驅動未來地面作戰之新動力

Mobile Nuclear Power for Future Land Combat

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本文在介紹一種具有存活性和使用非石油燃料的機動核能設備，可機動支援偏遠戰區作戰。我們的理論基礎來自今天地面部隊所面臨二項正浮現的威脅所引發之急迫性，其一為石油開採、提煉、配送系統費用增加；其二為全球空對地長程精準武器數量的增加。我們著眼在美國快速部署海外的陸軍及陸戰隊所需核能，未將海、空軍納入，係因海軍已大量核能化，而空軍則是未來燃料改良的一些技術問題尚未獲得解決。

In this article, we introduce the concept of survivable, non-fossil fuel power plants that can be transported to remote theaters of operation. Our rationale arises from a sense of urgency for countering two emerging threats facing land forces today: the increasing cost and vulnerability of fossil fuel extraction, refining, and distribution systems; and worldwide proliferation of highly accurate weapons launched at long standoff ranges. Our vision spotlights nuclear energy for expeditionary U.S. Army and Marine Corps forces as opposed to sea and air because the Navy is already largely nuclear and because substantial Air Force fuel improvements face unresolved technology issues.

地面部隊能源的存活性理念來自機動性和匿蹤性。機動性至為重要，除可避免遭到導引武器攻擊外，也可支援分散在幅員遼闊戰區的部隊而不須仰賴固定儲油設施、煉油廠和輸油管線。在補充機動所需能源方面，我們置重點於地面作戰車輛使用之氫燃料和電力。

Our notion of land force energy survivability derives from mobility and stealth. Mobility is key in that it permits evasion of attack by coordinate-guiding weapons. Mobility also allows serving widely dispersed forces without reliance on extended power grids, fixed storage facilities, and processing plants. To complement mobile energy, we focus on land vehicles that use hydrogen fuel and electricity for power.

具有運輸性之機動核能設備可在戰場製造氫燃料和電瓶充電。我們的構想是在運輸方面可使用艦艇、駁船、運輸機或飛船，而在戰區機動方面則可使用拖車、火車、運貨台車、運輸機或飛船。

Transportable, mobile power plants permit manufacture of hydrogen in theater and recharging of vehicular batteries in the field. We envision transportability by ship, barge, cargo aircraft, or airship, and theater mobility by tractor trailer truck, railroad flatcar, cargo aircraft, or airship.

現代軍隊需要充裕能源以遂行作戰。能源消耗包括用於車輛之油料和用於照明、通訊、電腦、膳食料理、環境冷暖空調等電力。此外，軍隊也常奉派執行人道救援提供災區人民所需之電力。綜上所述之能源需求在作戰壓力和緊急情況下之供應性、可靠性及存活性方面頗有爭議。

Modern armies require copious amounts of energy to conduct their operations. Energy is consumed as fuel for a variety of vehicles and as electricity for illumination, communication, computing, food processing, and environmental heating and cooling. Modern military forces also are more often called upon to provide humanitarian relief in the form of electricity for civilian populations. Taken together, these energy demands argue for affordable, reliable, and survivable power under combat stress and emergency conditions.

有關這些問題的前景並不樂觀，由於可靠價廉的儲油量日減和全球油料需求競爭日烈，油價已迅速攀升。根據一些負責任的經濟及地質學者預測，未來油價仍將持續走揚，而在未來地區衝突中，數量日增的導引炸彈和飛彈將以存活力較低的固定煉油廠、發電廠、油輪及輸油管線為主要攻擊目標。

The outlook, however, is not promising regarding any of these issues. Due to dwindling reserves of reliable, inexpensive oil and competing worldwide demand, fuel costs have already begun to skyrocket, and responsible economists and geologists predict that they will go significantly higher. Moreover, proliferation of guided bombs and missiles threatens to make stationary refineries, power plants, storage vessels, generators, and power grids prime targets with low expected survivability in future regional conflicts.

大量依賴國外石油將造成另一個兩難局面。整個國安系統包括政府領導高層、軍方和情報單位都靠石油運作。經證實，目前儲備油料中95%都在北美洲以外地區控管，如此造成美國風險提高，可預見的未來已到達令人憂心的程度。

Overwhelming reliance on foreign oil poses an additional dilemma. The entire national security system, including the political leadership, military forces, and Intelligence Community, relies on fossil fuel to operate. With 95 percent of proven oil reserves controlled outside of North America,1 this poses a national risk that is monotonically increasing.

要解決此一兩難局面，唯有進行密集研究、計畫並及早採取因應措施。

To an alarming extent, then, the future has already arrived. Intensive study, planning, and early action to resolve this dilemma are warranted.

由於每桶100美元以上和每加侖4美元油價所造成的經濟疲軟已對美國人民產生影響。此等價格亦影響了軍事行動。美軍目前每日消耗油料達34萬桶，其中1.5%用於國內。2006年時，國防部油費支出為136億美金，較2005年高出25%。2006年以後油費支出已超出50%。白宮最近提出的預算因油價上漲而增列20億美金。可想見的是，未來數十年昂貴的石油和天然氣不但影響車輛部隊之演訓也影響先進武器的獲得。

The debilitating economic impact of $100+ per barrel for oil and $4+ per gallon for gasoline on the U.S. civilian population is well known. Such prices undermine military operations as well. U.S. forces currently consume 340,000 barrels of oil daily, 1.5 percent of all the oil used in the country.2 In

2006, the Department of Defense（DOD） energy bill was $13.6 billion, 25 percent higher than the year before. Petroleum costs have subsequently increased more than 50 percent. In its latest budget request, the White House added a $2 billion surcharge for rising fuel costs. It is conceivable that in coming decades, petroleum and natural gas will be so expensive that fuel will impinge on vehicular-intensive training exercises and on the acquisition of advanced equipment.

