required to have high mobility to operate in difficult terrain with superior high-speed characteristics. At the same time, high reliability, crew protection and offensive capabilities are also fundamental requirements of all platforms used in combat, increasing weight and incurring further energy penalties. It is, therefore,

¹⁸ Agence France-Presse, "Japanese Military Seeks Budget Increase", *Defence News*, 29 August 2008, <http://www.defensenews.com/story.php?i=3698911&c=ASI&s=TOP> (accessed 29 August 2008).

¹⁹ Scott C. Buchanan, "Energy and Force Transformation", *Joint Force Quarterly*, No. 42, 2006.

²⁰ United States Government Accountability Office, *Defence Management: Overarching Framework Needed to Guide and Oversee Energy Reduction Efforts for Military Operations*, Washington, DC: GAO, 2008.

not surprising that these conflicting requirements are difficult to satisfy in practice and the result is that military combat platforms are often very fuel-inefficient. The greatest challenge, therefore, is for land platform designers to reduce fuel consumption without sacrificing firepower, performance and protection.

First, weight reduction is the most basic way to increase fuel efficiency for land platforms. The fuel consumption characteristic of a land platform is directly proportional to the weight of the vehicle itself as a result of the friction losses from contact with the ground. One study noted that a platform could, for example, potentially double its operating range if its weight could be reduced by half.²¹ The greatest potential savings in platform weight can be achieved through the use of modern materials and design, such as employing lightweight, high-strength material as carbon-reinforced composites and space-frame construction principles.²²

Second, alternative propulsion technologies may present some viable options. The Hybrid Electric Vehicle (HEV) concept has demonstrated great potential for reducing oil dependency on the battlefield. While hybrid propulsion systems promise significant improvements in operational fuel economy, they also provide a ready source of electrical power for the increasingly wide range of sensors and next-generation armaments. At the same time, they offer other tactical benefits, such as reduced signatures, stealth, greater vehicle design flexibility, and even enhanced diagnostics and prognostics.²³

Contemporary HEVs are placed into two categories, parallel and series hybrids. The parallel hybrid comprises an internal combustion engine and an electric motor mechanically connected to the wheels, like the conventional automobile. The difference is that the electric motor provides additional power to assist the engine—the electric motor operates at low speeds and when the vehicle is stationary, while the combustion engine takes over at higher speeds. The series hybrid uses an internal combustion engine

²¹ JASON, p. 43.

²² Defence Science Board 2008, p. 41.

²³ North Atlantic Treaty Organisation Research and Technology Organisation (NATO RTO), “Electric/Hybrid Electric Drive Vehicles for Military Applications”, *Military Technology*, 31:9, pp. 132–144, 2007.

to run an electric generator, which produces the electrical power to provide locomotion via a number of electric motors connected either to the wheel axles or the wheel hubs. Despite their design variations, both versions are more fuel-efficient than conventional vehicles dependent on only internal combustion engines.²⁴

Even though hybrid-drive technology is yet to fully mature, it nevertheless is already a very promising option for military forces. For example, a recent study on the 1st Marine Corps Expeditionary Force (1 MEF) fuel usage patterns in Iraq found that even with a modest 20 per cent fuel savings possible with the current state of the art in hybrid-drive technology, 1 MEF would have been relying on 56,000 gallons less fuel per day, an equivalent of eliminating the need for 11 fuel truck resupply loads per day. The study further notes that the cascading effects of a reduced fuel logistics train would have yielded even more tactical benefits, such as the decreased vulnerability of the force to attack at fuelling points, fewer truck and helicopter fuel logistics sorties.²⁵

These enhancements are not mutually exclusive. Indeed, a multi-faceted approach combining a hybrid-electric drive system with an ultra-light and low-drag platform achieved a remarkable 82 per cent fuel savings in a civilian sport-utility vehicle concept car, thus improving its acceleration performance, safety and load-capacity attributes. Comparable advances appear feasible for light military platforms, such as front line reconnaissance vehicles.²⁶

Naval warfare: potential technological options

Naval warfare has a long and storied history. Given that three-quarters of the Earth's surface is marine, and that the success of many nation states is dependent on unfettered access to maritime energy and trade routes, it is hardly surprising that great strategic

²⁴ Michael Dumiak, "Going Green: Militaries Pursue Hybrid Vehicles to Replace Gas-Guzzling Fleets", *Defence Technology International*, pp. 14–18, May-June 2006.

