Mobile Nuclear Power *for* Future Land Combat

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In this article, we introduce the concept of survivable, non–fossil fuel powerplants 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.

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,

506th Expeditionary Communications Squadron (Bradley A. Lail)

Bladder farm at Kirkuk Regional Air Base, Iraq, provides fuel for operations

fixed storage facilities, and processing plants. To complement mobile energy, we focus on land vehicles that use hydrogen fuel and electricity for power.

Transportable, mobile powerplants 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.

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.

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, powerplants, storage vessels, generators, and power grids prime targets with low expected survivability in future regional conflicts.

Soldiers hook fuel blivets to C–47 Chinook for transport to forward elements

U.S. Army (M.W. Woods)

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.

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

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Motivation

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.

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:

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

■ 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.

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

■ 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.

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.

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:

■ 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.

■ 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."[5]

■ 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.

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.

Candidates for Vehicular Fleet

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.

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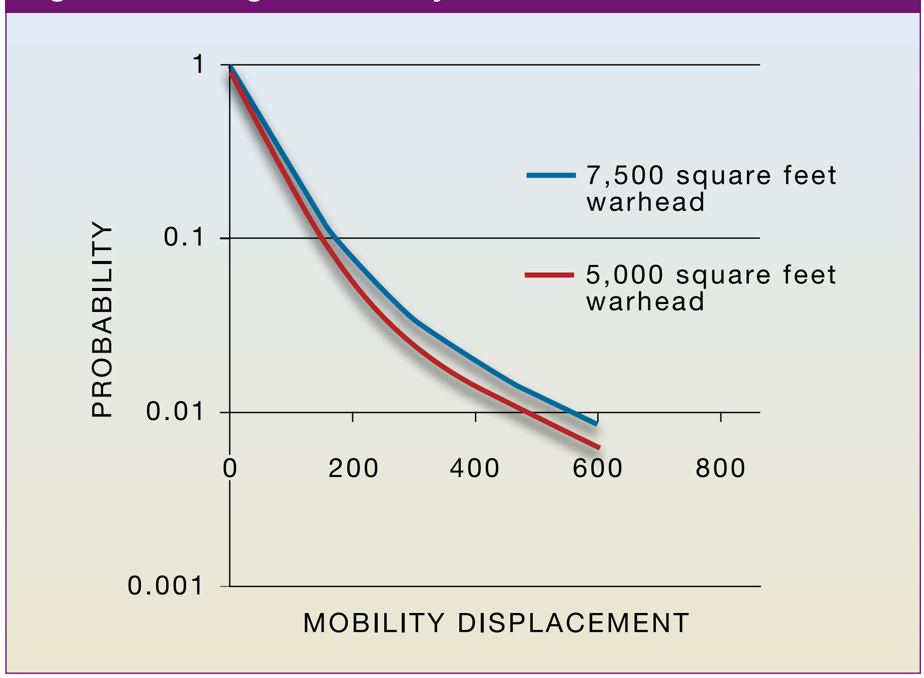
Over the longer term, military land fleets will consist of mixtures of electric vehicles, fuel-cell vehicles, hydrogen vehicles, and hybrids. All require energy rechargers or hydrogen fueling. We propose to provide both with theater-based mobile nuclear facilities.

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.

Battery-powered Electric Vehicles. Battery-powered all-electric vehicles are currently available commercially but are

Figure 1. Damage Probability of Mobile Reactor



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.

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.

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.[8]

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.

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.

Ohio Army National Guard Soldiers operate refueling point during training

196th Mobile Public Affairs Detachment (Zachary R. Fehrman)

Military Sealift Command fleet replenishment oiler USNS *Pecos* during underway resupply

U.S. Navy (Dustin Kelling)

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.

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.

Manufacturing Hydrogen

Alternative commercial methods for manufacturing hydrogen include:

- Room temperature electrolysis of water. Electrolysis is used to separate hydrogen and oxygen, the efficiency being about 70 percent.
- Methane-steam reforming (1,650°F). 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.
- Thermo-chemical decomposition of water (930–1,470°F) 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.
- Continuous steam-iron process (1,470°F). 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.
- 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.