美軍必須找到實用可靠的石油替代能源。油料豐富的庫儲量對戰場機動之重要性不言而喻。眾所周知，缺乏燃料會嚴重限制軍事行動，以下舉5個戰史為例：

一·1944年巴頓將軍揮軍進攻德國，因盟軍統帥艾森豪將軍把油料移撥英軍蒙哥馬利將軍所屬部隊而行動受阻。

二·德軍於地中海實施阻絕行動導致隆美爾部隊1943年的北非作戰因油料短缺而失利。

三·1944年美軍在法國隆恩峽谷一役因缺乏油料而導致攻擊頓挫。

四·二戰末期德空軍戰機因油料不足而遭致停飛。二戰結束前9個月德軍飛行員因油料短缺而訓練不足，其飛行訓練僅達總訓練時數三分之一。

The U.S. military must find a viable substitute for fossil fuel. Fuel abundance is critical on the battlefield since it enables maneuverability. It is well recognized that lack of fuel can impose severe limitations on operations.There are numerous historical examples:

一. George Patton's 1944 drive for Germany stalled because Dwight Eisenhower had to divert fuel to British forces under Bernard Montgomery.

二. As a consequence of interdiction in the Mediterranean Sea, German forces under Erwin Rommel literally ran out of gas in their 1943 North Africa campaign.

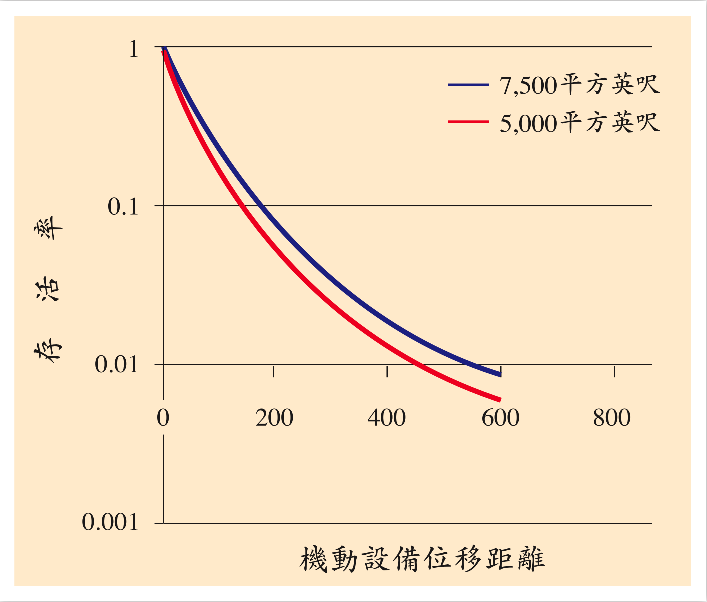
三. The 1944 drive by U.S. forces up the Rhone Valley in France was slowed by fuel shortages.

四. The Luftwaffe was grounded late in World War II due to lack of fuel. Because of fuel scarcity, German pilots were sent into combat in the last 9 months of World War II with only a third of the training hours actually required.

戰時一些石油開採、製造、輸配等基礎設施，隨著衛星導航之空對地飛彈和炸彈數量的增加，其存活率已嚴重降低。例如俄羅斯最近採用一款kh-38mk型空對地飛彈，該飛彈使用全球導航衛星系統（GLONASS），等同於全球定位系統（GPS），其精準度較GPS之35呎更佳且射程可達25哩。更不利的是長射程飛彈對基礎設施的威脅依然存在，潛艦發射洲際飛彈射程可達5,000～8,000哩，巡弋飛彈700哩，短程導彈則為400哩。目前導彈系統大多採用精準度較差之慣性導航，惟多數飛彈正提升為衛星導航，其性能等同kh-38mk型飛彈。

Wartime survivability of infrastructure for fuel extraction, manufacturing, and distribution has reached a critical state with the worldwide proliferation of satellite-guided standoff missiles and bombs. As a case in point, Russia recently introduced the Kh-38MK air-to-surface missile. It uses GLONASS（Global Navigation Satellite System） satellite navigation, equivalent to global positioning system（GPS） with accuracy of better than 35 feet, and has a standoff range of 25 miles.3 More ominously, threats with longer range also exist, typically 5,000 to 8,000 miles for intercontinental and submarine-launched ballistic missiles, 700 miles for cruise missiles, and 400 miles for short-range ballistic missiles.4 Currently, most of these systems employ comparatively inaccurate inertial guidance, but many are being upgraded to satellite navigation with performance equivalent to the Kh-38MK.