²⁵ Naval Research Advisory Committee, *Future Fuels*, Washington: Office of the Assistant Secretary of the Navy, 2006, p. 41.

²⁶ Defence Science Board 2001, p.49.

significance has been attached to control of the seas.²⁷ Naval combatants must be able to fight in multiple dimensions—above, on and under water—as well as engage targets on land in the littorals, and frequently have to operate far from home waters while remaining ready to switch between peace support and high intensity combat operations very quickly. This creates a set of demands that places a huge premium on flexibility of naval vessels.

Contemporary naval surface vessels are commonly powered by a combination of diesel and gas turbine engines, because such systems offer excellent fuel economy at low to medium speeds and offer tremendous power in a compact and light package. However, because contemporary ship designs utilise propulsion systems that are directly coupled to the prime mover, up to 90 per cent of a typical naval platform's available power is locked into its propulsion system. The present arrangement limits the power available for other functions of the ship, such as weapon, sensor and auxiliary support systems and thus requires additional generators which reduce platform design flexibility, adds complexity and limits future upgradability.²⁸

Although fuel supply is generally less of a problem for naval vessels than for land or air platforms,²⁹ naval platforms can nevertheless increase their war-fighting capabilities through reduced and more efficient use of fuel. For example, reducing energy use in naval platforms can reduce fuel costs and increase cruising range. Increasing cruising range can improve operational flexibility by increasing the time between refuelling and the distance that the ship can operate away from its next refuelling point. Furthermore, this has also the potential to reduce hot exhaust emissions and thus reduce its infrared signature.³⁰

²⁷ Timothy Garden, *The Technology Trap: Science and the Military*, UK: Brassey's Defence Publishers, 1989, p. 7.

²⁸ Paul Johnstone, "Electro Magnetic Propulsion for Warships", *Defence Today*, June Issue, 2008, p. 22.

²⁹ Defence Science Board 2008, p. 47.

³⁰ Ronald O' Rourke, "Navy Ship Propulsion Technologies: Options for Reducing Oil Use", *CRS Report for Congress*, Congressional Research Service, 2006, <http://www.fas.org/sgp/crs/weapons/RL33360.pdf> 2006 (accessed 9 August 2008), p. 2.

First, hull design improvements on platforms can lead to substantial fuel savings and are easily retrofitted onto existing platforms. These modifications include fitting platforms with a “bulbous bow”, installing a stern flap, or applying special coatings to the hull or propellers. Installing a bulbous bow can reduce a ship’s wave-making resistance and thereby increase its fuel efficiency. A study by the U.S. Navy estimated that fitting a bow bulb onto a DDG-51 Arleigh Burke-class destroyer could reduce its fuel consumption by almost four per cent, saving up to 2,400 barrels of fuel per year.³¹

A stern flap is a small plate that extends the bottom surface of a ship’s hull. It reduces the ship’s hydrodynamic resistance and increases fuel efficiency by varying amounts, depending on the ship’s size and design.³² Preliminary tests on destroyer-sized vessels by the U.S. Navy demonstrated an annual fuel reduction of 3,800 to 4,700 barrels, or about six per cent to seven per cent, per vessel annually. It is also worth noting that the aforementioned design efficiencies are cumulative—a 15 per cent increase in fuel efficiency was recorded on surface platforms which utilised both bulbous bows and stern flap modifications.³³

Second, alternative propulsion options are available for naval surface platforms in the form of hybrid-electric drive systems. Compared to the traditional mechanical-drive propulsion system with two separate sets of turbines—one for propulsion, the other for generating electricity to power the weapon, sensor and auxiliary systems—on most current surface vessels, an integrated electric-drive propulsion system can reduce fuel consumption by operating the single combined set of turbines to be run more often at their most fuel-efficient settings.³⁴ The hybrid-electric concept is similar to equivalent systems for land platforms, where the primary engine generates electrical power for vehicle subsystems and electric motors that provide locomotion. A non-combat surface vessel equipped with an integrated electric-drive system may consume 10 per cent to 25 per cent less fuel than a ship with a conventional mechanical-drive system. For combat

³¹ O’Rourke, p. 5.

³² Defence Science Board 2001, p. 54.

³³ O’Rourke, p. 7.