The most practical option with potential for in-theater mobility is electrolysis of ionized water. The inefficiency of electrolysis can be alleviated somewhat by conducting the process at high temperature (1,000–1,400°F) and high pressure (450 pounds per square inch).[9] Methane-steam reforming is also feasible, but the long-term scarcity of methane weakens the option. Thermo-chemical decomposition of water is considered too hazardous, and the two processes extracting hydrogen from coal are not conducive to mobility and are highly polluting. In selecting high-temperature water electrolysis, we therefore choose to allow mobility, low pollution, and availability to override efficiency and low cost.

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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 (see figure 2).

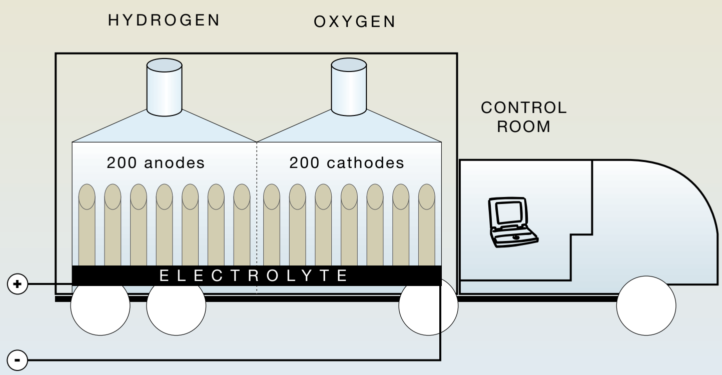
Candidates for Mobile Reactors

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

Figure 2. Schematic Mobile Electrolysis Unit



- 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 and Three Mile Island–type nuclear accidents
- resistance to terrorist attack. Tristructural-Isotropic (TRISO)–fueled reactors are attractive in this respect[12]
- 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 countries[13]
- a convincing waste disposal configuration
- resistance to explosive attack.

We have identified four reactor concepts[14] considered 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.

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.

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.

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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 scaled down to achieve mobility in anything significantly smaller than a Walrus airship.


All Army Future Combat System manned ground vehicles are hybrid electric

U.S. Army TARDEC (Paul Tremblay)

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.

Operational Concept

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 every day 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.

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.

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 fleet-wide monitoring of the reactors and electrolysis units by satellite to permit cost-saving, manpower-efficient troubleshooting.

Strategic Implications

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 do not 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 economy
- providing a means to supply low-cost power in support of humanitarian missions around the world.

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 theater-mobile 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.

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 be made 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
- minimized energy supply chain
- energy with national self-sufficiency
- reduced energy infrastructure
- sustainability
- increased survivability
- increased affordability
- greater tactical efficiency.

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. **JFQ**

NOTES

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9 "Electrolysis: The Electrolysis Process," available at <www.global-hydrogen-bus-platform.com/Technology/HydrogenProduction/electrolysis>.

10 Matthew L. Wald, "Hydrogen Production Method Could Bolster Fuel Supplies," *The New York Times*, November 28, 2004.

11 The Walrus Hybrid Ultra Large Aircraft was terminated in 2007. A smaller scale version is planned. Note that Walrus in principle offers 12,000-mile transportability in less than 7 days, comparing favorably with sealift (approximately 30 days) but unfavorably with the C–5A/B (1–2 days).

12 Tristructural-Isotropic (TRISO) fuel is used in a number of high-temperature gas reactors. Compared to the fuel in pressurized water reactors, TRISO is proliferation resistant and offers a self-contained waste storage configuration. It is also robust to explosive attack; exposure of radioactive materials to the environment would be minimal and difficult to exploit in a dirty bomb.

13 Breeders are legally producing electricity in France, Britain, Japan, China, and Russia.

14 For an entry-level discussion of reactor concepts, see Marvin Baker Schaffer, "Nuclear Power for Clean, Safe and Secure Energy Independence," *Foresight* 9, no. 6 (2007).

15 The C–5 Galaxy with modernization improvements is expected to be operational well into the 21st century. See "C–5 Galaxy," available at <www.af.mil/factsheets/factsheet.asp?id=84>.

16 To a lesser extent, the same mobility argument applies to survivability against short-range mortar and rocket attack. Because of their relative inaccuracy, they are scatter weapons with inherently low effectiveness.

17 Robert A. Pfeffer and William A. Macon, Jr., *Nuclear Power: An Option for the Army's Future*, available at <www.almc.army.mil/alog/issues/SepOct01/MS684.htm>.