由於攻擊飛彈彈頭破壞範圍為5,000～8,000平方公尺，由此可估算出機動核能設備進行不等距離移動時產生之效益。圖中遭受飛彈破壞可能性和機動設備位移間之關係以曲線表示。當位移為0時，遭破壞可能性為0.9以上，而位移為600呎（含）以上時，破壞可能性則不到0.009。由此可清楚看出機動性可有效反制導彈攻擊。近期幾個戰例可強化以上論述：



機動核反應器在飛彈攻擊下之存活率圖

資料來源：《聯合武力季刊》，2009年，第1季。

一.一次波灣戰爭期間（沙漠風暴），伊軍唯一在美軍空中轟炸下存活的飛毛腿飛彈（裝載於輪車之機動型飛彈），後來重創了以色列特拉維夫和沙烏地阿拉伯。

二.美空軍參謀長麥克皮克上將1991年在〈機動目標攻擊之挑戰研究報告〉中披露，沙漠風暴作戰期間，制壓伊拉克飛毛腿飛彈行動遭遇困難。該型飛彈機動發射架經證明具備顯著之規避和存活性，雷達和紅外線感應器無法辨識攻擊目標之真偽。

三.2006年以黎戰爭期間，以色列空軍無法阻止黎巴嫩回教民兵組織1,000枚以上之車載型火箭對以國城市的攻擊。

Since attack missile warheads have damage areas of 5,000 to 7,500 square feet, we can estimate the benefits of random movement for a mobile reactor. Calculations are summarized in figure 1, in which damage probability is plotted against displacement. When the displacement is 0, the damage probability is more than 0.9. However, when the displacement is 600 feet or more, the damage probability is less than 0.009 for either warhead extreme.

Clearly, mobility acts as a powerful countermeasure against coordinate-guiding munitions. Recent history reinforces the premise:

一.During the first Gulf War（Operation Desert Storm）, the only Iraqi Scud missiles that survived the U.S. air assault were of the mobile（wheeled）variety. These missiles later rained on Tel Aviv and Saudi Arabia.

二.A 1991 study by Air Force Chief of Staff General Merrill McPeak revealed the challenge of targeting mobile targets: “Efforts to suppress Iraqi launches of Scud missiles during Desert Storm ran into problems. Mobile launchers proved remarkably elusive and survivable. Objects targeted were impossible to discriminate from decoys（and clutter）with radar and infrared sensors.”

三.In the 2006 war in Lebanon, the Israeli air force could not stop more than 1,000 Hizballah truck-mobile rockets from striking Israeli urban areas.

不論戰爭大小，擁有充裕油料乃成功致勝關鍵。美軍在伊戰期間每日消耗油料168萬加侖。沙漠風暴作戰有名的側翼機動迂迴行動，每日消耗油料達450萬加侖，5天機動作戰油料需求達7萬噸。發展具有存活性、不依賴石油和固定基礎設施以支援散布在廣大戰區部隊的厚實戰力資源要靠精打細算。

Abundance of fuel is critical for success in big and small wars. U.S. forces in Iraq consume 1,680,000 gallons daily. The famous flanking maneuver during Operation Desert Storm burned 4.5 million gallons of fuel per day. After 5 days of combat, the maneuver required 70,000 tons of fuel.6 Prudence dictates development of abundant military power sources that are survivable, independent of petroleum, and require little fixed infrastructure to serve dispersed forces.

作戰車輛燃料之選擇
Candidates for Vehicular Fleet

短期而言，地面作戰車輛可能使用傳統及合成油料，雖已開始實施但充其量不過是一項降低依賴外國石油的權宜措施。合成油料不比石油便宜且其排放之污染氣體種類、數量和石油相同。合成油料亦具備和石油相同之弱點，就是須依賴固定煉油和輸油基礎設施。

In the near term, it is likely that military land vehicles will be powered by blends of conventional and synthetic fuels. This practice has already begun, but at best it is an act of expedience that reduces reliance on foreign sources. Blended fuels are not significantly less expensive than petroleum, and they emit similar kinds and amounts of pollutants. Blends and synthetics also suffer from the same vulnerabilities as fossil fuels in their dependence on fixed refining and distribution infrastructure.

長期而言，地面作戰車輛將由電動車、油電兩用車、氫燃料車和多種燃料車組成，這些車輛全都需要充電和製氫設備。對此我們特別推薦戰區機動核能設備。多數車輛燃料科技之研發係由主要汽車製造廠提供資金，為瞭解軍用車輛燃料之選擇，特將民間汽車公司研發情形簡述如下：

Over the longer term, military land fleets will consist of mixtures of electric vehicles, fuel-cell vehicles, hydrogen vehicles, and hybrids. All require energy rechargers or hydrogen fueling. We propose to provide both with theater-based mobile nuclear facilities. Most of the research and innovation in vehicular fuel technology is funded by major automobile manufacturers. To gain insight into the options for military vehicles, we briefly survey the approaches taken by the civilian automotive industry.

電池電動車：全車係以電池提供電力之電動車，目前可循商購獲得，不過價格昂貴且車速較慢（道路良好情況下每小時50哩以下），目前正密集研究改良中，惟尚需10年時間。目前使用電池有鋰電池、鋅電池、鐵磷酸電池和鈦酸鋇電池等。

Battery-powered Electric Vehicles.