³⁴ Johnstone, p. 23.

platforms, fuel consumption savings of 15 to 19 per cent is possible. In addition, electric drive systems enable the use of innovative propeller configurations that can reduce ship fuel consumption by up to an additional 15 per cent due to their improved hydrodynamic efficiency.³⁵

The electric-drive propulsion system is also making inroads in the British and French naval forces. The Royal Navy's Type-45 *Daring* class destroyer, equipped with a electric drive system, is capable of sailing 7,000 nautical miles at a speed of 18 knots without refuelling. Its predecessor, the Type-42 class destroyer with a traditional mechanical drive, could only manage 4,000 nautical miles at the same speed.³⁶ The *Queen-Elizabeth* class aircraft carriers currently under construction will feature a similar integrated electric-drive propulsion system.³⁷ The French *Mistral*-class amphibious assault and command ships are also equipped with electric propulsion systems.³⁸

Alternative energy sources based on hydrogen fuel cell systems are another option for reducing oil dependency for surface platforms. For example, the U.S. Navy found that naval gas turbine engines typically operate at 16 to 18 per cent efficiency, because naval platforms usually sail at low to medium speeds that do not require peak use of the power plant. However, the fuel cell system that the U.S. Office of Naval Research (ONR) is developing will be capable of achieving up 52 per cent efficiency. As a result of this improvement, the Navy notes that a DDG-51 *Arleigh Burke*-class destroyer's gas turbine generator operating for 3,000 hours would consume 641,465 gallons of fuel while a fuel cell alternative would consume just 214,315 gallons, or 33 per cent as much as the conventional gas turbine if operated for the same period. The Navy has estimated, using past fuel prices, that shifting to fuel cell technology could save more than US\$1 million per ship per year in operating fuel costs. Other potential advantages of fuel cell

³⁵ O'Rourke, p. 9.

³⁶ Anthony J. Watts (Ed.), *Jane's Warship Recognition Guide*. London: HarperCollins Publishers, 2006, p. 138.

³⁷ United Kingdom Ministry of Defence, "Aircraft Carrier Alliance: Delivering the Nation's Flagships", July 2008, http://www.royal-navy.mod.uk/upload/pdf/CVF_design_innovations_-_3_July.pdf (accessed 8 August 2008).

³⁸ Watts, p. 335.

technology include reduced maintenance costs, greater stealth through reduced emissions and acoustic signature, and finally, greater ship design flexibility.³⁹

Air warfare overview and potential technological options

Contemporary military air combat platforms are designed to maximise performance through the combination of jet turbine propulsion which generate high thrust ratings, and aerodynamically optimised, lightweight airframe designs.⁴⁰ However, the penalty associated with the emphasis on performance is great fuel consumption. As a result, propulsion systems and fuel payload typically account for 40 per cent to 60 per cent of gross takeoff weight of the aircraft itself, and the performance of the propulsion system has an enormous effect on flying performance.⁴¹

Unlike land and naval platforms, alternative propulsion technologies directly applicable to air combat platforms are non-existent today, chiefly due to the fact that the jet turbine engine, which powers many of today's air combat platforms, remains vastly superior to other forms of propulsion systems in all performance characteristics. The power-to-weight ratio of jet turbines, for example, is three to six times that of aircraft piston engines.⁴²

Despite the unavailability of alternative propulsion options for air combat platforms, there are still a number of technological options that may assist in reducing oil dependency. First, air platform design efficiencies appear to provide the most fundamental step to achieving improved fuel-economy. Second, jet turbine design improvements can potentially reduce fuel consumption while providing superior performance characteristics. Third, alternative fuels are being investigated by the U.S. Air Force (USAF), and have already been tested on a number of front-line combat

³⁹ O'Rourke, p. 11.

⁴⁰ Wayne Pearson, *The More Electric/ All Electric Aircraft – A Military Fast Jet Perspective*, London: Institution of Electrical Engineers, 1998, p. 1.

⁴¹ National Research Council, *Uninhibited Air Vehicles: Enabling Science for Military Systems*, Washington, DC: National Academy Press, 2000, p. 6.

⁴² *Ibid*, p. 60.

platforms. Finally, unmanned air platform systems offer the potential to drastically reduce oil dependency as a result of their pilotless designs. This section explores some of these options.