Battery-powered all-electric vehicles are currently available commercially but are notoriously expensive, underpowered, and marginal in practicality. Their batteries require substantial improvement for military use. Typical vehicle ranges without recharging are 50 to 100 miles, and speeds are low（less than 50 mph under good road conditions）. Intensive research is being undertaken to improve that situation, but solutions appear to be 10 years away. Current battery candidates include lithium-ion（many variants）, zinc-air, iron-nanophosphate, and titanium dioxide–barium titanate.

油電混合內燃引擎車：本車為近期發展電動車的一項成就。低速行駛時使用電池馬達，高速行駛時使用碳化氫為燃料之內燃引擎，為一省油車，每克燃料可提供35～45匹馬力，惟行駛

數百哩後需要充電。目前有數十種商用型問市。軍方現正敦促研發適用於作戰之油電混合車，目前技術已臻成熟，預期2010年初完成研發。不過本車只能暫時解決行駛距離不足問題，對降低燃油費用和減輕對外國石油依賴助益不大。

Hybrid Electric–Internal Combustion Vehicles Hybrids are the near-term implementation of electric vehicles. They combine battery-powered electric motors for low-speed operation and hydrocarbon-fueled internal combustion engines for higher speeds. The result is a fuel-efficient vehicle, often delivering 35 to 45 mpg but requiring recharging every few hundred miles. Dozens of commercial models exist. Military Services are pressuring developers to provide near-term hybrid vehicles suitable for combat operations. The technology appears sufficiently mature to expect implementation as early as 2010. However, hybrids are again only an expedient solution that improves road mileage. They do not reduce costs and only marginally reduce dependence on foreign fuel sources.

氫燃料電池車：本車以氫和大氣層中的氧經化學作用後產生電和水。氫離子經由薄膜（又稱質子交換膜PEM）和氧離子結合，當氫經電離化後產生電子經由電路驅動馬達。燃料電池未來潛力不大，要以有效電力驅動車輛，燃料電池應組合成蕊塊，不過電池蕊塊價格昂貴，美國能源部的目標是以大規模生產方式將價格訂在每千瓦30美金。一個100千瓦的電池蕊塊具有134匹馬力，價格為3,000美金。目前上路的燃料電池車為數不多。2001年賓士F-CELL型轎車由一具由質子交換膜（PEM）驅動之65千瓦的感應馬達，行駛距離達110哩，每磅氫燃料可行駛26哩。最近上市的本田FCX/FCX-CLARITY型及雪佛蘭EQUINOX型等二款車行駛距離180～270哩，時速90～100哩，各自擁有107～134匹馬力。2015～2020年時應有更多性能更佳且價格更廉的車型問市。

Fuel Cell–Powered Vehicles. In fuel cell vehicles, hydrogen is chemically reacted with airborne oxygen to produce electricity and water. The hydrogen is channeled as ions through membranes, called Proton Exchange Membranes （PEM）, and then combined with ionized oxygen. The electrons created when the hydrogen is ionized are directed through a circuit, enabling electricity to drive a motor. Fuel cells are of relatively low potential. To be useful in powering vehicles, they must be assembled in stacks. However, fuel cell stacks are costly. The Department of Energy goal for large-scale fuel cell production is $30 per kilowatt （kW）. A 100–kW stack equivalent to 134 horsepower would cost $3,000. Currently, there are only a small number of fuel cell vehicles on the road. The 2001 Mercedes-Benz F-Cell had a PEM-driven 65–kW induction motor. With a range of 110 miles, it got 26 miles per pound of hydrogen. More recently, Honda fielded the FCX/FCX Clarity and Chevrolet fielded the Equinox. They have ranges of 180 to 270 miles and achieve speeds of 90 to 100 mph with 107 to 134 horsepower, all respectively.7 By 2015–2020, there should be many more of higher performance and lower price.

轉化氫燃料車：大多數燃料電池車使用儲存在高壓容器內的氫氣，不過也有使用儲存於傳統油箱內的液體燃料如甲醇。後者需要轉化處理器以釋放氫。這種轉化器可經由催化作用將燃料轉化成氫和二氧化碳。氫可作為燃料，二氧化碳和水蒸汽則排放到大氣層中。本車裝滿油箱可行駛300～400哩，其缺點為較複雜、昂貴且需額外維修。目前就純氫和轉化氫二者比較，何者得以勝出尚不明朗。

Reformer-fed Fuel Cells.

Most fuel cell vehicles use gaseous hydrogen stored in high-pressure tanks. However, it is also possible to use liquid fuels such as methanol stored in conventional tanks. The latter need reformers—processors that release hydrogen. The reformer catalytically converts fuel into hydrogen and carbon dioxide. Hydrogen drives the fuel cell; carbon dioxide and water vapor are released to the atmosphere. Reformer-fed fuel cells achieve 300 to 400 miles per tank. However, they are complex, costly, and require additional maintenance. It is not clear which method, pure hydrogen or reformer-produced hydrogen, will prevail.

氫內燃引擎車：本車內燃引擎使用液態氫或氣態氫。有一種技術可將液態氫以每平方吋5,000磅壓力在室溫下儲存於燃料箱內可行駛200哩。目前正在研究如何將壓力提高、行駛較遠距離和一些其他儲存方法。2001年BMW推出一款750hl型低溫冷卻液態氫後又推出數十種氫系列實驗車。目前市面有二款車，一款是使用氫為單一燃料；另一款則使用氫或汽油兩種燃料。目前液態氫燃料車尚未量產。

Hydrogen Internal Combustion Engine Vehicles.