For military aircraft, design efficiency appears to be the most promising method to reduce oil dependence for air forces. Air platform design efficiencies can be pursued in the areas of structural design and configurations, as well as weight reduction. Advances in materials and design processes will enable the design of stronger, lighter aircraft with simpler, unified structures that are easier to manufacture. Composite materials, in particular, will allow bonded joints and reinforcement technologies for complex loads. Lighter weight structures based on advanced materials and computer-aided designs enable significant fuel savings without compromising performance or structural integrity. Such fuel savings extend to a number of air force platforms such as combat, transport and tanker aircraft, and potentially even helicopters. Platform configurations can be modified to reduce aerodynamic drag from skin friction. Further advances in the use of composites in platforms are possible, and the U.S. Air Force Research Laboratory (AFRL) is pursuing research into new materials that can even “morph and repair” themselves as well as dissipate heat, thus increasing aircraft flight performance. Furthermore, complex hybrid materials based on nanotechnology in development promise further weight savings, improved durability and increased heat resistance.⁴³

The potential energy savings and the resulting performance enhancement from increased usage of advanced materials for air force platforms do appear to be significant. According to the AFRL, these new configurations can be up to 40 per cent more fuel efficient than conventional designs. Savings of such magnitude will significantly reduce aircraft fuel consumption, greatly enhancing mission performance. For example, emerging commercial aircraft, such as the new Boeing 787 “Dreamliner”, features lightweight composite materials such as carbon laminate, carbon sandwich, fibreglass and aluminium, which are estimated to be the most important single factor in achieving fuel

⁴³ Gregory J. Lengyel, *Department of Defence Energy Strategy: Teaching an Old Dog New Tricks*, Washington, D.C.: The Brookings Institution, 2007, pp. 53–54.

savings of 20 per cent compared to a conventionally built passenger aircraft of similar shape and size. Composites such as these also resist fatigue and corrosion, reduce maintenance and curb emissions.⁴⁴

In the longer term, the culmination of these design and material improvements could result in the realisation of radical aircraft concepts such as the Blended-Wing Body (BWB) aircraft, which could fundamentally alter the design of heavy platforms such as bombers and transports. The DSB noted that the BWB concept could offer up to two times the gain in range and payload over conventional large aircraft designs—for example, a mission requiring a B-52 Stratofortress bomber and nine KC-10 Extender fuel tankers might be performed instead by a much smaller strike package of just one BWB bomber and one BWB tanker. The combination of efficiency improvements to both the combat and support platforms demonstrates how enhancement of fuel efficiency can translate into enormous potential for improved operational effectiveness.⁴⁵

Second, efficiency improvements to propulsion systems—predominantly jet turbine engines—can significantly contribute to reducing oil consumption. The overall efficiency of jet propulsion systems defines how much of the available fuel energy is converted to useful thrust, after taking into account the inherent losses in converting mechanical power within the engine itself to actual thrust output. Present-day gas turbine engines can convert only about 40 per cent of the available energy in fuel into thrust, while modern high-bypass turbine engines for transport aircraft are about 30 per cent efficient. However, gas turbines on air combat platforms such as fighters and bombers typically convert 20 to 25 per cent to useful thrust. Thus, there are still substantial performance improvements that could be extracted from these engines.⁴⁶

At the forefront of engine efficiency programmes is the Versatile, Affordable Advanced Turbine Engines (VAATE) initiative. VAATE is a joint government and industry cooperative effort comprising the U.S. DoD, the National Aeronautics and Space

⁴⁴ Defence Science Board 2008, pp. 42–43.

⁴⁵ Ibid. p. 39.

⁴⁶ Lengyel, p. 53.

Administration (NASA), the Department of Energy (DoE), as well as six major engine companies and three airframe manufacturers.⁴⁷ The goal of this ambitious programme is to improve air platform turbine engine capabilities beyond those of a year 2000 baseline engine while reducing engine cost, fuel consumption and maintenance requirements. Under the aegis of VAATE are two key technology initiatives, the Highly Efficient Embedded Turbine Engine (HEETE) and the Adaptive Versatile Engine Technology (ADVENT), which investigates different aspects of engine design and construction. HEETE initiatives are expected to produce engines that are lighter and generate more power, potentially increasing thrust-to-weight ratio by 60 per cent when compared to year 2000 baseline engines. At the same time, HEETE expects to improve engine fuel efficiency by over 25 per cent.⁴⁸ The other initiative, ADVENT, aims to develop innovative methods that will allow engines to adjust airflow characteristics in flight to suit conditions, optimising fuel efficiency as well as reducing aerodynamic drag. It is expected that ADVENT will improve air platform performance by up to 35 per cent in subsonic flight and 14 per cent in supersonic flight, when compared to year 2000 baseline engines.⁴⁹

Third, synthetic fuels may provide viable substitutes for the oil-based kerosene fuels that air forces utilise today for mobility energy. Synthetic fuel may be produced by a process known as the Fischer-Tropsch (FT) synthesis, developed in Germany before the outbreak of the Second World War. FT synthetic fuel, produced from coal, sustained much of the German combat forces during the conflict due to the nation's lack of oil resources.⁵⁰ Further improved since WWII, the FT process converts feedstock such as coal, tar sands and shale oil into useful liquid hydrocarbon synthetic fuels for internal combustion and gas turbine engines.⁵¹ Other innovative ideas for oil-substitution have been pursued as well, such as producing fuel from biomass waste materials such as food scraps, paper and even algae. Two civilian firms under the aegis of the U.S. Tank-Automotive Research,

⁴⁷ Ibid. p. 54.

⁴⁸ Defence Science Board 2008, p. 42.

⁴⁹ Ibid. p. 43.

⁵⁰ Goralski and Freeburg.

⁵¹ See Michael J. Hornitschek, *War Without Oil: A Catalyst for True Transformation*, Occasional Paper No. 56, Centre for Strategy and Technology, Alabama: Air University, 2006 and Naval Research Advisory Committee, *Future Fuels*, Washington: Office of the Assistant Secretary of the Navy, 2006.

Development and Engineering Centre (TARDEC), are developing portable generators which can convert any carbon-containing material into a mixture of carbon monoxide and hydrogen gas, which is then synthesised into useful liquid hydrocarbon fuel.⁵²

Recent flight-testing by the U.S. Air Force (USAF) using a blend of traditional jet fuel and coal-based synthetic fuel has demonstrated encouraging results. The USAF's F-15E Strike Eagle became the first fighter platform in the world to fly on a synthetic fuel blend of 50 per cent jet fuel and 50 per cent synthetic fuel on 19 August 2008. The F-15E jet reached an altitude of 50,000 feet and attained a top speed of Mach 2, performing at an operational envelope far surpassing the previous blended-fuel tests on the B-1 and B-52 bombers. Just over a week later, the USAF successfully tested the advanced F-22 Raptor on the same fuel blend.⁵³ International interest in synthetic fuel technology for military jets seems to be growing. It was reported that air force leaders from other nations, such as Britain and France, have commenced discussion with the USAF on the possibility of using synthetic fuel on their own air combat platforms, such as the French Dassault Rafale multi-purpose fighter aircraft.⁵⁴

Finally, deploying unmanned aerial vehicles (UAV) can offer substantial fuel savings for air forces. UAVs can significantly reduce energy use in the battle space while providing increased persistence, intelligence, survivability and lethality. Both remote controlled and autonomous UAVs can be made lighter, more fuel efficient and operationally more effective than their manned counterparts through significant weight reductions as a result of their smaller overall size and the removal of the aircrew and the human support systems. In addition, the removal of the aircrew reduces not only the associated aircraft weight but also the fuel intensive infrastructure required to train and maintain pilot

⁵² Prachi Patel-Predd, "Fuel from Waste: A Portable System Converts Biowaste into Jet Fuel for the Military", *MIT Technology Review*, 21 December 2007, <http://www.technologyreview.com/Energy/1974/?a=f> (accessed 8 August 2008).

⁵³ Caitlin Harrington, "F-15E Flies on Synthetic Fuel Blend", *Jane's Defence Weekly*, 21 August 2008.

⁵⁴ Caitlin Harrington, "International Interest Grows in U.S.- led Alternative Fuel Push", *Jane's Defence Weekly*, 24 April 2008.

proficiency, resulting in additional energy savings—a classic example of the multiplier effect.⁵⁵

In situations where UAVs can adequately substitute for manned platforms, they offer significant potential in terms of persistence and endurance. For example, the latest generation of reconnaissance UAVs being designed by the AFRL could save as much as 97 per cent of the fuel used by the three manned airborne-surveillance platforms it could replace—the Joint Surveillance and Target Attack Radar System (JSTARS), Airborne Warning and Control System (AWACS), and Rivet Joint surveillance aircraft. According to the DSB study, one UAV sortie could provide the same level of reconnaissance coverage of nine manned-aircraft sorties, and the nine tanker sorties required to sustain the manned platforms.⁵⁶