It is also possible to fuel internal combustion engines with gaseous or liquid hydrogen. One technique is to store the gaseous form in onboard tanks at 5,000 pounds per square inch and at room temperature in quantities sufficient for about 200 miles. Research is under way to extend this to higher pressures and even more mileage, as well as to other methods of storage. In 2001, BMW unveiled a cryogenically cooled liquid-hydrogen sedan, the 750hL. This prototype had a 330-cubic-inch, 12-cylinder engine, and a 36-gallon fuel tank. Since then, BMW has fielded several dozen experimental sedans in the Hydrogen 7 Series. Two versions are available: a monofuel system with an engine tuned for only hydrogen, and a bifuel configuration with gasoline as the other fuel. Volume production of liquid hydrogen–fueled vehicles, however, has not been undertaken to date.

氫燃料儲存法：有關氫儲存法有多種不同技術。經研發一種使用金屬氫化物在壓力下可吸收氫並藉加熱時將氫轉化釋放。典型之氫化物為鎂基、鉀基或鋁基之化合物，其壓縮氫之壓力須較海平面大氣壓力高出3～30倍。整體言之，氫化物儲存法實際效益尚有待證實。氫化物有毒且不穩定，其儲存容器重量較重且昂貴。另一種儲存技術使用阿摩尼亞，它可以在催化轉化器內釋放出氫，且不會排放有毒廢氣。阿摩尼亞在室溫和大氣壓力下溶解於水，儲存非常方便，在壓力下可以液態或氣態燃料方式供應改良式內燃引擎使用。

Alternative Methods for Storing Hydrogen

Over and beyond onboard tanks, there are a variety of additional techniques for storing hydrogen and subsequently using it as fuel. The most thoroughly researched involves the use of metal hydrides that have the ability to adsorb hydrogen under pressure and reversibly release it upon heating. Typical hydrides are magnesium-, lithium-, or aluminum-based, and they require hydrogen compression to 3 to 30 times the air pressure at sea level. Overall, hydride storage of hydrogen has not yet proved practical. Hydrides are toxic and volatile, and their storage containers are heavy and expensive. Another storage technique exploits the use of ammonia. It releases hydrogen in a catalytic reformer with no harmful waste discharge. Ammonia is conveniently storable at room temperature and atmospheric pressure when dissolved in water. Under pressure, it is suitable as liquid or gaseous fuel in modified internal combustion engines.

氫燃料之產製
Manufacturing Hydrogen

氫燃料商業用途製法有以下數種：

一.室溫下水電解法：係將氫和氧分離，其效益為70%。

二.甲烷還原法（華氏1,650度）：大多用於商業用途，產生之廢氣為二氧化碳。此種用高溫產製程序適合高溫氣體冷卻之核子反應器。

三.熱化學分解法（華氏930～1,470度）：以硫酸為催化劑，未來頗具潛力的熱化學分解為三氧化硫製程周期。本法尚未商業化是因為在高溫下長期具抗酸性的材料仍在研發中。

四.氧化鐵分解法（華氏1,470度）：本法基本化學反應係以氧化鐵分解產生氫和較高氧化鐵狀態。在產製過程中會產生煤氣，由於會造成大量空氣污染，是否能長期製造仍有疑問。

五.生煤汽化法：以高純度生煤在高溫下和蒸汽及氧作用而產生氫和氧化碳。此產製過程類似甲烷還原法，但會造成較多污染且效果亦較差。產製過程中產生雜質包括含硫之碳酸鈉和硫化物。

Alternative commercial methods for manufacturing hydrogen include:

一.Room temperature electrolysis of water. Electrolysis is used to separate hydrogen and oxygen, the efficiency being about 70 percent.

二.Methane-steam reforming （1,650oF）. Steam reforming of natural gas is the method most commonly used commercially. A waste product is carbon dioxide. This high-temperature process lends itself to the extreme heat available with gas-cooled nuclear reactors.

三.Thermo-chemical decomposition of water （930–1,470oF） catalyzed by sulfurous acid. A potential thermo-chemical process is the sulfur trioxide cycle. Commercialization has not been achieved, however, because materials capable of long-term exposure to strong acids at high temperature have not been demonstrated.

四.Continuous steam-iron process（1,470oF）. The basic reaction is the decomposition of steam by iron oxide to yield hydrogen and a higher oxidation state of iron. The process takes place in the presence of producer gas obtained from coal. However, long-term utility of the process is questionable due to extensive air pollution.

五.Coal gasification. Finely ground coal is reacted with steam and oxygen at high temperature, the reaction producing hydrogen and carbon dioxide. The process is similar to methane-steam reforming but is substantially more polluting and less efficient. Impurities include sulfur-containing ash and hydrogen sulfide.