Limitations of technological alternatives

For land forces, hybrid-electric drives may hold great promise and are already being deployed by some military forces, but the technology is far from perfect. The vulnerability of electrical systems to extreme conditions frequently encountered on the battlefield and the issue of energy storage present some of the greatest technical hurdles for HEVs. The onboard electronic control systems for current hybrid-electric drives are based on silicon conductors that are susceptible to heat damage. Therefore, powerful cooling systems are required to keep temperatures low, especially when the platform is deployed in desert or tropical environments. However, these cooling systems are often large, adding unnecessary bulk as well as requiring power better applied elsewhere. Energy storage for the electrical power generated by the prime mover is another issue. Current battery options remain limited—lithium-ion batteries offer good capacity and are

⁵⁵ Thomas D. Crowley, Tanya D. Corrie, David B. Diamond, Stuart D. Funk, Wilhelm A. Hansen, Andrea D. Stenhoff, and Daniel C. Swift, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy*, McLean VA: LMI Government Consulting, 2007, p. E-15.

⁵⁶ Defence Science Board 2008, p. 48.

lightweight, but remain prohibitively expensive, while the cheaper conventional lead-acid batteries are heavy.⁵⁷

Furthermore, the performance demands of combat platforms are yet to be satisfactorily met by the current crop of alternative fuels. For example, while hydrogen is touted by some observers as the ultimate long-term solution for the military's energy needs,⁵⁸ several technical challenges prevent hydrogen fuel from being a direct replacement for oil just yet. The storage of hydrogen presents the first and perhaps most fundamental challenge. Liquid hydrogen has to be cryogenically stored at -253 degrees Celsius in order for it to exist in a liquid form, an arrangement that consumes energy equivalent to 30 per cent of the energy being stored. Even when stored in its typical gaseous state, pressurised tanks are required, which impose a weight penalty of up to 20 times more than the amount of hydrogen being stored—limiting how much fuel can be practically carried on platforms.⁵⁹ As field testing has discovered, hydrogen-powered fuel-cell systems on tactical platforms yielded less than half the mileage of their equivalent gasoline-based counterparts, a direct consequence of the weight penalty incurred from hydrogen storage. It remains uncertain whether a practical hydrogen storage system can be designed to store enough fuel for extended operational distances.⁶⁰

The limitations of alternative fuel technology also extend to air force platforms. While the USAF has successfully flight-tested a blend of FT-synthetic fuel with conventional jet fuel on a number of front-line combat and transport platforms, the long-term effects of introducing the new type of fuel on airframe longevity is uncertain. New types of fuel need to be evaluated over time in actual flight conditions, as there may be a risk of the airframe seals deteriorating over a period of several months.⁶¹ The high cost of synthesised fuel may prohibit it from widespread use despite strong interest by the

⁵⁷ Dumiak 2006, p. 18.

⁵⁸ See Hornitschek 2006 and Peter Kushnir, "Hydrogen As an Alternative Fuel", *Army Logistician*, 32:3, pp.10–12, 2000.

⁵⁹ Naval Research Advisory Committee 2006, p. 15.

⁶⁰ Ramon Lopez, "Energised: Search for Alternative Energy Drives Fuel-Cell Research", *Defence Technology International*, May-June 2006, p. 24.

⁶¹ Grace Jean, "Research Aims for 'Game-Changing' Technologies", *National Defence*, 91:636, 2006, p. 43.

USAF—the cost of a gallon of FT-synthetic fuel costs approximately US\$18 a gallon, compared to about US\$2.40 per gallon of conventional jet fuel.⁶²

Moreover, environmental damage issues stemming from the production process of FT synthetic fuels remain unresolved. The DSB noted in its latest report in 2008 that the viability of the FT-based synthetic fuel technology is questionable. According to the report, capital and production costs are high, putting investments at long-term risks. The environmental control technologies needed to allow the plants to operate over the long term have only been demonstrated on a limited scale and their costs are highly uncertain. Environmental impact from the FT-synthesis process is significant, demanding a large supply of water and producing large amounts of contaminated wastewater that must be treated. As a result, the DSB concluded that:

*These large expenditures could be used for more productive contributions to DoD's most pressing energy challenges, rather than demonstrating synthetic fuel technologies that do not appear to have a viable market future or contribute to reducing battle space fuel demand.*⁶³

Considering the aforementioned findings—the high costs of synthetic fuel, their unproven effects on aircraft longevity, and the significant challenges that remain in their production process-- it is difficult to see how synthetic fuels could be (as touted in a range of defence publications) the “next big thing” in air mobility.

The dominance of established infrastructure and technologies

The dominance of the ubiquitous internal combustion engine and the jet turbine for mobility, deployed for the first time in the First and Second World Wars respectively, and the slow pace of energy transitions are perhaps the greatest challenges yet to be

⁶² Masood Farivar, “Focus on Energy: U.S. Military Targets Fuel Use – Hurricanes, Rising Costs Prompt Effort to Seek Alternatives”, *The Wall Street Journal Asia*, 9 January 2007.

⁶³ Defence Science Board, 2008, p. 51.

surmounted if oil dependence for the military is to be eliminated. As scientist Vaclav Smil notes:

Technical progress has two distinct modes as gradual, ever-working improvements of established techniques that boost efficiencies, increase reliability and lower costs are repeatedly (but irregularly, unpredictably and often inexplicably) interspersed with abrupt revolutionary development, periods of astonishing progress that overturn old paradigms and establish new ways that may last not only for generations but for centuries.⁶⁴

According to Smil, the greatest technical breakthrough in modern history took place between 1867 and 1914 when the synergy of electricity, steam and water turbines, internal combustion engines, inexpensive steel, aluminium, explosives and electronic components laid the lasting technical foundations of today's energy-dependent civilisation. A second evolutionary leap, smaller in scale but not in importance, occurred during the 1930s and 1940s, with the introduction of new power and propulsion technologies in the form of gas turbines and nuclear fission, alongside other technical innovations such as electronic computing and semiconductors.⁶⁵ All of these technologies have directly translated into military applications in one form or another, as evidenced by the deployment of revolutionary combat platforms such as the tank, submarine and jet aircraft.

The success of the aforementioned propulsion technologies may prove to be the biggest challenge for alternative energy and propulsion development. The steam turbine, the most important continuous high-load prime mover of the modern world, was invented by Charles Parsons more than a century ago, and it remains fundamentally unchanged—gradual advances in metallurgy made it merely more efficient. The oil-powered internal combustion engine, the most important transportation prime mover of industrialised

⁶⁴ Vaclav Smil, *Energy at the Crossroads*, notes for a presentation at the Global Science Forum Conference on Scientific Challenges for Energy Research, Paris, 17–18 May 2006, p. 5.

⁶⁵ *Ibid.* p. 5.

nations today, was first deployed during the same decade as the steam turbine, and remains conceptually unaltered to this day. Finally, the gas turbine, the most important prime mover of modern flight, is now entering its fourth generation of service.⁶⁶ The gas turbine jet engine, which is the mainstay of today's air force combat platforms, remains vastly superior to other forms of propulsion systems in all performance characteristics.⁶⁷ The enduring existence of the internal combustion engine and the gas turbine is testament to their effectiveness. Thus, as long as these forms of prime movers remain, military forces will continue to be inextricably tied to an oil-based infrastructure. And for the near future this situation is unavoidable. Despite the promise of new technologies, significant issues remain to be solved before they can be reliably and widely deployed in military applications.

Organisational and cultural impediments to change

Finally, organisation and cultural change is essential to effect a successful energy transformation, because warfare is inherently a human enterprise. But what exactly constitutes organisational or cultural change? According to some studies, the DoD will have effected a culture change when senior leaders instinctively recognise that they are directly accountable for energy consumption, when they understand that efficiency produces its own "effect" in increasing combat capability, and they continually strive to improve efficiency because they can appreciate the fact that energy is a key consideration in all military activities and operations. Only then will energy efficiency be a defining characteristic of DoD operations and facilities.⁶⁸

Obstacles against the deployment of alternative energy and propulsion technologies also exist within the organisations that seek change themselves, in the form of established norms and behaviour. But most importantly, the impetus of the transformation has to come from the very top of the chain of command. Because a transformation entails fundamental and often radical change, strong and inspirational leadership is vital.

⁶⁶ Ibid. p. 7.

⁶⁷ National Research Council, p. 60.

⁶⁸ Lengyel, p.47.