未來戰區機動最實際的選擇是使用水離子電解法。以往電解法效果較差，問題可在製氫過程中以高溫（華氏1,000～1,400度）和高壓（每平方吋450磅）方式解決。甲烷還原法也是選項之一，惟缺點是甲烷長期缺貨將對此形成不利。熱化學分解法危險性高，自煤中提煉氫不適合機動且造成高度污染。選擇高溫水電解法具有機動性、低污染、效果佳和低價格等優點。假設500萬瓦的電可提供水電解和加熱之電力就可產製足夠的氫，每天產量達2萬加侖可供應400輛車燃料所需。構思中的電解設備可裝在1輛平板拖車上，其體積長50呎、寬8呎、高10呎。

Assuming 5 megawatts （MW） of electricity is available for powering electrolysis and heating water, enough hydrogen can be manufactured to fuel more than 400 vehicles per day.10 This involves production of 20,000 gallons of liquid hydrogen daily. The electrolysis unit can conceptually be mounted on a flatbed truck with dimensions 50 feet long by 8 feet wide by 10 feet high

機動核能設備之選擇
Candidates for Mobile Reactors

為符合運輸條件，本設備設計上應有嚴格限制，其體積要小到可裝入1架運輸機內，其重量也有限制，以C-5A/B型運輸機而言，重量限制在90～140噸，體積為19呎x13.5呎x100呎。另一選擇為計畫由國防高級研究計畫局研發之大型飛船，其載貨量可達500～1,000噸。考量運輸性將導致核反應器未來朝組合式發展。機動核反應器限制多，理想的反應器宜具備下列條件：

●封閉之冷卻和調節系統；
●無危險性且不起化學作用；
●可接受氦、二氧化碳、重水和液態金屬，但液鹽具危險性不適用；
●可自行吸收少量熱水和廢水；
●大多數作業為機械化；
●作業安全性；
●負空隙係數（當反應器爐心溫度上升時，功率下降）；
●被動式冷卻（冷卻劑流失時不會損及燃料，由於輻射和對流作用，爐心溫度自然下降，如此可避免車諾比和三哩島核外洩事件再度重演）；
●可抵抗恐怖分子攻擊（三層結構之等方性，供應反應器之TRISO燃料為較佳選擇）；
●可抵抗核武攻擊；增殖反應堆（BREEDER REACTORS）可產生鈽（PU）金屬元素，違反美國政策；
●增殖反應堆可確保燃料不會遭竊且已有其他國家採用；
●對核廢料處理具備公信力；
●能抵抗爆裂物攻擊。

The requirement to be transportable imposes severe design restrictions. The reactors must be relatively small to fit into a military transport aircraft. The weight constraint of the C–5A/B Galaxy is 90 to 140 tons and the size limitation is 19 feet by 13.5 feet by 100 feet. As an alternative, the proposed Defense Advanced Research Projects Agency Walrus Hybrid Ultra Large Aircraft–type airship had a conceptual capacity of 500 to 1,000 tons of cargo.11 Transportability also implies a degree of modularity so the reactor can be loaded as an integral unit.Mobile reactors impose an even more extensive set of constraints. Mobile nuclear reactors would preferably have:：

■ closed cooling and moderating systems；
■ nonhazardous and desirably inert；
■ helium, carbon dioxide, heavy water, liquid metals acceptable;liquid salts deemed not suitable due to hazard potential；
■ self-contained operations with minimal heat or waste effluents；
■ largely robotic operation；
■ inherently safe operation；
■ negative void coefficient （that is, the power reduces when the reactor core temperature goes up）；
■ passive cooling （that is, loss of coolant will not damage the fuel;the core temperature eventually cools due to radiation and convection）;these characteristics preclude Chernobyl andThree

Mile Island–type nuclear accidents.；

■ resistance to terrorist attack. Tristructural-Isotropic （TRISO）–fueled reactors are attractive in this respect.；

■ resistance to nuclear weapon proliferation possibilities.；

■ breeder reactors produce plutonium and violate U.S. policy.；

■ breeder reactor safeguards to prevent fuel pilfering, however, are possible and have been employed in other countries13；

■ a convincing waste disposal configuration；

■ resistance to explosive attack.。

我們確認下列四種反應器構想可適合作戰部隊使用，不過須進一步改良以增加機動性。這些反應器在設計上應將體積縮小以符合戰區機動運輸之限制。

一、遠場模組氦反應器（RS-MHR）：為氣冷式反應器，由通用原子公司（General Atomics）推薦，使用TRISO燃料具有多項優異性能且具備安定性、防盜性、防污染性。該公司已研發二具10MW及25MW反應器。

二、複合式機動反應器（MMR）：由SANDIA 公司推薦，為一種列陣式自行吸收，可供運輸之氣冷式組件。雖然細部資料不詳，每一組件均適合機動，對支援作戰車輛燃料頗具競爭力。

三、高溫測試反應器（HTTR）：和RS-MHR型類似，但功率較大（30MW）。之所以單獨列項說明是因為本反應器自1998年起就已在日本開始運作，而RS-MHR型仍在構思階段。本反應器特別連結氣態甲烷氫轉化廠，其體積應縮小以利較飛船小的載具載運俾利機動。

四、小型封閉式運輸獨立型反應器（SSTAR）：為一快速增殖反應堆、安全，以氦作為冷卻劑，可防人擅自更動。原則上本反應器不會違反美國政策禁令。本系統壽命達30年，所有產生之廢料均密封在內。LIVERMORE公司設計一款10-MW型，重量200噸，可用小型飛船或卡車載運。該公司也可能設計體積較小系統，重量減為90～100噸，長度38公尺，直徑7.5呎，功率4.5～5MW。

We have identified four reactor concepts14considered appropriate for a field army, although further refinements are needed for added mobility. As we will later observe, these specific designs would have to be scaled down to conform to theater mobility constraints.