According to a 2003 GAO study on organisational practices, top leadership that is “clearly and personally” involved in the transformation represents stability and provides an identifiable foundation for subordinates to rally around during uncertain times. Therefore, it is essential that top leadership must set the direction, pace and tone for the transformation.⁶⁹

However, it cannot be said that contemporary initiatives for energy transformation have the same quality of leadership and focus. While the U.S. DoD has a number of concurrent efforts under way to reduce mobility energy demand, it lacks key elements of an overarching organisational framework to guide and oversee these efforts. As a result, the DoD cannot be certain that its current efforts will be fully implemented and will translate into a significant reduction in its reliance on oil-based fuels.⁷⁰ While the DoD has identified energy as one of its transformational priorities, its current approach to mobility energy is far from consistent. First, it lacks top leadership, with a single executive-level official—supported with dedicated resources and funding—who is directly in charge of mobility energy matters. Second, it lacks a comprehensive strategic plan for mobility energy. Finally, the DoD requires an effective mechanism to communicate and coordinate energy transformation efforts across the land, air and sea services of its forces. The absence of a framework for mobility energy that includes these elements consequently stymies the progress of current efforts to reduce oil dependency.⁷¹

Moreover, the lack of knowledge and awareness among military personnel of alternative energy and propulsion technologies is another major stumbling block in efforts to reduce oil dependency. Alternative energy and propulsion systems remain largely unappreciated, and traditional notions of plentiful oil remain entrenched in their culture. There is little reference in army doctrine and policy regarding operational use of alternative technologies, and whatever little information is available on these technologies in key

⁶⁹ United States Government Accountability Office, *Results Oriented Cultures: Implementation Steps to Assist Mergers and Organisational Transformations*, Washington, DC: GAO, 2003, p. 12.

⁷⁰ United States Government Accountability Office, *Defence Management: Overarching Framework Needed to Guide and Oversee Energy Reduction Efforts for Military Operations*, Washington, DC: GAO, 2008, p. 15.

⁷¹ *Ibid.* p. 15.

army publications is scarce and outdated. As a consequence, the continued use of outdated doctrinal belief by the army leadership regarding traditional energy sources without serious consideration of the benefits of alternative technologies significantly limits opportunities to explore more efficient means of generating, converting and utilising energy.⁷²

Conclusion

Contemporary military platforms are without doubt much more sophisticated in terms of lethality than their World War counterparts. Today's platforms are a complex "system of systems" which feature advanced offensive and defensive subsystems, enhanced electronic and communications equipment all working in synergy to support the war-fighter. It is easy to forget that, underneath the impressive array of equipment, is a propulsion system and energy source that remains conceptually unaltered since their invention decades ago. While efforts are underway to discover new and reliable forms of energy to provide mobility for these vehicles, there are currently no apparent solutions that can provide superior alternatives to current forms of locomotion. However, it remains clear that so long as the military combat platform fleet and its associated logistics remain dependent on oil-based infrastructure, the issues discussed in this paper will continue to endure.

At some juncture in the future, military organisations will have to consider the strategic and economic viability of legacy vehicles and systems that are reliant on oil at a time when new propulsion systems may mature sufficiently to have military utility, and alternative sources of energy may become more cost effective and environmentally acceptable. This consideration will have significant implications for military organisations, although some platforms and systems will continue to remain oil dependent owing to their highly specialised and demanding circumstances, and may have to be specifically designated as prioritised oil users until technology allows a practical

⁷² Gordon D. Kuntz, "Renewable Energy Systems: Viable Options for Contingency Operations", *Points of View*, 2007, <http://www.aepi.army.mil/internet/Renewable-Energy-Systems.pdf> (accessed 28 August 2008).

alternative. Thus, in the near future, energy transformation may be evolutionary rather than revolutionary due to the legacy of, and investment sunk in, current and long-established methods of oil-based energy conversion, as well as the remaining, accessible oil stocks that are yet to be claimed from underground. Potential advances in fossil fuel extraction and refining technologies may allow the extraction of currently untapped resources, particularly from oil shale and tar sands. However, this approach will continue to expose the global market and by extension military organisations to price fluctuations and the associated risks from continued fossil-fuel dependency.

Thus, three main conclusions can be drawn from the analysis above. First, it is clear that there is a need to explore alternatives to reduce military oil dependency, uncertain oil prices and global supply notwithstanding, to ease the burden of logistical delivery of huge quantities of fuel just to maintain combat units on the field. After all, it takes fuel just to deliver fuel, a vicious cycle which is getting increasingly acute as the recent operations in Iraq have demonstrated. Second, it is less clear if a complete solution can be discovered among the multitude of technological innovations that are being explored. It seems that instead of a single “silver bullet” alternative, the next energy transformation will involve a combination of one or more types of technologies from design efficiency, alternative fuel and alternative propulsion research. Third, formidable challenges need to be addressed before military oil dependency can be eliminated. They range from the technical, resolving issues that new technologies often create, to the cultural, changing the mindsets of the organisation to dispel deeply-held beliefs about plentiful and assured oil supply, and to embrace new ways of thinking and technology.

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