一.The Remote-site Modular Helium Reactor （RS–MHR） is a gas-cooled reactor proposed by General Atomics. It uses TRISO fuel in batch operation and has most of the desirable characteristics of a mobile reactor. It is passively safe, secure from fuel theft and waste pollution, and resistant to terrorist and explosive attacks. Two reactors have been investigated by General Atomics, rated at 10 and 25 megawatts electric.

二.The Multi-mobile Reactor （MMR） concept involves an array of self-contained, factory-built, transportable gas-cooled modules proposed by Sandia National Laboratories. Although many details are lacking, each module is appropriate for mobility, and the power is compatible with the requirements needed to fuel field army vehicles.

三.The High Temperature Test Reactor （HTTR） is similar in concept to the RS–MHR but somewhat larger （30 MW）. It is described separately because it has been operational in Japan since 1998 whereas the RS–MHR is conceptual. The HTTR is specifically configured to couple to a steam-methane hydrogen reforming plant. It would have to be scaleddown to achieve mobility in anything significantly smaller than a Walrus airship.

四.The Small, Sealed, Transportable, Autonomous Reactor （SSTAR） is a fast breeder reactor concept that is passively safe, has helium as coolant in one version, and is tamper-resistant. In principle, it would overcome U.S. policy prohibiting breeder reactors. The system has a 30-year lifetime, and all the waste products are sealed inside. Livermore Laboratories has designed a 10 –MW version weighing 200 tons. That would be transportable in a scaled-down Walrus or on a truck,but it should also be possible to design a smaller system. A version scaled to 90 to 100 tons would have estimated dimensions of 38 feet in length by 7.5 feet in diameter and a power of 4.5 to 5 MW.

支援地面作戰構想
Operational Concept

我們建議以一具核反應器和一組氫電解設備支援一個史崔克（Stryker）旅之作戰（通常編制3600官兵）。每旅有400輛戰車，其中350輛為輕型攻擊戰鬥車。以一具功率4.5～5MW之反應器，每天可充分供應400輛車所需的氫燃料和電力。因目前有33個步兵、裝甲和裝騎戰鬥旅，我們擬以100具反應器和100組製氫設備（含備份零件）取代前方地區油料補給點（FARPs），並賦予一個新名稱「前方地區核能補給點（Nuclear FARPs）」。機動構想可視戰場情況每日移動一次為原則，以公路機動方式每次移動數百呎。前方補給點間之機動使用C5A/B運輸機或飛船載運，這些程序仍須詳細規劃並以核補給點存活為優先考量。

We propose to support a Stryker Brigade （nominally 3,600 Soldiers） with one mobile power reactor and a mobile hydrogen electrolysis unit. Each brigade has about 400 vehicles, 350 of which are light-assault vehicles. The 4.5– to 5–MW reactor could provide enough hydrogen and electricity to fuel 400 vehicles daily.Since there are currently 33 combat infantry and armor/cavalry brigades, we propose to field 100 reactors and 100 electrolysis units including spares. These mobile facilities would replace traditional Forward Area Refueling Points （FARPs）. Descriptively, we call them “nuclear FARPs.” The mobility concept is to move the nuclear FARP everyday or so under battlefield conditions. These will be movements of hundreds of feet by road. Movement between FARPs, however, would be by C–5A/B or by airship.15 Such procedures, admittedly needing refinement, underlie the survivability of a nuclear FARP.

我們假設在掌握空優情況下，可排除敵以戰機和無人駕駛之戰鬥載具對我空襲。如此，對我有威脅的僅剩下長程衛星和地面導引飛彈，以空對地攻擊方式對我展開攻擊。機動可確保在此種飛彈攻擊下之存活性。須注意的是，有必要防護核反應器產生的熱訊號以避免成為追熱導彈的目標。可使用頂罩式帳棚和鼓風機以達到外圍散熱和偽裝的目的。

We assume air and space superiority conditions that preclude the use of enemy manned aircraft and unmanned combat air vehicles. That leaves only long-range satellite and terrain-guided missiles as viable methods of standoff attack.16 Mobility ensures survivability against such fixed-coordinate missiles. Note that it will be necessary to shield the heat signature produced by the reactors; otherwise, they will be vulnerable to heat-seeking guidance. Thermal shielding can be achieved with overhead canvas and blowers to disperse heat peripherally. Overhead canvas would also enable a degree of camouflage.

美軍在運輸反應器技術方面有廣泛經驗，1968～1976年間，由拖船Sturgis號載運功率45 MW之核反應器提供巴拿馬運河社區所需電力。其他攜帶式核反應器也分別在懷俄明州、格陵蘭及南極等地區運轉過。

The U.S. Army has had extensive experience with transportable reactor technology. From 1968 to 1976, a 45–MW nuclear reactor on the barge Sturgis provided power for the Panama Canal community.17 Other portable nuclear reactors were operated in Wyoming, Greenland, and Antarctica.It may also be possible to provide fleetwide monitoring of the reactors and electrolysis units by satellite to permit cost-saving, anpower-efficient troubleshooting.

戰略意涵
Strategic Implications

作戰車輛的機動性和存活性以及不依賴石油燃料的獨立性，就戰略意涵而言相當深奧。它們包括：

●供應作戰車輛價廉充裕之自足性燃料且不會造成大氣污染；

●解決戰區內定點之固定油料產製及輸配設施之弱點；

●減少載運數以噸計之油料行駛數千英哩對戰區作戰部隊後勤支援之負荷；

●提供全球人道援助任務所需低成本能源。

Strategic implications of a mobile and survivable fleet of vehicles independent of fossil fuels would be profound. They include:：

■ fielding combat vehicles with affordable, self-sufficient sources of abundant fuel that donot contribute to atmospheric pollution providing fuel to a dispersed fleet in a survivable, sustainable manner；

■ eliminating vulnerable in-theater, single point, fixed-location sources of fuel manufacture and distribution；

■ diminishing the logistic footprint associated with hauling fuel tonnages over thousands of miles to supply an operating theater military force；

■ developing a mobile testbed for modular nuclear-powered electricity to provide alternatives for the fossil fuel crisis now gripping the world economyproviding a means to supply low-cost power in support of humanitarian missions around the world.。

昂貴石油價格和低存活性之石油固定開採、提煉、輸配系統導致陸軍在未來作戰時發生危險，陸軍應認清未來作戰車輛之動力是氫和電的組合燃料。令人欣慰的是該組合燃料由戰區機動核反應器和製氫設備供應，而相關技術才剛開始且可經由商購獲得。軍用型電動車目前尚未完成研發，須待10年後才有可能。惟民用型燃料電池車、氫燃料車和油電混合車等均已接近量產。軍用型預訂2010～2020年可完成。陸軍應就未來車輛之存活性、供應性和燃料獨立性儘早策定需求和計畫。

The cost of fossil fuels combined with the low survivability of fixed extraction, refining, and distribution systems puts the Army’s land-based fleet of combat vehicles in jeopardy for future conflicts. The Army should define a new fleet of vehicles powered by a combination of electricity and hydrogen. Preferably, this fleet would be energized by theater-mobile nuclear reactors and theatermobile hydrogen manufacturing facilities. Appropriate technology for these vehicles, reactors, and manufacturing facilities is just beginning to become available commercially.Electrically powered vehicles with military potential are not currently available but may become practical in a decade or so. However, fuel cell–powered vehicles, hydrogen-powered vehicles, and hybrids are all approaching commercial viability. Military versions can be expected in the 2010–2020 timeframe. The Army needs to define its requirements and plan for the future fleet in terms of survivability, affordability, and independence of fuel sources.

可以設想幾種不同型式機動核反應器之重量為90～100噸，可用C-5A/B運輸機或Walrus型飛船系列載運。公路運輸則以平板拖車載運。該反應器可產生4.5～5MW電力，足夠提供每日400輛車所需之氫及電力。高溫電解設備為合適之製氫設備，也具機動性和由一具機動核反應器供應動力。構想之機動燃料供應系統之一般效應既深奧又具革命性，它可提供下列效益：

●部隊重量減輕且機動性更高；
●流暢之後勤支援；
●因攜帶燃料減輕而增加彈藥攜行量；
●能源補給鏈小型化；
●國家能源自給自足；
●減少能源基礎設施；
●供應持久性；
●增加存活率；
●增加供應性；
●擴大戰術功效。

Mobile nuclear reactors in several varieties can be postulated. They weigh 90 to 100 tons and can be transported on a C–5A/B transport aircraft or a Walrus-type airship derivative and locally on a flatbed truck. They produce power of 4.5 to 5 MW, sufficient to provide hydrogen and electricity to fuel about 400 vehicles daily. One appropriate type of hydrogen manufacturing facility is a high temperature electrolysis unit. It also can bemade mobile and can be powered by a mobile nuclear reactor.The general benefits of the mobile fueling system postulated are profound and revolutionary. They provide for:：

■ a lighter, more mobile military；
■ streamlined logistics；
■ more ammunition resulting from；
■ reduced fuel tonnage；
■ inimized energy supply chain；
■ energy with national self-sufficiency；
■ reduced energy infrastructure；
■ sustainability；
■ increased affordability；
■greater tactical efficiency.。

對於新型作戰車輛有必要予以詳細計畫，包括作戰車輛、機動核反應器、機動製氫設備和運輸機、飛船及卡車等設備之規格。也要依據軍用標準發展一套新的作戰構想，根據核動力衍生之機動性、供應性和可靠之能源將使陸軍在可見之未來具備遂行作戰之潛力。本文構想謹提供國防部和陸軍部作廣泛密集之研究。

Detailed planning for the new land vehicle fleet is needed. It should include specifications for land vehicles, mobile reactors, mobile hydrogen manufacturing facilities, and transport aircraft, airships, and trucks. A concept of operations needs to be developed in accordance with military standards.Mobile, affordable, and reliable power sources based on nuclear power have the potential to permit viable operations of the Army for the foreseeable future. The concept warrants extensive study by the Department of Defense and the Department of the Army.

資料來源：《聯合武力季刊》
資料時間：2009年第一季